SPACE SHUTTLE INFRARED PYROMETRY

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ABSTRACT

In March of 1982 4700 temperature measurements were made of the space shuttle lower surface during its entry from orbit. These measurements were taken in less than 7 ms from a distance of 52 km (32 miles) by an electro-optical "pyrometric" system aboard the NASA C141 Kuiper Infrared observatory. The total system is described briefly with the detector amplifiers, system grounding and noise described in detail.

INTRODUCTION

Early in 1976, NASA-Ames Research Center expressed an interest in the Infrared Imagery of heated surfaces such as the Space Shuttle during entry. Such a system was designed and built for NASA Ames by Martin Marietta in 1978 and 1979. It was delivered to NASA for installation aboard the Kuiper C141 airborne Infrared Observatory in early 1980, The heart of the optical system is the F/17 91.5 Cm reflecting telescope which was inertially stabilized during the shuttle passage through its field of view. See Figure 1. The heart of the detector system is 600 indium antimonide sensors in two linear arrays. The measurements referred to were produced by 2/3 of the shuttle image passing at right angles over approximately 68 of the detectors in one of the linear arrays. The system functioned as a "push broom camera". Each time the shuttle had moved about a foot, the output current of each detector had been amplified to a high level signal, sampled, converted to a 12 bit number and stored in electronic memory. One significant feature of the system is that all key electronic hardware is off-the-shelf. Two hundred Burr Brown 3554 wide band operational amplifiers were used with 7 1/2 meg ohm feedback resistors for the first stage current amplifiers. These were packaged in a conventional manner on forty PC boards. Twenty Datel analog-to-digital conversion data system modules were used to provide the required throughput of 4,000,000 samples per second (48 megabits/second). The system noise level on a typical channel is two counts out of the 4099 counts that represents full scale. The system design measurements range was 600° K to 1700° K. The nominal detector current at these two temperatures was .27 nanoamperes and 300 nanoamperes respectively. The two count noise floor represented about .16 nanoamperes of detector current.

OVERALL SYSTEM DESCRIPTION

Figure 2 is a block diagram of the system. The 600 detectors in two linear arrays are grouped into 200 subsets of three detectors each. This is possible because the shuttle image is not large enough to fall on more than one detector in each subset. Each subset has its own image plane amplifer channel. Each of the 200 amplifier channels is assigned to one of ten multiplexer gates in one of 20 analog to digital conversion modules. Each conversion module provides 20,000 sps on each channel. Conversion is to 12 bits. A 60 bit wide buss transfers the data to a one million bit memory. The data also drives a 12 bit adder and is summed to generate a data save function. Front panel switches on the electronics rack are provided which allow the data save criteria to be set into the logic. When the leading edge of the shuttle image crosses the first row of detectors, the large signal increase causes the output of the adder to exceed the data save criteria and a data save function is generated. The system, which has been writing memory continuously, will then write only enough additional word locations to guarantee the storage of the complete shuttle image. After which the system will begin to write into a second block of memory continuously and repeat the data save process when the shuttle image arrives at the second linear array.

In addition to the 20 data system modules and the memory, the electronics rack also contains all power supplies, a precision voltage calibrator, all manual controls and displays, a DVM, oscilloscope, 9 cards of logic and one servo amplifier board.

A key feature of the system is the calibration mode. Just prior to a data take, all channels are calibrated end to end by the injection of current into each image plane amplifier. A multistep calibration is performed and the data written into memory for use in data reduction. The logic also provides an interface with one of the existing aircraft mini-computers. Both calibration data and shuttle data are transferred to that system for recording.

During the data take mode the servo amplifier drives the small tracking telescope in one degree of freedom. The image in the tracking telescope is modulated by a rotating reticle such that position information of the approaching shuttle, relative to the aircraft, can be extracted from the resulting detector signal and provided to the computer to generate all required servo signals for driving the tracking telescope and the main telescope. Approximately 25 seconds is available to move the large telescope up to ±2 degrees in elevation and have the shuttle pass through its field of view.

