DEVELOPMENT FLIGHT INSTRUMENTATION FOR THE REDESIGNED SOLID ROCKET BOOSTER FOR THE SPACE SHUTTLE PROGRAM

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ABSTRACT

The NASA Marshall Space Flight Center, in Huntsville Alabama, decided in July 1986, to upgrade the development flight instrumentation (DFI) system to monitor the performance of the redesigned solid rocket boosters. On September 29, 1988 Space Shuttle Discovery was successfully launched from Kennedy Space Center, Florida with the redesigned solid rocket boosters carrying the upgraded DFI system which consists of 24 electronic black boxes, over 200 sensors, and 91 cable assemblies. Many contractors supplied parts of the DRI system to NASA Marshall, two thirds of the black boxes were designed and developed by the Aydin Vector Division. The remaining boxes were supplied by Kodak Data Tape, in Pasadena, California and Teledyne Brown Engineering, in Huntsville, Alabama. This paper will show the entire DFI system with particular emphasis on the major subsystems such as the PCM subsystem which consisted of one Programmable Master Encoder and three Remote Slave Encoders, the Frequency Division Multiplexer and the Wideband signal conditioner units. These units conditioned all of the information received from the sensors and multiplexed this data into one encoded PCM data stream and two independent FM composite outputs.

INTRODUCTION

On January 28, 1986 the space shuttle program experienced a major disaster. The Challenger exploded during liftoff taking the lives of seven astronauts and totally destroying one of America’s Space Shuttle Systems. On this fateful day the shuttle program came to a temporary halt. A full scale investigation to determine the cause of the accident was immediately started by the U.S. Government and NASA.

The cause of this accident was discovered to be a faulty solid rocket booster joint which allowed hot exhaust gases to escape and ignite the external fuel tank. Scientists and engineers from NASA and the booster contractor began the redesign effort of the solid rocket boosters. Many months of redesign and retesting followed. As the redesign and retesting effort progressed, NASA began work on an improved development flight instrumentation system to monitor the effects of the redesigned booster. The DFI system was patterned after its predecessor utilizing the latest state-of-the-art technology in instrumentation systems. Increased reliability, measurement capacity, accuracy, and safety of flight were stressed by NASA and all associated contractors. This paper will describe the DFI instrumentation system that was developed, manufactured, qualification tested, and subsequently flown on STS-26 on September 29, 1988.

DFI SYSTEM OVERVIEW

The DFI system consisted of 24 electronic black boxes, over 200 sensors, and 91 cable assemblies. The system was installed in each booster in the forward skirt area (Figure 1). The quantity of measurements taken on STS-26 was 698. These measurements were located throughout the boosters as shown in Figure 1.

The DFI system consisted of one main power distributor, two frequency division multiplexers, two wideband signal conditioners, one PCM subsystem which consisted of one master encoder and three remote encoders, one chamber pressure signal conditioner, one tape recorder, and one battery. Each of these boxes were interconnected as shown in Figure 2.

The DFI system utilized on previous shuttle flights was basically the same as the present system. All data was multiplexed by two FDM units and one PCM unit, and recorded on tape. During liftoff, one DFI output was recorded on the orbiter tape recorder while all data from the other DFI outputs was recorded on the DFI recorder. After recovery of the boosters the tapes were analyzed to determine the flight test results.

The redesigned system used the previous tape recording concepts except that the PCM subsystem was improved for speed, accuracy, and increased channel capacity. Two wideband signal conditioner units were added to the system to replace the previous signal conditioners which were scattered throughout the boosters and required external adjustment prior to each flight.

DFI DISTRIBUTOR

The DFI distributor provided the interface between the DFI system, operational flight instruments, ground support equipment, and the solid rocket motors. The isolation between the operational equipment and the DFI system was the main contribution of the distributor. All power up sequencing for the DFI system was directed thru the distributor via the calibration commands, mission events, and operate commands which were received from ground support equipment and operational equipment. The distributor design, development and manufacturing was the responsibility of Teledyne Brown Engineering in Huntsville, Alabama. Teledyne Brown also had the DFI system design responsibility.

DFI TAPE RECORDER

The recorder used on the present DFI system is identical to the one used on previous flights. The purpose of the recorder is to store the multiplexed outputs from each FDM unit and the PCM subsystem. The recorder contained 14 tracks for recording 4 redundant outputs from each FDM unit and 3 outputs from the PCM master encoder. The original DFI system concept had 2 tape recorders, one for flight recording, and one impact recorder to prevent loss of data at water landing impact. During preflight qualification testing in the mid 1970’s, NASA discovered that the flight recorder was not used any longer. The DFI tape recorder was supplied by Kodak Data Tape, in Pasedena, CA under sub-contract from Teledyne Brown Engineering.

