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Failure of the ERBE Scanner Instrument Aboard NOAA 10 Spacecraft and Results of Failure Analysis

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Executive Summary

The Earth Radiation Budget Experiment (ERBE) scanner instrument aboard the NOAA-10 spacecraft was launched into orbit in September 1986 and began making routine Earth radiation measurements in November 1986. On May 22, 1989, the instrument was operating in the normal Earth scan mode and at the normal cross-track azimuth position of 0 degrees. At 17:03 UT, in the middle of a 4-second scan cycle, all values in the instrument primary data output (DIG A) went to zero. The DIG B data indicated that the elevation beam motor power had remained on, and the analog data showed increases in several temperatures at the time of the malfunction.

Since the malfunction, all of the instrument operational modes and data storage commands have been exercised, along with some typical pulse discrete commands to instrument heaters. The tests were unsuccessful in restoring the instrument to normal operation, but have provided the data needed to analyze the malfunction. In the final test performed, the instrument was powered off and powered back on about 3 hours later. The instrument was powered off in an attempt to bleed off excess charge which might have been deposited in a gate by a radiation event. This report discusses command testing, the instrument responses during the tests, and describes the analysis, together with results and conclusions, which was performed to determine the cause of the malfunction.

The data output from the instrument, both housekeeping and radiometric, appear to be valid, and the instrument responses to several of the operational mode commands are completely normal. However, the instrument fails to correctly execute either the automated (preprogrammed) internal or solar calibration sequences. And, unfortunately, the instrument will not perform correctly in any operational scan mode. When the instrument is commanded to operate in any of the operational scan modes, it stops scanning after scan beam initialization, and all values in the DIG A data revert to zero. Sending a CPU Reset command at any time restores the DIG A data to normal values.

The increase in housekeeping temperatures at the time of the malfunction and the subsequent decreases following first CPU Reset command were nearly identical to those seen after the failure of the NOAA-9 scanner instrument. This appears to be the extent of the similarity between the two failures. The NOAA-9 scanner instrument DIG A data were not restored to valid values by the CPU Reset command and the instrument never responded to any mode commands.

The problem with the NOAA-10 scanner instrument was traced to a failure in the internal address decoding circuitry in one of the ROM (Read Only Memory) chips in the instrument. Unfortunately, there is no method of reprogramming the processor. It is recommended that the CERES instruments and other instruments with extended mission requirements, which rely on computers for their operation, be designed with the capability to be reprogrammed by ground commands.

Background

Overview of Instrument Operational Design Features

The scanner instrument was designed to perform a wide range of operations. An overview of the instrument operational design features is given here, and further details can be found in reference 1. The azimuth beam can rotate between 0 and 180 degrees in the local horizon plane, and the rotation plane of the elevation (scan) beam is normal to the azimuth plane. Each instrument has its own computer which is used to direct and control instrument operations. Commands can be issued directly from the ground or from command tables uplinked and stored in the spacecraft computer memory. Table 1 is a list of the instrument operational commands. A mode command directs the instrument to perform a specific function or to change its operational mode. Data storage commands store azimuth angle data required in some of the azimuth-rotation commands. The automated calibration sequence commands (8A1 and 8A2 in table 1) direct the instrument to perform the sequence of mode commands listed in table 2 in the order and at the relative times shown. No other mode commands can be executed while an automated calibration sequence is in progress. The solar calibration sequences are slightly different for the instruments on the ERBS and NOAA spacecraft and the sequence for the instruments on the NOAA spacecraft, only, is shown in table 2b.

In-Flight Operations

The scanner instrument on NOAA-10 is one of three which have been launched into Earth orbit as part of the Earth Radiation Budget Experiment. Each ERBE scanner instrument is paired on a different spacecraft with a nonscanner (fixed field of view) instrument. The first instruments were launched into orbit on the ERBS spacecraft by the Space Shuttle Challenger on October 5, 1984. ERBS is operated by NASA from the Goddard Spaceflight Center in Greenbelt, Maryland. The spacecraft is in a 600-km altitude orbit with right ascension of the ascending node precessing westward at about 4 degrees per day. The other instruments were launched into orbit aboard the NOAA-9 and NOAA-10 TIROS-N weather satellites in December 1984 and September 1986, respectively. The NOAA spacecraft are operated by NOAA from Suitland, Maryland. Both spacecraft are in nearly

Table 1
Scanner Instrument Operations Commands

Operational Mode Commands

Command Description	Hexadecimal Cmd Code
Azimuth to 0 deg position	811
Azimuth to 90 deg position	812
Azimuth to 180 deg position	813
Azimuth to position A	814
Azimuth to position B	815
Azimuth scan between 0 and A	816
Scan to stow position	821
Normal Earth Scan	822
Nadir Earth Scan	823
Short Earth Scan	824
Mam Scan	825
SWICS off	891
SWICS at level 3	892
SWICS at level 3 - modulated	893
SWICS at level 2	894
SWICS at level 2 - modulated	895
SWICS at level 1	896
SWICS at level 1 - modulated	897
Internal calibration sequence	8A1
Solar calibration sequence	8A2

Azimuth Angle Data Storage Commands

Command Description	Hexadecimal Cmd Code
Address for azimuth position A	419
Address for azimuth position B	41B
Data, Most significant byte	2xx
Data, Least significant byte	1xx

Note: xx indicates actual azimuth position data.