THE MEASUREMENT TRANSFER FUNCTION

An analogous way to look at this infared pyrometric temperature measuring system is to compare it to a normal telemetry system. The thermal energy in the surface tiles of the shuttle is the source of the carrier power, quantum processes at the atomic level generate the carrier frequencies and the tile surfaces are the radiating antennas. This is commonly known as black body radiation. As the tile temperature increases, both the center frequency and amplitude of this broadband radiation increases but both of these effects are accounted for in the calibration of the receiving system. Because of the band limiting filter in the receiving system (2.0 to 2.6 microns), the telemetry signal can be thought of as amplitude modulated roughly as a 5th power of temperature at a center frequency of 130,000 GigaHz (wavelength of 2.3 microns). The antenna pattern from a given increment of shuttle radiating surface is essentially a hemisphere so only a single calibration curve is required to relate shuttle surface temperature to digital counts for each channel. The receiving antenna for the signal is the 91.5 cm mirror in the aircraft mounted telescope. It and its secondary constitute a parabolic reflector. In the focal plane of the telescope are 600 individual receiving elements. Each is an indium antimonide diode detector which converts the received IR photons into electrical current. The received signal strength is independent of range because as the range increases and signal strength decreases as a function of the square of the range, the radiating area of the shuttle surface seen by a given detector increases as a square of the range. The two effects cancel. With the shuttle surface at 1700K° approximately .5 microwatt of IR energy falls on each one twentieth of a millimeter square detector. That energy is converted into .33 microamps of current. The first transresistance operational amplifier pulls the detector current through a 7.5 megohm feedback resistor generating -2.5 volts. A second operational amplifier provides a gain of 4 and bandlimits the system to about 30 KHz. The resulting -5 to +5 volt signal is then carried through about 20 feet of twisted shielded pair to its assigned channel in the data system. There it is sampled and converted to twelve bit numbers and stored in memory. This describes the analog measurement function end to end. The nonlinear nature of the measurement is shown in the typical laboratory calibration data in Table 1.

IMAGE PLANE TRANSRESISTANCE AMPLIFIER

Figure 2 is the schematic for a single image plane amplifier. The detector is used in the zero voltage mode. It is a single ended current source working against system ground. The 3554 operational amplifier has its positive lead referenced to this same ground. The detector substrate ground, being common to the 600 detectors, essentially dictated a single ended system from the detectors to the AID converters.

The greatest single risk in the electronics system design was the decision to package conventional parts on PC boards and produce a physically large image plane package. The concerns were the large amount of input capacitance of each amplifier, the distribution of a single ground reference to 40 PC boards and the effects of conducted noise. Several amplifiers were tested for this critical application and the Burr Brown 3554 was selected because of its ability to maintain low output noise with high input capacitance and its slew rate and rapid settling time in response to the steep current ramp function produced when the shuttle image leading edge moves across a detector. Figure 5 is test data from early in the program. The amplifier test circuitry was about the same except the feedback resistor around the 3554 operational amplifier was only 1.98 megohms. In the final design this was 7.5 megohms. The IR pulse was generated by chopping an IR beam with a rapidly rotating toothed disk. The data was taken at 10 times the normal sample rate to characterize the overshoot and settling time. Some of the 3554 characteristics are: open loop gain 100,000, gain bandwidth product 225 to 1700 MHz, settling time to .01% = .2 micro sec., and a slew rate of 1200 v/micro sec. In addition the total channel noise output in the test circuit was only 1.8 mv peak to peak with 39 picofarads of input capacitance. It was much higher with the other amplifiers tested. This provided confidence that conventional packaging could be used and that three detectors and 20 inches of unshielded lead wire could be tolerated in the final design.

AMPLIFIER PC BOARD

Figure 4 shows the layout of the key parts on the PC board. It is a four layer board with circuitry on the component side, ±15 volt power on the two internal layers and a full ground plane on the back. Five channels of detector current are brought in on one end of the board and all other functions are brought in on the opposite end. The power planes end at the input amplifiers so that the sensitive input signal circuitry stray capacitances see only the ground plane in their own board and the ground plan in the adjacent board. The only components on the sensitive end of the board are the 7.5 meg ohm feedback resistor, the calibration resistor of the same size and the 15 picofarad trim capacitor. The board also contains a maximum of decoupling capacitance.

GROUNDING AND NOISE

In the design phase a conventional method of system grounding could not be conceived because of the constraints imposed by the single ended nature of the image plane detectors, the image plane amplifiers and the data conversion modules. The lack of differential balanced signals anywhere in the design resulted in a single ground system being common all the way from the detectors to the rack mounted logic power supplies. The system was designed such that several configurations of grounds and shields could be conveniently tested in the full up system configuration and the one resulting in the lowest noise levels selected. It is interesting to note that the best to the worst grounding systems varied by a factor of 30 in noise levels but schematically were essentially identical.