WIDEBAND SIGNAL CONDITIONING UNIT (WBSC)

The WBSC units were connected to analog data sensors for acceleration, vibration, strain, and timing measurements. The input frequency of the data was 250 Hz to 8000 Hz. Two WBSC units were used in each booster. Each unit was configured via plug-in signal conditioner modules to accept the specified types of sensor outputs and condition them into 0 to 5V signals for further processing by the FDM units. The types of signal conditioners provided by the WBSC units are voltage, full or quarter bridge completion/ amplification/filter circuits, charge amplifiers, and constant current low impedance voltage conditioners.

Each WBSC unit contained 28 charge amp type circuits, 2 auto balance bridge conditioners, 4 voltage conditioners, and 4 bridge completion circuits. These 38 conditioners were programmed to 30 outputs via 2 plug-in program selection cards. The mix and type of conditioners to be used for each configuration was flexible for each unit. The WBSC unit contained its own power supply module which provided the sensor excitation voltages, and the voltages required to operate the unit. Two plug-in overhead cards were used for the unit calibration and built-in test equipment (BITE) status indicators.

The calibration circuit responded to the system calibrate command from the distributor and switched all bridge and charge amplifier channels from data mode to cal mode. The timing, voltage isolation, and thermisistor channels remained in the data mode at all times.

The bite circuit provided two discrete outputs which indicated the WBSC power supply status for each of two groups of 15 channels. The power voltages for each group of 15 outputs were summed into one discrete bite output which indicated a logic one (1) if the group was operational, or a logic zero (0) if the group failed. These bite indicators were sent to the distributor for further processing to the ground support equipment. This output was used to monitor the WBSC health status prior to launch. For a detailed block diagram of the WBSC unit see Figure 3. The WBSC were supplied by Aydin Vector Division.

FREQUENCY DIVISION MULTIPLEXER UNIT (FDM)

Two FDM units were used in each booster. Each unit contained two independent 15 Fm channel multiplexers which accepted 30 inputs, from each WBSC unit. Each multiplexer contained one crystal controlled oscillator for tape speed compensation and provided up to 4 multiplexed outputs, mux 1 contained 4 outputs and mux 2 contained 3 outputs. Each output was provided by an individual driver amplifier module. Two outputs were connected to the tape recorder, the third output was connected to the distributor for ground support, and the fourth output from mux 1 was forwarded to the orbiter recorder via the distributor. The fourth output was used to verify event timing of each booster via the time code signals from each booster. The IRIG-B time code was generated by the master PCM encoder, conditioned by the WBSC unit, multiplexed by the FDM, and sent to the orbiter recorder for right and left booster timing comparison.

Each FDM multiplex consisted of 3 plug-in cards which contained 4 CBW VCO channels, 1 card which contained 3 CBW VCO channels and one crystal reference oscillator, and 2 cards which contained up to 4 mixer/driver amplifiers per card. Each output was transformer coupled to provide the required isolation from the distributor and tape recorder.

The FDM also contained its own power supply which converted the 28 Vdc input power to the required FDM operating voltages and provided input power isolation. Five plug-in overhead cards provided the calibration circuits and bite indicators.

The calibration circuit consisted of a set of 4 plug-in cards, two of which provided the precision calibration voltages of 0, 1.25, 2.5, 3.75, 5.0 Vdc, and a 50 Hz oscillator. The other two cards contained the cal/data switches, 15 inputs per card. The FDM calibrator has two modes of calibration, manual or automatic. In the manual mode the FDM could accept commands from the distributor and switch from data to any one of the 5 dc calibration levels or the 50 Hz ac level. In the automatic mode the FDM would automatically step from data thru each of 5 dc cal levels, the 50 Hz ac level back to data mode. Each level was held for one second. The FDM cal commands were sent over 3 verification control lines which provided logic 000 thru logic 111 (decimal 7). All zero, or open inputs provided the data mode. All other inputs logic 001 thur logic 1ll commanded manual or automatic modes.

The bite circuit provided three discrete outputs which monitored the multiplexed composite outputs and indicated a drop in composite level of 3 dB or more. One bite output summed the mux 1 tape recorder outputs, the second bite output summed the mux 2 recorder outputs, and the third bite output reported the status of the fourth mux 1 output which went to the orbiter recorder. One additional status bit was used to determine if the FDM was in the data or cal mode. A logic 1 indicated data mode and 0 indicated cal mode.

The FDM units were supplied by Aydin vector Division. All FDM units functioned identical to previously supplied units except that they incorporated the latest state-of-the-art parts, materials and processes. See Figure 4 for a block diagram of the FDM unit.