Table 2
Scanner Instrument Automated Calibration Sequences

(a) - Internal Calibration Sequence

Step No.	Elapsed Time Hr:Min:Sec	Hex Command	Event Description
1	00:00:00	8A1	Begin Internal Cal Sequence
2	00:00:32	897	SWICS Level #1 Modulated
3	00:02:08	895	SWICS Level #2 Modulated
4	00:03:44	893	SWICS Level #3 Modulated
5	00:05:20	891	SWICS Off
	00:08:00		*See note 1
6	00:08:32	897	SWICS Level #1 Modulated
7	00:10:08	895	SWICS Level #2 Modulated
8	00:11:44	893	SWICS Level #3 Modulated
9	00:13:20	891	SWICS Off
	00:32:00		*See note 2
10	00:32:32	897	SWICS Level #1 Modulated
11	00:34:08	895	SWICS Level #2 Modulated
12	00:35:44	893	SWICS Level #3 Modulated
13	00:37:20	891	SWICS Off

Note 1 - Black Body Heaters Turned On By Pulse Discrete Command

Note 2 - Black Body Heaters Turned Off By Pulse Discrete Command

(b) - Solar Calibration Sequence For NOAA Spacecraft

Step No.	Elapsed Time Hr:Min:Sec	Hex Command	Event Description
1	00:00:00	8A2	Begin Solar Cal Sequence
2	00:00:32	824	Short Earth Scan
3	00:01:04	811	Azimuth to 0 degrees
4	00:01:36	814	Azimuth to Position A
5	00:06:24	825	MAM scan
6	00:11:44	815	Azimuth to Position B
7	00:18:08	814	Azimuth to Position A
8	00:23:28	824	Short Earth Scan
9	00:24:00	811	Azimuth to 0 degrees
10	00:28:48	822	Normal Earth Scan

Sun-synchronous orbits (825 to 875 km altitude), each with a different mean local time for its orbit node crossing. The ERBS orbit produces a more severe and more variable thermal environment at the spacecraft than the orbits of NOAA-9 and NOAA-10, but the higher altitude orbits of the NOAA spacecraft produce more severe space radiation environments.

All the scanner instruments have been operated primarily in the normal Earth scan mode and at an azimuth position of either 0 or 180 degrees to provide continuous measurements in a cross-track scan plane. The instruments on ERBS and NOAA-10 have been operated at other azimuth angles during periods of low Sun beta angle (angle between Sun and orbit momentum vectors) to prevent the detectors from scanning the Sun. For brief periods of time, the instruments on ERBS and NOAA-9 have been operated at an azimuth position of 90 degrees to obtain measurements in the along-track scan plane. Internal calibrations of all the scanner instruments have been performed about every two weeks. Solar calibrations have been less regular because of instrument azimuth beam rotation and scanner elevation beam anomalies, problems which are discussed in the next section. Only one solar calibration was ever performed with the scanner instrument on NOAA-10.

Previous Instrument Anomalies

All three scanner instruments have experienced the scan beam anomaly problem. The problem is usually characterized by sluggishness when the scan beam is in one of the boost (high-acceleration) portions of a 4-second scan cycle, and the sluggishness is sometimes accompanied by a rise in some of the scan drive electronics temperatures. The problem was observed with each of the instruments about 3 months after launch into orbit. The problem has been severe at times, causing the scan beam to hang up or stop during a scan. The investigation reported in reference 2, which covered the scan beam anomaly on ERBS and NOAA-9, concluded that the most probable cause of the scan beam anomaly was a problem in the scanner beam bearing lubrication system. The investigators found a high probability that the rise in temperature, which accompanies the anomaly, is due to the instrument operating continuously in the high power mode which is normally only associated with the boost mode (high-acceleration) portion of the scan cycle. The investigators correctly predicted that the problem would also occur with the scanner instrument on the NOAA-10 spacecraft. No evidence was found that the scan beam anomaly was related to the instrument computer.

An azimuth beam rotation anomaly has occurred from time to time on all three scanner and nonscanner instruments. In the azimuth beam rotation anomaly, the azimuth position sensor apparently reads erroneous position data when commanded to change azimuth modes, causing the azimuth beam to rotate incorrectly and usually to end up at the wrong azimuth position. The problem was first observed with the instrument on the ERBS spacecraft on February 20, 1985 when the azimuth beam did not return to its normal position of 180 degrees after a routine solar calibration. The problem resulted in the detectors directly scanning the Sun, causing a change in the spectral response of one of the detectors. On the NOAA-10 spacecraft in November 1986, the anomaly was observed during the first attempt to perform a solar calibration of the scanner instrument. The anomaly resulted in the decision to discontinue solar calibrations of the instrument. The anomaly was studied in 1985 and 1986, and it was concluded that the anomaly was caused by the Sun interfering with the azimuth position sensor during beam rotation. Stray Sun light probably illuminates the azimuth position sensor photo detector causing erroneous position data. The instrument computer does not appear to be responsible for the azimuth rotation anomaly.