Figure 6 is a grounding schematic/pictorial. In two places the grounding is brute forced, The base of the image plane is a 30 inch diameter 5/8 inch thick aluminum plate which serves as a pressure barrier between the passenger cabin and the unpressurized telescope cavity on the aircraft. This plate is electrically insulated from the aircraft structure and used as the ground reference for the image plane amplifiers. The same heavy material is used for the card cages which are bonded electrically to the plate. Then the 7 1/2 inch square ground plane on the back of each of the forty PC boards is wedged tightly against the surface of the card slots milled into the heavy plate. Two ground wires are brought from the detector substrate for redundancy. One wires goes to the ground plane on board #1 and the other to board #40. Signal current from all 200 amplifier channels is returned through this massive ground network to the two ground wires and then down to the detectors. The reason for this extreme care in the image plane grounding becomes clear when the input to the transimpedance amplifier is examined. The amplifier has a gain of 100,000 with 20 inches of wire routed to it. Any noise or voltage gradient of 5 nanovolts from DC to 50 KHz in the signal ground plane loop creates about one count of system noise. The second critical ground is for the 20 data system modules. The modules are mounted in three vertical columns in a custom designed chassis. The front of the chassis is about 21" square. To provide as low impedance ground as possible for these modules, heavy copper buss bar (1/4 x 1 inch) is installed around the perimeter of the chassis and two more heavy bars placed vertically between the three data module columns. All joints are silver soldered or soldered and bolted. A short wire is run from the digital card ground in each module to the nearest buss bar. The only problem at this point was how to cable the image plane amplifiers to the data system modules. They are separated by 20 feet. All modules are cabled the same. Only one will be described. Each data modules handles 10 analog channels which originate on image plane amplifier boards. Ten twisted, shielded pairs are used. The positive signal from each amplifier is routed to one conductor of a twisted pair and wired to one multiplexer gate input in the data module. The ten ground wires are bundled together and wired to the data module input ground on the analog board. Note that this ground is tied internally to the module digital ground by the manufacturer. The other end of the 10 ground wires are grouped into two sets of five and wired to the ground plane of the originating board. The shields for all ten twisted pairs are bunded and tied to the heavy data chassis buss bar ground as audio shields. The buss bar is then tied to the electronics chassis single point ground. Obviously all electronic power supplies were also referenced to this single point ground. Also to reduce system noise, every non-signal function wired to the image plane went through an RF filter and then a very low pass filter made from power resistors and large tantulum capacitors. Totally, 130,000 microfarads of filter capacitance is used in the image plane filters. An EMI cover was also installed over the image plane amplifiers to provide a protected electromagnetic environment.

SYSTEM NOISE LEVELS

In a normal noisy electronics laboratory most channels in this system would toggle one bit, a few two bits. Noise levels on the aircraft are about the same.

CONCLUSION

Two hundred channels of high gain, fast response, electronics was successfully designed and fabricated using off-the-shelf components. These electronics and the rest of the experimental system add a powerful new capability to the Kuiper Infrared observatory. The temperature data obtained on the referenced flight is not available for publication but every indication is that the signal processing electronics functioned as designed during the data take.

RELATED PUBLICATIONS

1. Swenson, B. L., Edsinger, L. E., Preliminary Analysis of Remote Infrared Imagery of Shuttle During Entry - An Aerothermodynamic Flight Experiment, NASA TM73,251, Ames Research Center, Moffett Field, California 94035, April 1977.

2. Chocol, C. J., Infrared Imagery of Shuttle, MCR76-564, Martin Marietta Corporation, Denver, Colorado 80201, NASA Contract NAS2-9381, August 1977.

3. Chocol, C. J., Remote Infrared Imagery of Shuttle Du ring Entry, Martin Marietta Corporation, Denver, Colorado 80201, NASA Contract NAS2-9381, August 1977, Published in SPIE Vol. 190 LASL Optics Conference (1979).