DFI PCM SUBSYSTEM

The PCM subsystem was a completely new design for this application. It consisted of one programmable master unit (PMU) and three identical remote slave units (RSU). The PMU was the central controller for the PCM subsystem. This unit contained 5 plug-in signal conditioner cards, 2 discrete digital multiplexer cards, a set of 2 cards which provided the IRiG-B time code outputs, 1 card for programming the PCM subsystem, a set of 2 cards for BITE outputs, and 11 cards of overhead functions. Thru the 5 signal conditioner cards, the PMU could accept up to 80 differential inputs, and 32 thermocouple measurements (16 type S and 16 type K). The discrete digital multiplexers could accept up to 40 discrete inputs, 20 per card.

The PMU communicated to the RSU’s by 5 differential paired lines. The PMU utilized 3 paired lines to send serial address data, word clock and bit clock information to the RSU’s. The RSU’s utilized the remaining 2 pairs of lines to send the data and returned bit clock to the PMU. The PMU had the capability of communicating to up to 4 RSU’s. Each PMU had 4 sets of 5 paired inputs. One set for each RSU. By using this type of communication, if one RSU lost a line, the other 3 units could still communicate to the PMU.

Each of the 3 RSU’s were identical in configuration. They contained 3 overhead cards, 13 signal conditioner cards, consisting of one RTD conditioner, 3 each 350 ohm quarter bridge cards, 7 each 1000 ohm quarter bridge cards, and 2 full bridge cards. Six excitation cards provided the excitation voltages for all of the bridges. This complement of cards allowed each RSU to accept 16 RTD inputs, and 112 bridge inputs, for a total of 128 measurements. The total PCM subsystem capability was 128 x 3 = 384 plus 80 PMU inputs = 464 and 40 discretes.

The PMU was designed and developed similar to Aydin Vector standard data acquisition systems utilized on many previous aerospace programs. Some improvements and program unique features were included in the design. One of the most flexible features was the external EE PROM programming of the systems. The entire flight format content was under program control of the user, including the frame sync patterns, word locations, bit rates, channel gains and offsets, frame length’s etc. The system could be programmed by the user via an 8 wire interface utilizing RS-232 protocol. The programming interface was compatible with a IBM PC-AT, PC-XT or equivalent computer. The EE PROM was capable of storing up to 2 flight formats. In the DFI system the bit rate was fixed at 384 K bits per second because of the tape recorder frequency response. The PMU was capable of 3-4 times more speed than required. The word size was fixed at 10 bits per word, however the unit was designed for up to 12 bits per word.

In order to handle the large quantity of measurements, up to 464, a track split circuit provided up to 4 PCM subset outputs for tape recording. The contents of each subset output was also under program control so the user could specify the measurements contained in each subset output. For critical measurements selected words could be programmed into all four outputs for redundancy. The PCM subset outputs were connected to the tape recorder and on PCM composite output was provided for ground support.

The capability of programming the channel gains and offsets was used to preset the bridge balance during the pre-launch testing. Up to 32 offsets and 8 gains from 1X to 250X were provided by a programmable gain amplifier (PGA). One PGA was contained in each PMU and RSU in the PCM subsystem. The offsets and gains were programmed on a channel-by-channel basis. The gains were typically fixed by the type of measurement and projected range. The offsets were initially programmed to the nominal offset for each channel. Static measurements were taken after the system was connected to the sensors. Data analysis determined the required offset which was then reprogrammed into the EE PROM prior to flight. This method allowed NASA to balance all bridges and sensors prior to flight and this enhanced the data accuracy.

The PCM subsystem included a calibration circuit to calibrate all bridge circuits. When a logic zero was applied to the cal command input, for a time duration of at least one major frame, the master unit would broadcast a cal command instruction over the master/remote data bus. When a logic one (1) was applied to the cal command input, the master would generate the cal instruction for up to one additional major frame and cease broadcasting the cal instruction until a logic zero was again applied to the cal command input. When the cal instruction was being broadcast a fixed value shunt resistor was connected across all bridges. The output response was predetermined by the resistor value and the individual channel gain and offset.

The bite circuitry, contained in the PMU on 2 plug-in cards, was used to validate the health of the PCM subsystem prior to launch and the accuracy of the data during flight. The bite circuit has two modes of operation, the absolute mode and range mode. In the absolute mode data was compared to a bit pattern whose word size and format are identical to the valid word.

In the range mode, data was compared to low and high threshold limits pre-programmed in the bite circuit. The bite circuit provided seven flag outputs for evaluation. By comparing a selected data word in the PCM steam to predetermined parameters the bite output flag indicated pass, flag high, or fail, flag low. For the DFI PCM subsystem the bite was programmed to monitor the major frame sync pattern, major frame word count, time code carrier present, and analog calibration of one channel in the master unit, and each remote unit. The absolute mode was utilized for all monitors except the analog calibration which used the range mode. In order to use the range mode, a precision voltage was injected into one pre-selected master unit analog channel, and a precision resistor was installed on one selected RTD channel in each remote unit. These channels were pre-programmed in the PCM steam and compared to low and high limits in the bite circuit which in turn set the applicable flags to a pass/fail condition. This featur allowed the user to evaluate the input to output condition of each PCM box in the PCM subsystem in real time. By inclusion of the bite flags in the PCM output stream the status of the system was verified during the flight. The bite functions, limits, and modes were also programmed via the RS-232 interface.