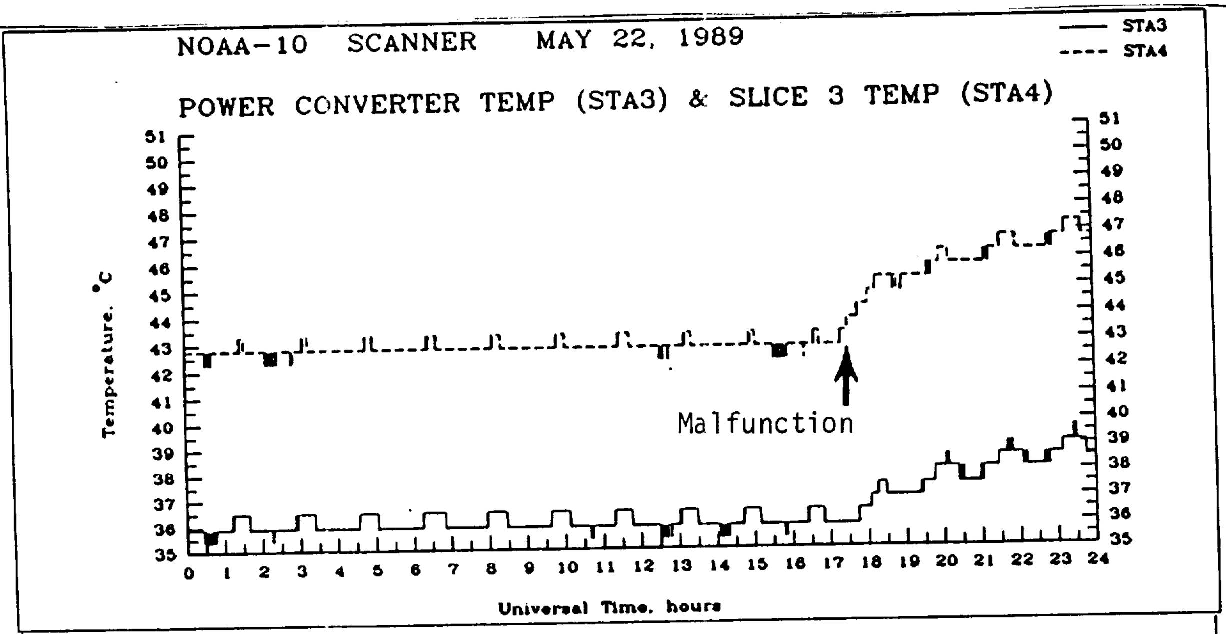
The scanner instrument on the NOAA-9 spacecraft failed on January 20, 1987, and all attempts to restore the primary (DIG A) data output have been unsuccessful. Similarities between the scanner failure on NOAA-9 and the scanner malfunction on NOAA-10 are discussed in the next section.

Description of Malfunction and Troubleshooting Approach

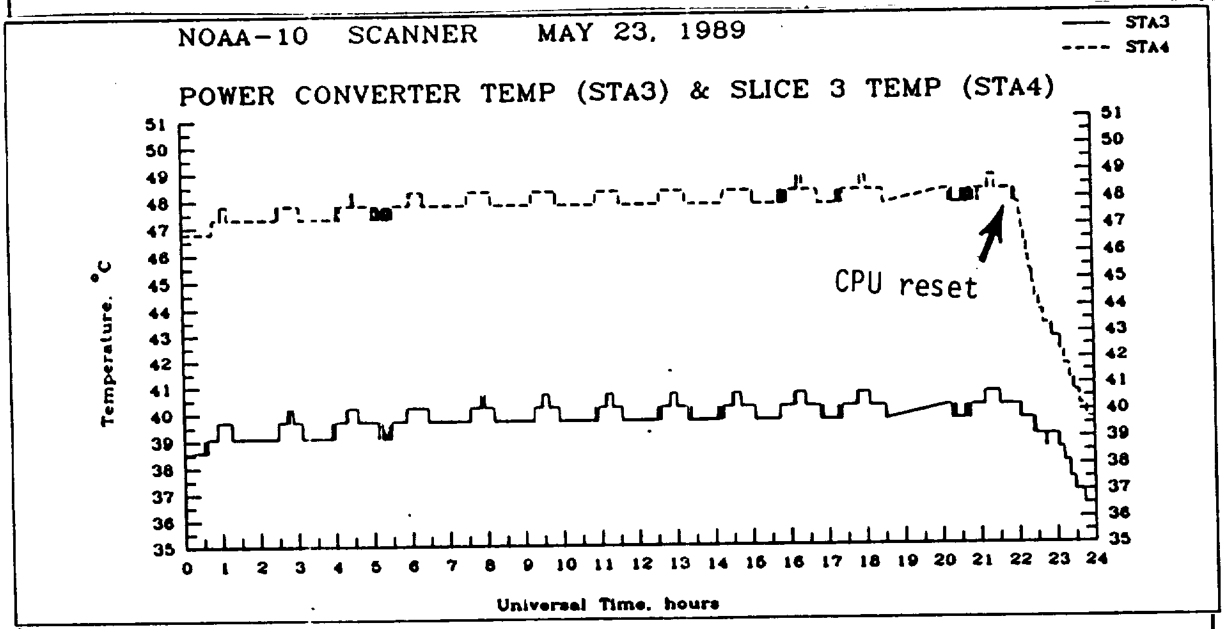
Malfunction, Preliminary Testing and Analysis