T°K	COUNTS
600	5
800	58
1000	262
1200	732
1400	1490

TABLE I
TEMPERATURE/COUNTS

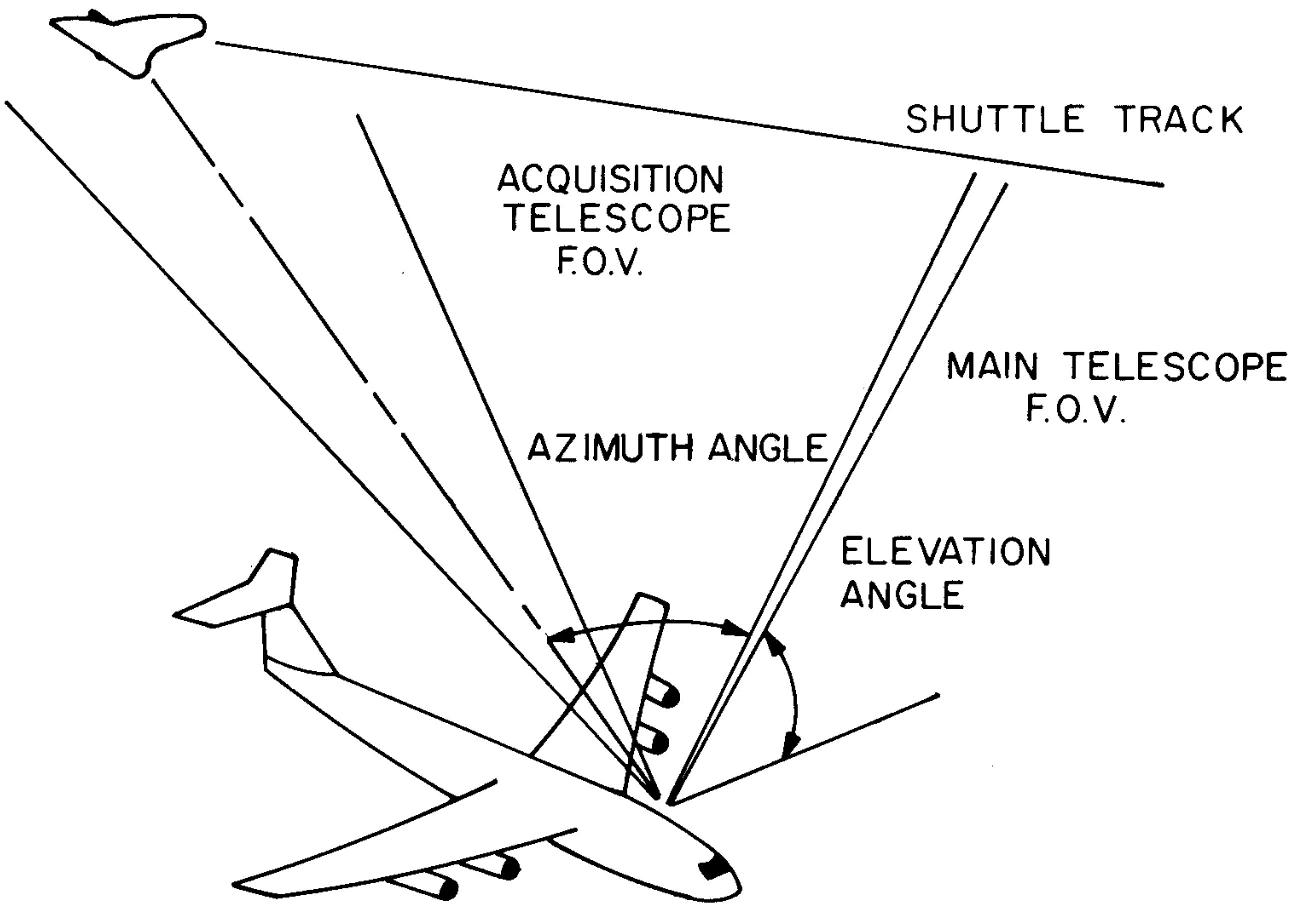