The time code generator circuitry was contained in the master unit utilizing two plug-in cards. The signal was generated in a modified IRIG-B format. The signal was a 1 kHz sine wave, modulated by a serial modified IRIG-B format, signal BCD was modified to contain only seconds and minutes as BCD information and binary information for milliseconds. A reset line was provided such that the generator could be reset to zero time, upon command from the distributor, and restart counting from zero. The output from the time code generator was included in the PCM data steam and also inserted in the WBSC/FDM units for timing correlation.

The PCM subsystem was designed, developed, and qualification tested by Aydin Vector Division under subcontract with Teledyne Brown Engineering. See Figure 5 for a block diagram of the programmable master unit and Figure 6 for the remote slave unit.

CONCLUSION

The entire DFI system was delivered to Kennedy Space Center in June 1988. The system was installed in the boosters of STS-26 prior to roll out on 4 July 1988. The system was checked out by NASA personnel prior to roll out and again on the launch pad. On September 29, 1988, the DFI system was powered up at T-9 minutes in the launch count down. All bite signals indicated that all DFI boxes were operating within acceptable limits. Nine (9) minutes later Space Shuttle Discovery, STS-26, was successfully launched into space. The DFI equipment bite indicators were monitored via the orbiter during liftoff and boost phases. All bite indicators remained within the acceptable limits throughout the flight.

After successful booster separation, and splash down, both boosters were recovered and returned to the Kennedy Space Center. The DFI equipment was removed from the boosters and the tape recording was forwarded to Marshall Space Center for evaluation. No external damage was found to any DFI boxes.

In November 1988, Teledyne Brown Engineering, released a SRB DFI performance report of STS-26. This report summarized how each measurement performed. In summary, the DFI performance was highly successful. All measurements exhibited high quality recordings. Over 94% of the measurements contained good data, 33 sensors provided no data because they were damaged during liftoff. In general, NASA was extremely pleased with results obtained by the DFI system.

ACKNOWLEDGEMENT

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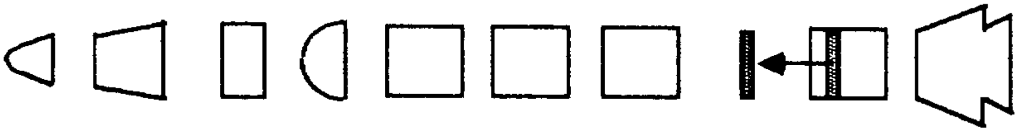
DFI MEASUREMENTS (LEFT/RIGHT)



MEAS LOC. / TYPE MEAS.	NOSE CAP	FRUSTRUM	FWD SKIRT	DOME	FWD MOTOR SEGMENT	FWD/MID MOTOR SEGMENT	AFT/MID MOTOR SEGMENT	ETA RING	AFT MOTOR SEGMENT	AFT SKIRT & NOZZLE	TOTAL
STRAIN				2/2	17/25	18/18	34/34	4/0	73/73	41/41	189/193
FORCE		6/6	6/6					6/6		2/2	20/20
ACCEL		2/2									2/2
VIBRATION			13/13	3/6		2/2	3/3	3/3	6/6	10/10	40/43
PRESSURE		1/0	4/4		12/0					6/6	23/10
TEMP.	1/0	3/0	3/3	1/1		3/3	3/3			21/19	35/29
HEAT FLUX	1/0	2/0						2/0		7/2	12/2
VOLTAGE			8/8					1/1			9/9
CURRENT			3/3								3/3
TIME			1/1								1/1
EVENTS			25/25							1/1	26/26
TOTAL	2/0	12/6	65/65	6/9	29/25	23/23	40/40	16/10	79/79	88/81	360/338
GRAND TOTALS:			LEFT - 360				RIGHT - 338		LEFT AND RIGHT - 698		