At 17:03 Universal Time on May 22, all values in the primary output data (DIG A) of the scanner instrument on NOAA-10 went to zero. The bilevel data (DIG B) and several instrument temperatures and voltages (analog), which are output on a different data buses than that of the DIG A data, remained valid. The DIG B data indicated that the scanner elevation motor power remained on after the malfunction, and figure 1(a) shows how two of the instrument analog temperatures began to increase at the time of the malfunction.

The first CPU Reset command was executed on May 23. The CPU Reset causes a hardware reset of the instrument computer. This clears the computer registers, restarts the stored program, and resets some scanner hardware. The scanner elevation motor power was turned off by the CPU Reset, and figure 1(b) shows that the analog temperatures began to decrease at that time. The CPU Reset command also restored the primary (DIG A) data to valid values. After the instrument was sent a normal Earth scan command (see table 1), the scan beam apparently executed a normal 16-second initialization sequence. This conclusion is based on the output of the elevation beam position sensor and the radiometric detectors. At the end of the initialization



(a) - Day of malfunction



(b) - Day after malfunction

Instrument Temperatures Following Malfunction
Figure 1

sequence, the elevation motor power was apparently turned off automatically, and the DIG A data again reverted to zero values. Elevation position data, transmitted following a subsequent CPU Reset, indicates that the scanner elevation beam appeared to have achieved position lock at the normal Earth scan space-look position. Several times on May 23 and 24, the instrument was sent CPU Reset commands, followed by normal Earth scan mode commands. In every case, the instrument response was identical to the response received the first time these commands were sent on May 23. On May 26, a CPU Reset command, only, was sent to the instrument, and no other commands were sent until May 31. The DIG A data remained valid, and instrument housekeeping and radiometric data showed typical responses to the in-orbit heating environment during this five-day period.

Before the malfunction on May 22, the instrument was operating in the normal Earth scan mode and at the cross-track azimuth position of 0 degrees. The instrument had been operating continuously in the normal Earth scan mode since December 5, 1986. The azimuth beam had been rotated to the cross-track position of 0 degrees on April 16, 1989, a few days after the spacecraft had exited a full-Sun orbit condition. An automated internal calibration had been performed on May 10, 1989. Thus, the last command which had been executed by the instrument was a SWICS off command (see table 2a). Instrument data for May 21 and for the period before the malfunction on May 22 indicate no unusual behavior of the instrument. The scan beam was a little sluggish, but the sluggishness was much less severe than that observed during some earlier periods, particularly from January to March 1987.

The DIG B data and analog temperatures of the scanner instrument on the NOAA-9 spacecraft showed nearly identical responses at the time of the failure on January 20, 1987, and at the time of the first CPU Reset command. However, there were no other similarities observed between the malfunction of the scanner instrument on the NOAA-10 spacecraft and the failure of the scanner instrument on the NOAA-9 spacecraft. The DIG A data of the instrument on NOAA-9 was never restored to valid values, and the instrument has never responded to any commands after the initial CPU Reset command.

Command Tests and Instrument Responses

All the instrument operational mode and data storage commands were tested during the period from June 5 to September 15, 1989, and two heaters were turned off and on via pulse discrete commands (see table 3). Most of the commands were sent during communication linkups between the spacecraft and the operations control center at NOAA/NESDIS in Suitland, Maryland, and Langley personnel were at NOAA during some of the command testing. This