FIGURE 1 IMAGE AQUISITION

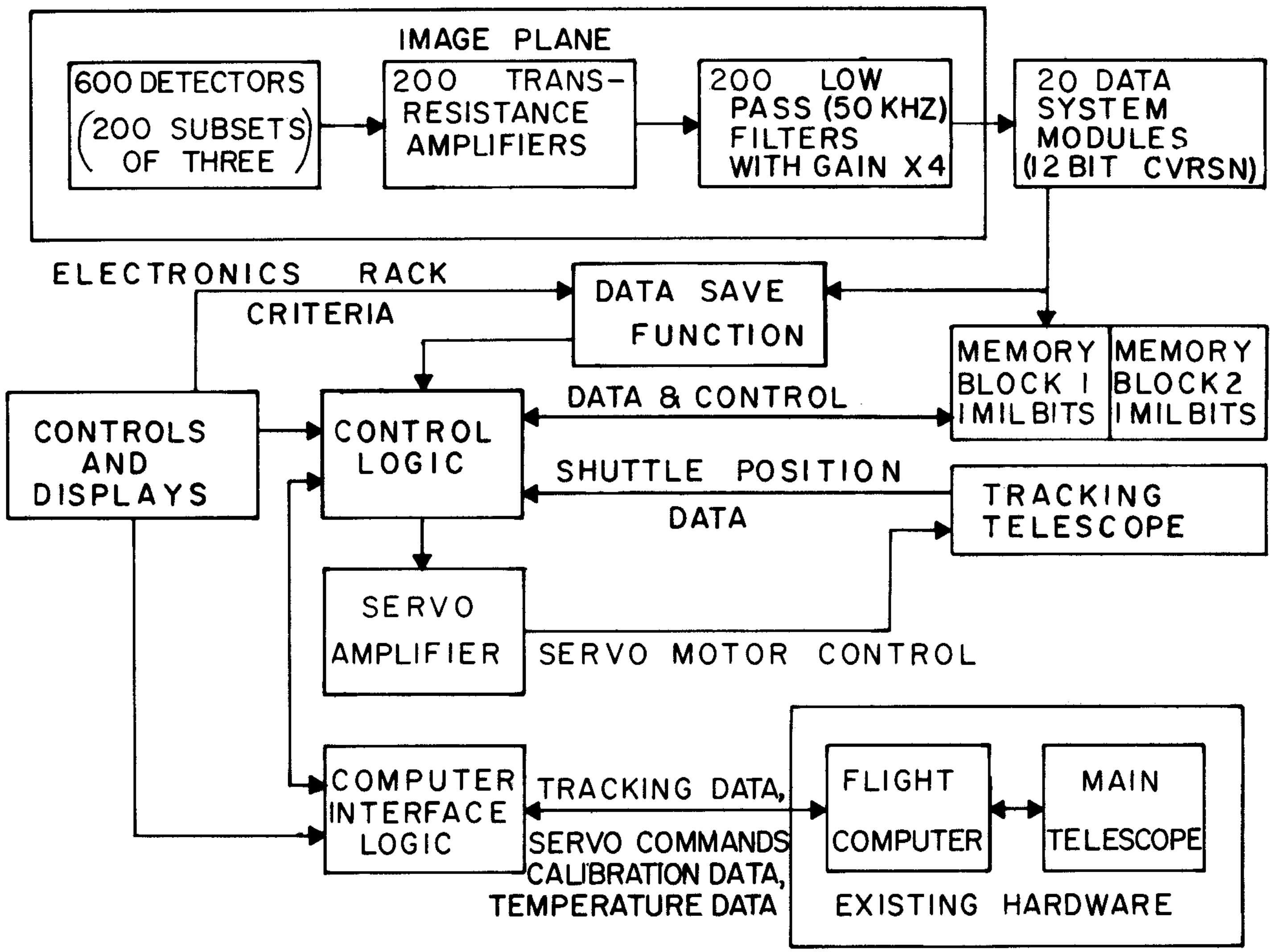

FIGURE 2 ELECTRONICS BLOCK DIAGRAM

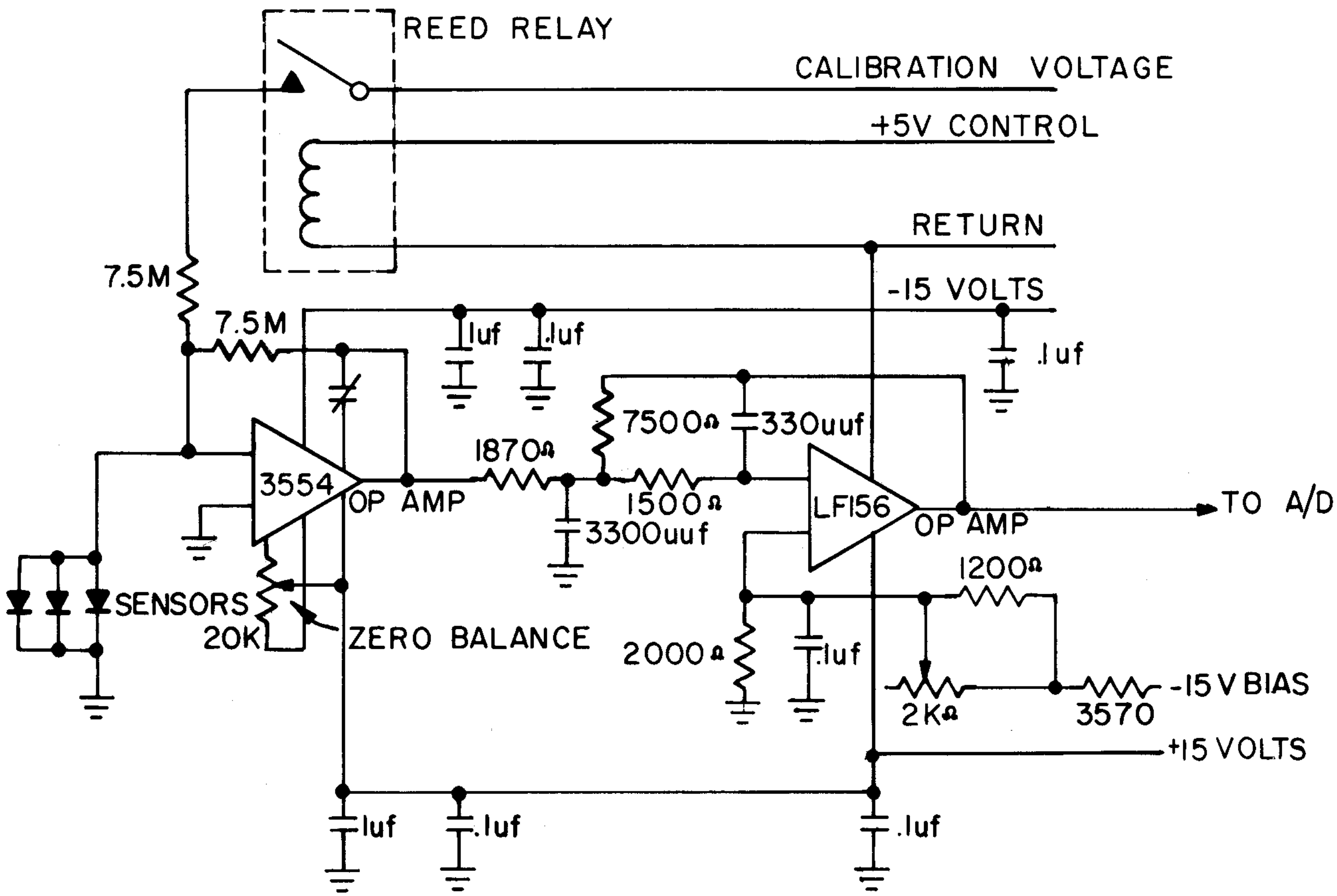