NOTE: THE DFI SYSTEM WAS MOUNTED IN THE FWD SKIRT

FIGURE 1

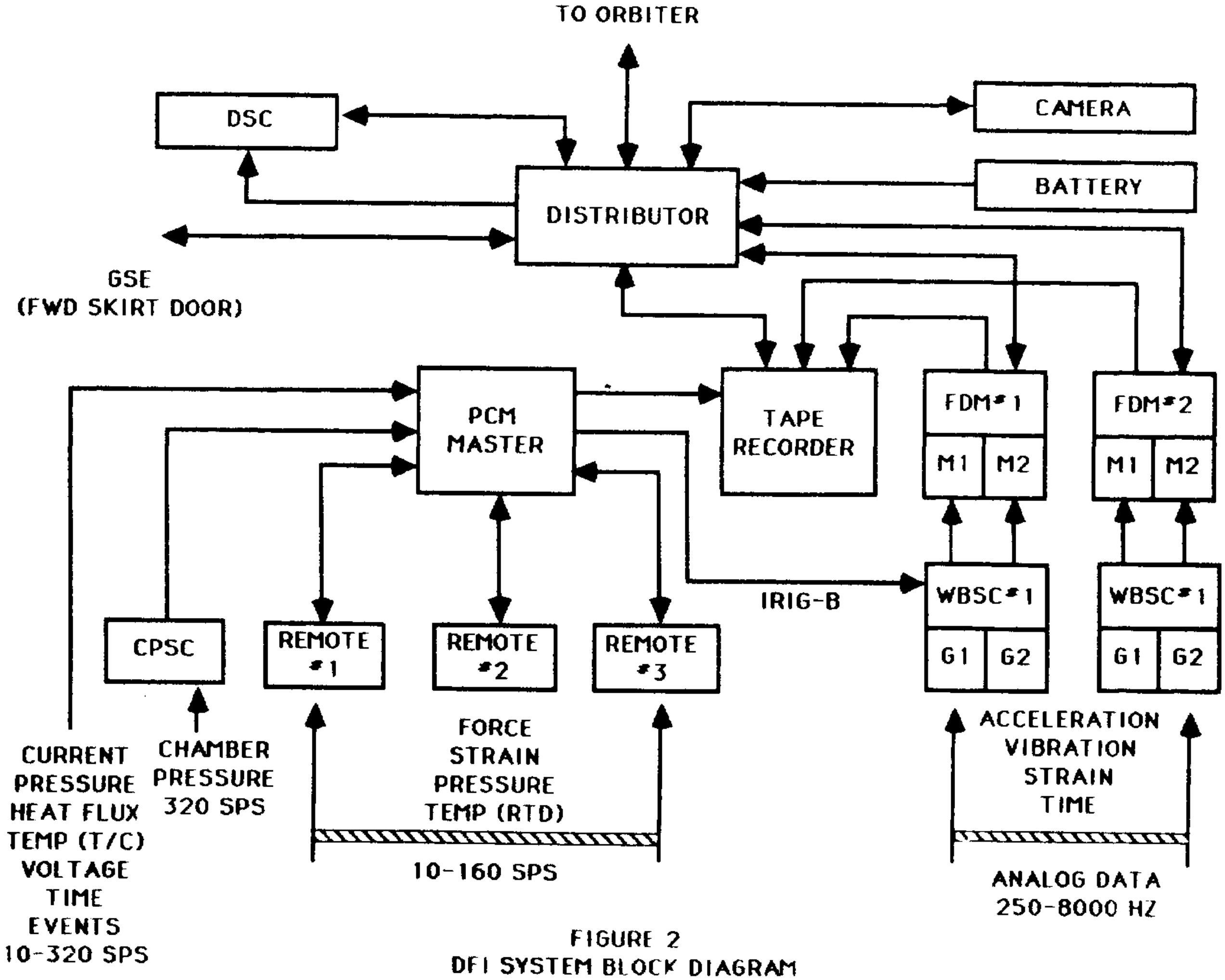


FIGURE 2
DFI SYSTEM BLOCK DIAGRAM