Table 3
Instrument Command Tests and Responses

Command	Date	Instrument Response
	On/Off Commands To Heaters	
PEDESTAL HEATER ON	Jun 1	Bi-level data showed heater ON
PEDESTAL HEATER OFF	Jun 1	Bi-level data showed heater OFF
BLACK BODY HEATERS ON	Jun 1	Bi-level data showed heaters ON
BLACK BODY HEATERS OFF	Jun 1	Bi-level data showed heaters OFF Black body temperatures responded normally.
	Data Storage Commands	
AZIMUTH ANGLE A	Jun 5	Instrument processed address and data commands normally for 20-degree azimuth value.
	Operational Mode Commands	
SWICS MODULATED -		
LEVEL #1	Jun 19	SWICS amplifier output normal
LEVEL #2	Jun 2	SWICS amplifier output normal
LEVEL #3	Jun 19	SWICS amplifier output normal
SWICS UNMODULATED -		
LEVEL #1	Sep 5	SWICS amplifier output normal
LEVEL #2	Sep 5	SWICS amplifier output normal
LEVEL #3	Sep 5	SWICS amplifier output normal
ROTATE AZ TO 0 DEG	Jun 6	Azimuth beam rotation normal
ROTATE AZ TO 90 DEG	Sep 6	Azimuth beam rotation normal
ROTATE AZ TO 180 DEG	Sep 6	Azimuth beam rotation normal
ROTATE AZ TO ANGLE A (20 DEGREES)	Jun 6	Azimuth beam rotation normal
ROTATE AZ TO ANGLE B (45 DEGREES)	Sep 6	Azimuth beam rotation normal
ROTATE CONTINUOUSLY	Sep 6	Azimuth beam rotation normal
BETWEEN 0 AND 35 DEG	Sep 6	Azimuth beam rotation appeared to be normal.
NORMAL EARTH SCAN	May 23	Scan beam initialize, scanner motor power turned off, DIG A data reverted to zeros (all scan mode commands).
SHORT EARTH SCAN	Jun 6	
NADIR EARTH SCAN	Jun 7	
SOLAR MAM SCAN	Jun 7	
SCAN TO STOW	Jun 7	
AUTOMATED INT CAL SEQ	Jul 5	Incorrect Sequence. Mod SWICS level #3 command turned on and off several times. (Table 4a)
AUTOMATED SOL CAL SEQ	Sep 15	Incorrect Sequence (Table 4b).

arrangement permitted the instrument behavior and responses to the commands to be monitored directly, and for go/no-go decisions on testing to be made in real time. Table 3 lists each of the commands sent, by category, the date on which the command was exercised, and comments on the instrument response to the command. Some of the commands were exercised more than one time, and the execution date listed for a command is the first date of execution for which all the DIG A data were available in the data stream. The two-month lapse between the internal calibration sequence test on July 5 and the next commands issued on September 6, was used to analyze the data output from the execution of the internal calibration sequence. The responses to the commands are discussed in this section, and a detailed analysis of the output data is presented in the next section.

The responses of the two heaters which were tested on June 1 were completely normal and are believed to be representative of responses for all heaters. Therefore, no further heater testing was performed.

The instrument responded normally to all azimuth mode commands. The command to rotate continuously between angle 0 degrees and angle A (35 degrees in this case) had not been previously tested in flight. The azimuth angle data for 20 degrees which was processed by the data storage commands on June 5 were used in the successful azimuth beam rotation to 20 degrees on June 6.

Only the modulated SWICS commands, which are executed during the internal calibration sequences, had been previously executed in orbit, and none of the 6 SWICS commands had been tested individually in orbit. The responses to all the SWICS commands, however, are believed to be completely normal. The magnitudes of the SWICS amplifier outputs at all levels were identical to the levels typically observed during internal calibrations.

The responses to all the scan mode commands were identical to the responses to the normal Earth scan commands executed on May 23 and 24. In each case, the scanner elevation beam appeared to go through a 16-second initialization sequence and to be positioned at the space look angle of 14 degrees at the end of the sequence. The elevation motor power was then turned off automatically, and the values of the DIG A data reverted to zeros.

The automated internal calibration sequence command (Hex command code 8A1) stored in the NOAA-10 spacecraft computer command table is issued routinely every two weeks. However, July 5 was the first calibration date after the malfunction for which the output of the complete calibration sequence was available in the DIG A data stream. The DIG A data were invalid when the first sequence was issued on May 24 (no CPU Reset command was in effect), and the command sequences on June 10 and June 26 were interrupted by CPU Reset commands which were issued prior to completion of the sequences. The CPU Reset commands were issued from the ground when it appeared that the internal calibration sequence had terminated abnormally. The instrument responses have been identical for all internal calibration sequence commands issued since July 5. Table 4a compares the instrument responses during a typical calibration before and after the malfunction. Figure 2 shows typical SWICS amplifier output for normal and abnormal sequences. A total of 13 mode commands (including the internal calibration sequence command) are issued during both normal and abnormal command sequences, but the commands and the relative times at which they are executed are incorrect for the abnormal sequence. The level #3 modulated SWICS command is seen to be turned on and off 6 different times during the nearly 10-hour execution period of the abnormal command sequence.

Table 4b compares the execution of the first five commands in the automated solar calibration sequence for a normal execution and the abnormal execution on September 15. The command echo word showed an invalid command code (804) at the time when a short Earth scan mode command (824) should have been executed. The third command (rotate in azimuth to angle A) was correct in the abnormal sequence, but it was executed more than 2 hours late, and the invalid command code, 804, appeared again in the command echo a little over 2 hours after the valid command. A MAM scan command was executed about three and one half hours after the beginning of the sequence. The instrument response was identical to that during the execution of all scan mode commands since the malfunction. After the DIG A values went to zero, a CPU Reset command was sent, restoring the DIG A data.

The final test of the instrument was performed on October 17 when the instrument was powered down, and after about 3 hours, powered back up. During the three hour period when instrument power was off, several housekeeping temperatures dropped below their normal operating values. After power-up, a normal Earth scan command was executed, and the instrument response was again the same as for all previous scan mode commands. A CPU Reset command was then executed, which restored the DIG A data to valid values. Housekeeping temperatures returned to their normal operational range within a few hours. The instrument will be left in the power-on state, and the instrument output will be monitored. There are no plans to perform further testing of the instrument.