FIGURE 3 DETECTOR CURRENT AMPLIFIER SCHEMATIC

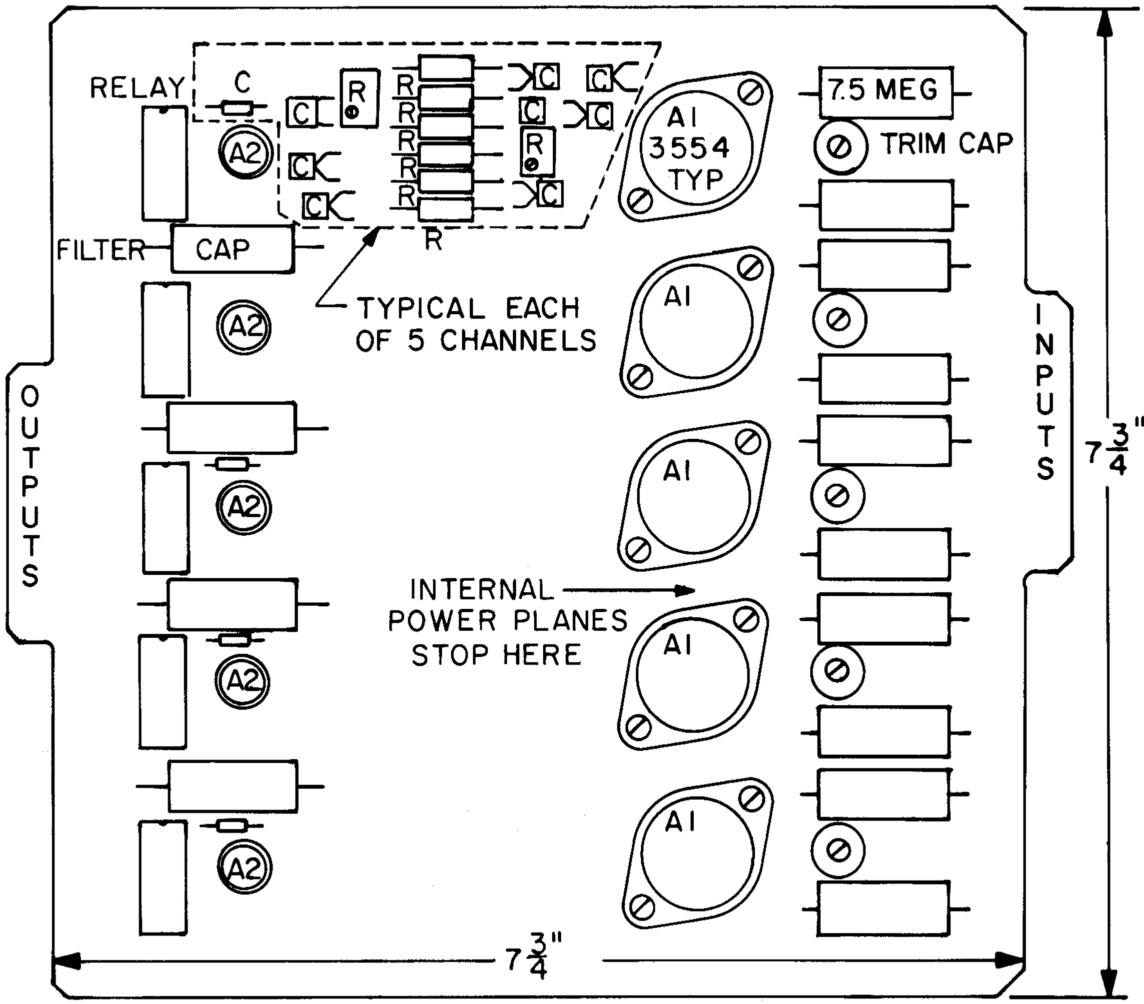