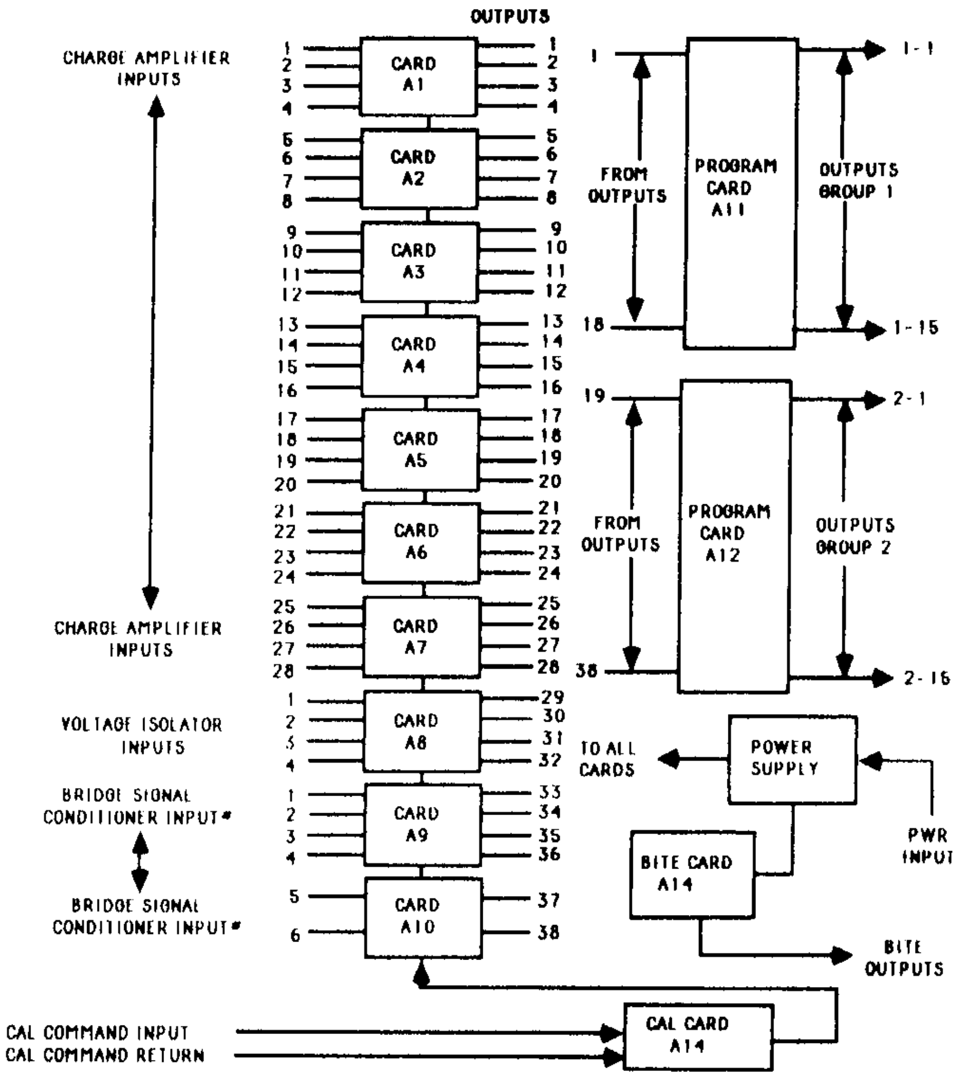


FIGURE 3
WBSC BLOCK DIAGRAM

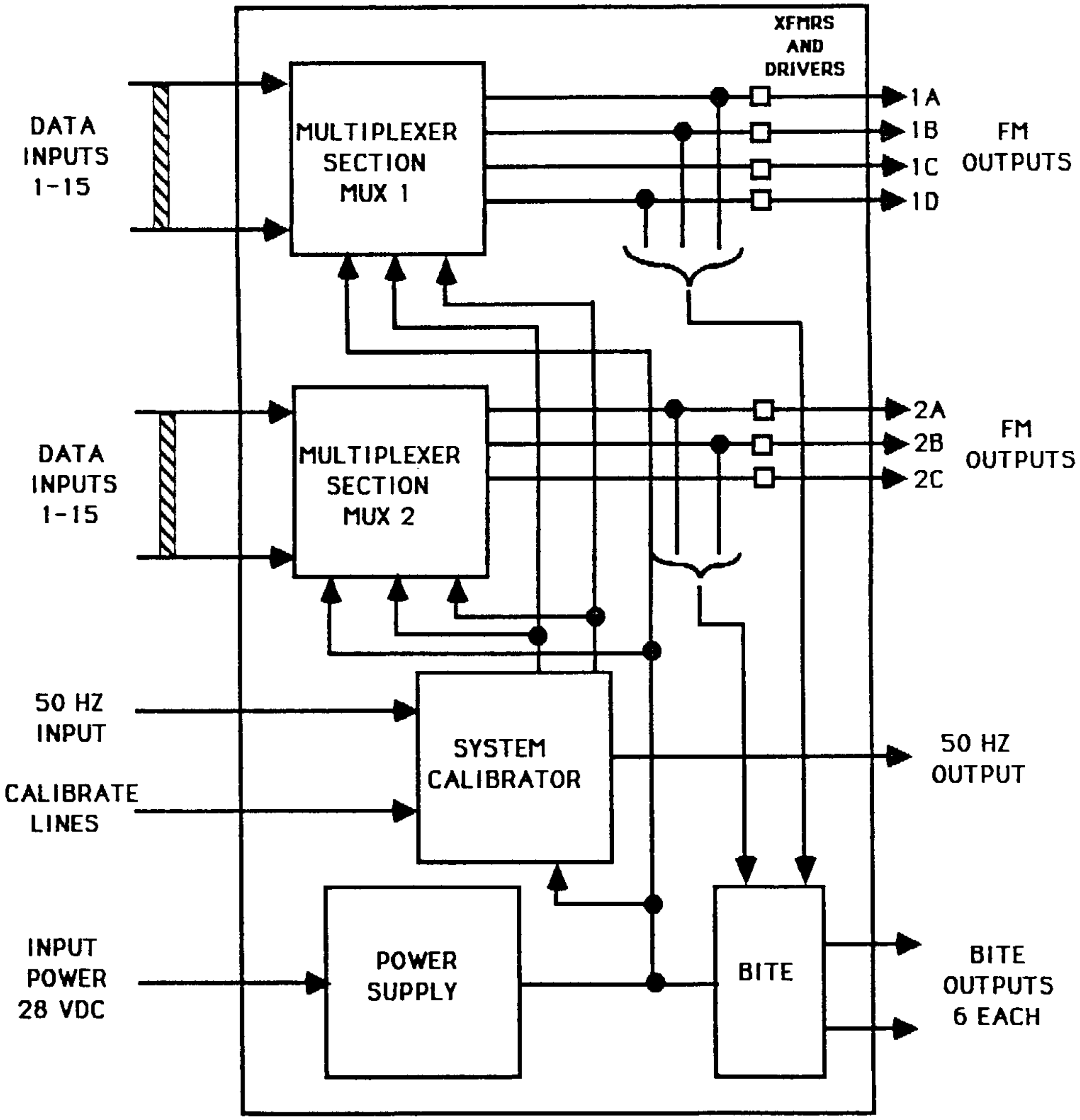


FIGURE 4
FDM BLOCK DIAGRAM