Table 4
Comparison of Calibration Sequences Execution Before and After the Malfunction

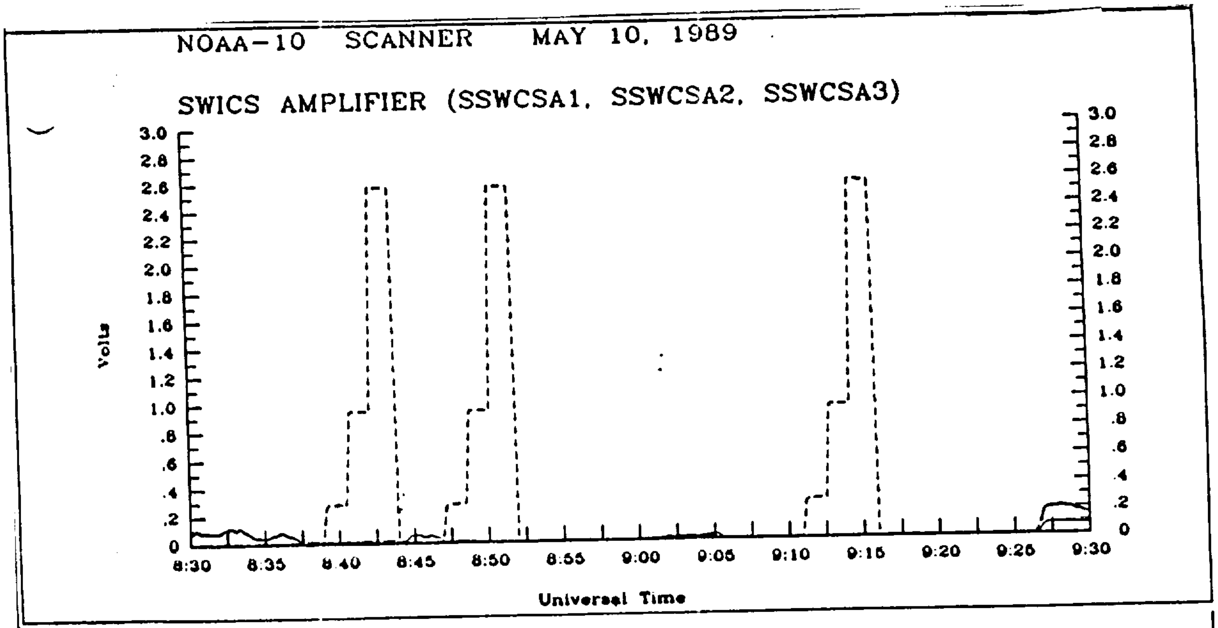
(a) - Internal Calibration Sequence

	Before Malfunction (Normal)		After Malfunction	
Step No.	Elapsed Time (H:M:S)	Event Description	Elapsed Time (H:M:S)	Event Description
1	00:00:00	Int Cal Seq Cmd (8A1)	00:00:00	Int Cal Seq Cmd
2	00:00:32	SWICS Lev #1 Mod (897)	00:00:32	SWICS Lev #3 Mod
			00:08:00	*See note 1
			00:32:00	*See note 2
3	00:02:08	SWICS Lev #2 Mod (895)	02:16:32	SWICS Off
4	00:03:44	SWICS Lev #3 Mod (893)	04:33:04	SWICS lev #3 Mod
5	00:05:20	SWICS Off (891)	04:38:24	SWICS Off
	00:08:00	*See note 1		
6	00:08:32	SWICS Lev #1 Mod (897)	04:41:36	SWICS lev #3 Mod
7	00:10:08	SWICS Lev #2 Mod (895)	06:50:40	SWICS Off
8	00:11:44	SWICS Lev #3 Mod (893)	06:58:08	SWICS lev #3 Mod
9	00:13:20	SWICS Off (891)	09:10:24	SWICS Off
	00:32:00	*See note 2		
10	00:32:32	SWICS Lev #1 Mod (897)	09:14:40	SWICS lev #3 Mod
11	00:34:08	SWICS Lev #2 Mod (895)	09:40:16	SWICS Off
12	00:35:44	SWICS Lev #3 Mod (893)	09:41:52	SWICS lev #3 Mod
13	00:37:20	SWICS Off (891)	09:43:28	SWICS Off