FIGURE 4 DETECTOR CURRENT AMPLIFIER BOARD

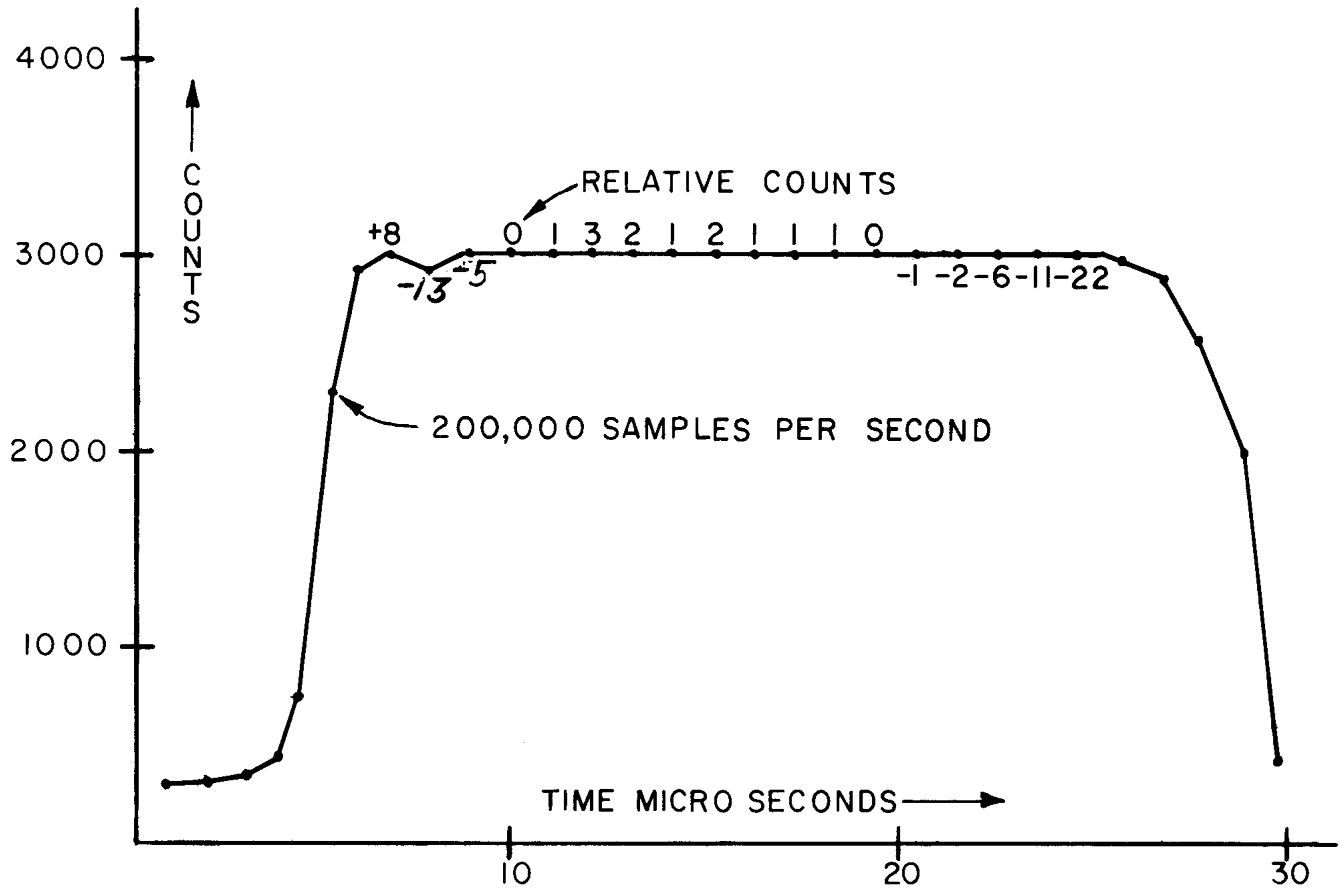

FIGURE 5 TRANSIENT TEST OF INFARED PULSE