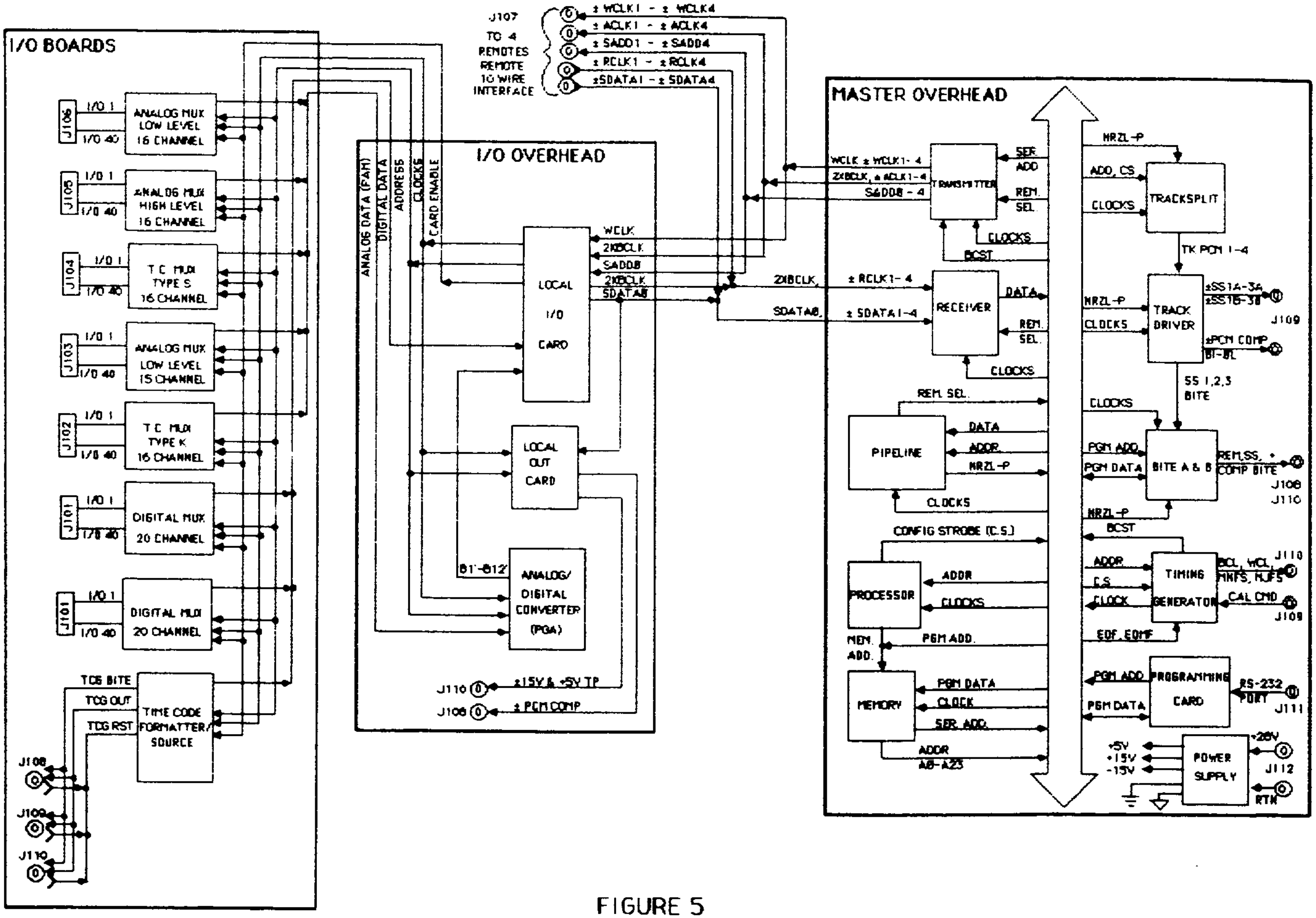
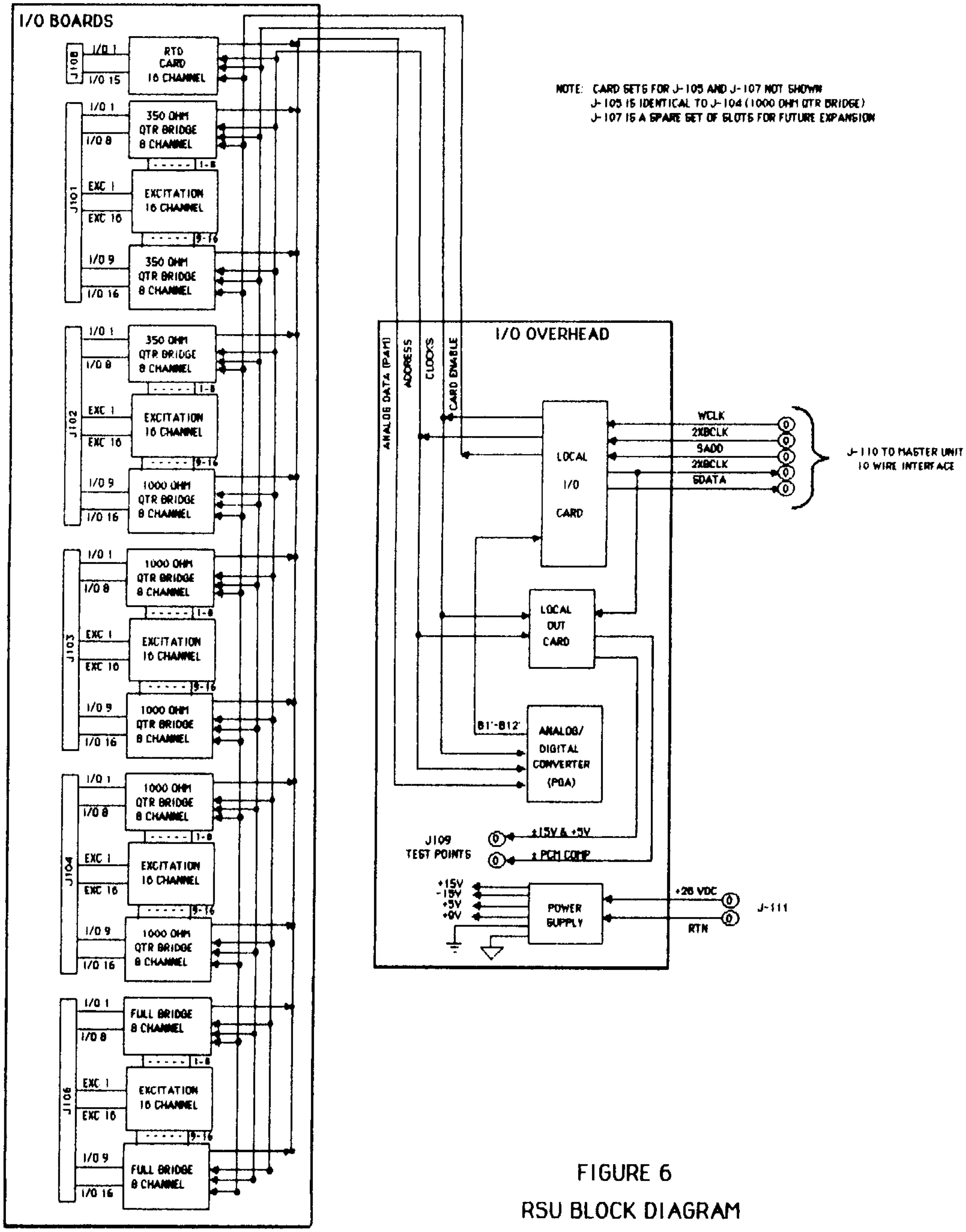


FIGURE 5
PMU BLOCK DIAGRAM



NOTE: CARD SETS FOR J-105 AND J-107 NOT SHOWN
J-105 IS IDENTICAL TO J-104 (1000 OHM QTR BRIDGE)
J-107 IS A SPARE SET OF SLOTS FOR FUTURE EXPANSION

FIGURE 6
RSU BLOCK DIAGRAM