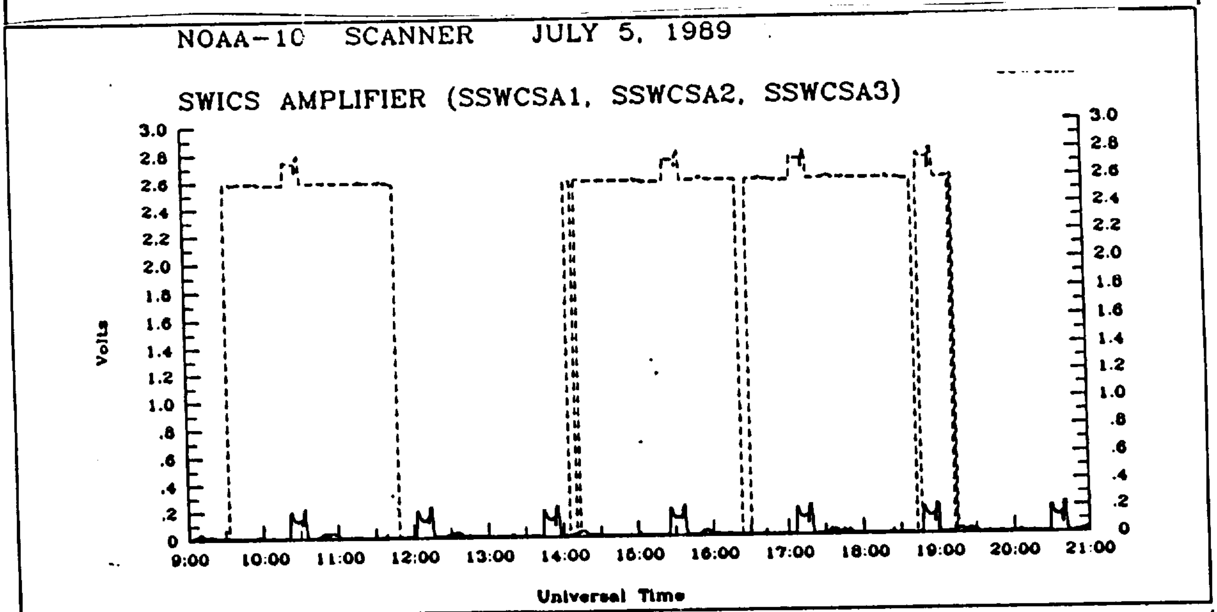
Note 1 - Black Body Heaters Turned On By Pulse Discrete Command
Note 2 - Black Body Heaters Turned Off By Pulse Discrete Command

(b) - Solar Calibration Sequence

	Before Malfunction (Normal)		After Malfunction	
Step No.	Elapsed Time (H:M:S)	Event Description	Elapsed Time (H:M:S)	Event Description
1	00:00:00	Solar Cal Seq Cmd (8A2)	00:00:00	Sol Cal Seq Cmd
2	00:00:32	Short Earth Scan (824)	00:00:32	Invalid Cmd - Hex cmd code 804
3	00:01:04	Azimuth to 0 deg (811)	02:16:32	Azimuth to 0 deg
4	00:01:36	Azimuth to Pos A (814)	02:18:08	Invalid Cmd - Hex cmd code 804
5	00:06:24	MAM scan (825)	04:33:04	MAM scan



(a) - Normal sequence



(b) - Abnormal sequence

Internal Calibration Response
Before and After Malfunction
Figure 2

Failure Analysis

The flight data gathered over the period from May 22 to July 5 was reviewed and analyzed in a attempt to identify the failure mode, probable cause of the failure, and guidelines for restoration of instrument operation. Initial review of the data indicated that many instrument functions were still operating normally. Thus to simplify the analysis process, the assumption was made that the malfunction was the result of a single point failure. The instrument data for each response was analyzed to eliminate subsystems and components as potential causes of the malfunction.