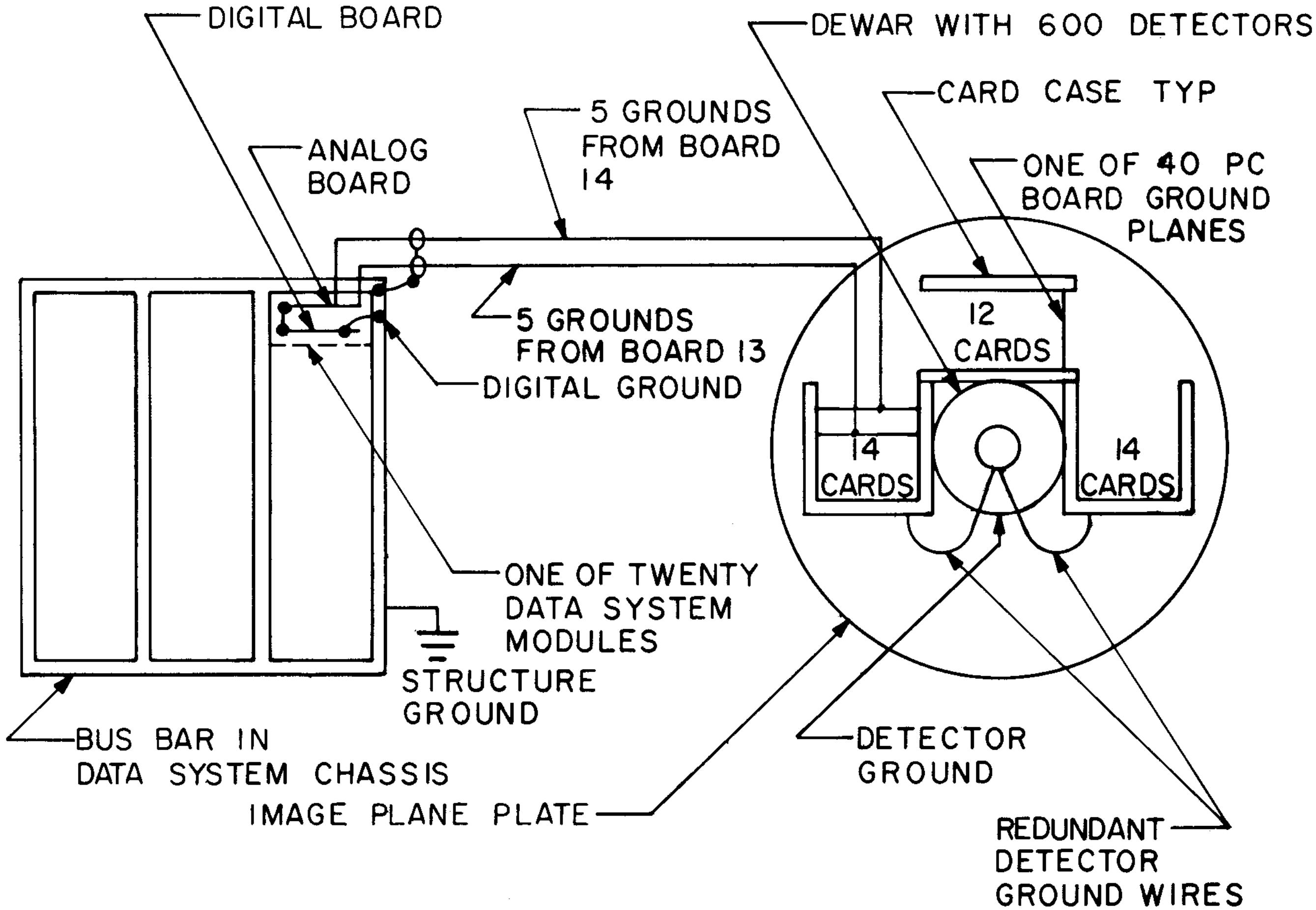

FIGURE 6
TYPICAL GROUNDING FOR EACH DATA SYSTEM MODULE AND PAIR OF IMAGE PLANE AMPLIFIER BOARDS