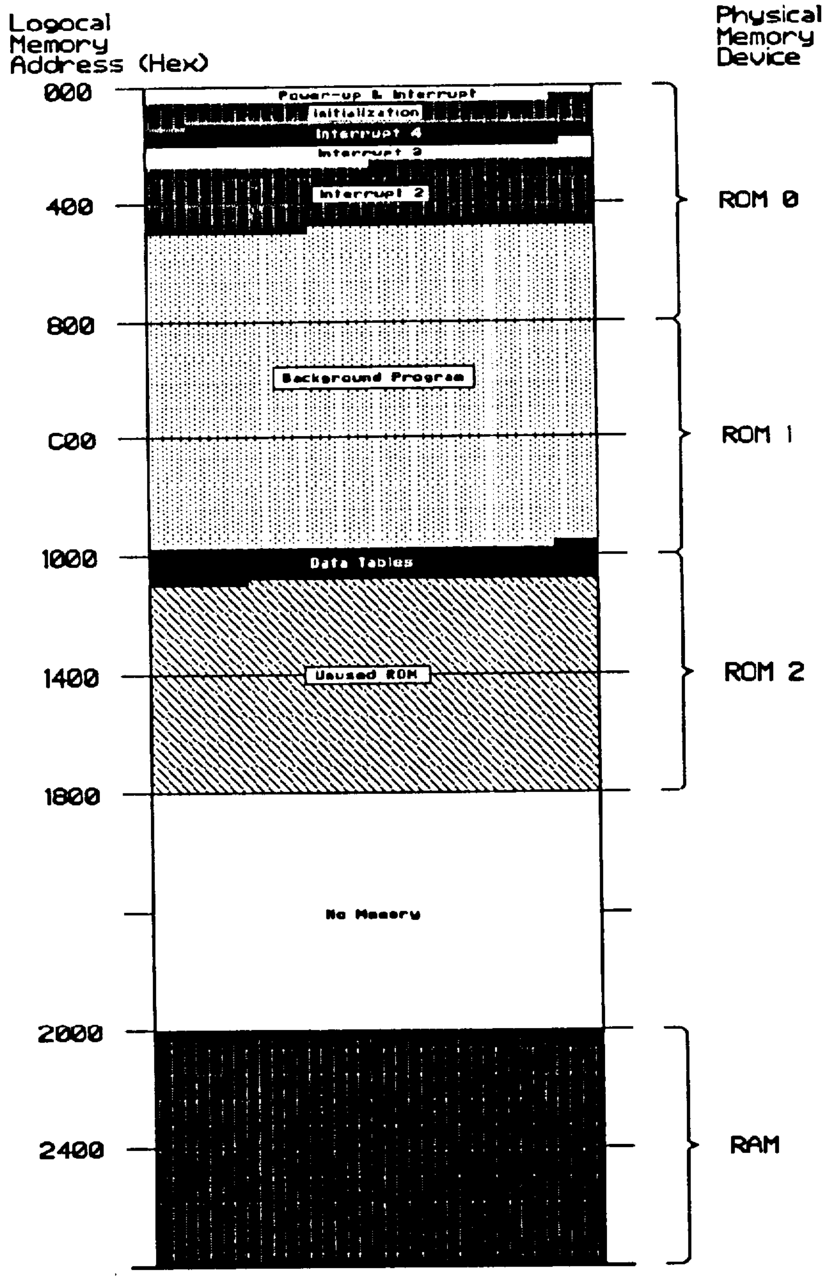
Observations and Analysis

Reset Command

The CPU Reset command causes a hardware reset of the microprocessor; which in turn causes all internal registers to be cleared and a restart of the firmware code. The ROM code initialization causes the RAM memory to be cleared and initialization of selected scanner hardware including removal of power from the elevation motor drive circuit. The fact that the processor responded to a reset instruction and normal data transfers were restored, indicated that the spacecraft command and data transfer circuitry, spacecraft 1.2M Hz clock, counter and interrupt circuits are functioning normally, and that the microprocessor, ROM, and RAM memories are functioning normally for at least a substantial portion of the instruction set and memory area. Initialization, data acquisition, and telemetry transfers require proper operation of substantial portions of the background program as well as interrupts 3 and 4, and use large variable blocks in the RAM memory. See memory map figure 3.

Spacecraft DIG A Data Transfer

Analysis of the hardware and software responsible for the transfer of DIG A data from the instrument microprocessor to the spacecraft interface indicates that the transfer of meaningful data from the microprocessor memory to the spacecraft interface is totally dependent on correct and timely execution of software routines by the microprocessor. In the event that the microprocessor fails to transmit data to the spacecraft instrument the interface hardware will transmit a continuous stream of zeros when prompted.



ERBE Scanner Memory Map
Figure 3

Since the DIG A data stream is restored following a reset, it is unlikely that there is a failure in the instrument serial data interface hardware or the spacecraft interface. It is far more likely that the microprocessor is not sending the data because of a failure of the microprocessor or related circuits.

Azimuth Commands

The normal response of the scanner instrument to all azimuth commands indicated that the azimuth mechanism and drive are functioning normally, and supports the argument for proper computer operation. Execution of azimuth commands require the proper function of the interrupt service routine for interrupt 2 and a portion of the background program not required for initialization, data acquisition, or telemetry transfer. See memory map figure 3.

Scan Commands

There are 5 different scan mode commands (Normal, Nadir, Stow, Short, MAM), but each scan command begins with the same initialization sequence.

Scanner elevation position data is derived by counting pulses from an incremental encoder. Following an instrument power-up, the elevation position counter requires the initialization sequence to preset the counter as the scan head passes through the nadir (encoder index) position. However, as long as instrument power is not removed the counter should maintain the correct position value. The initialization sequence includes movement of the elevation scan head at a controlled speed in clockwise (CW) and counter clockwise (CCW) directions, and the acquisition of position lock at the space-look position (1000 encoder count).

The observed response to each of the scan mode commands was identical. For each scan mode command the scanner elevation beam was observed to drive nominally in both CW and CCW directions for the prescribed time periods. The DIG A data reverted to zeros before the elevation beam data indicated a position lock at space or the start of the requested scan sequence. The failure indications were similar to the initial malfunction. The DIG A data stream went to all zeros, but the increase in temperature was not observed and the DIG B data indicated that power had been removed from the scan motor drive. Elevation position data following a reset indicated that the scanner head was sitting at the nominal space look position (1000 counts). Analysis of position displacement data from subsequent initialization sequences also indicated that the head was actually resting at the nominal space-look position. This indicates that position lock at space was achieved at the end of initialization, and that the motor power was removed prior to the scanner drive receiving the first velocity command in the scan command sequence, the velocity command was not issued, or both of these events occurred.

This data is significant as the command path and the actual hardware commands issued to the scanner drive during initialization are identical to those issued at the beginning of each scan sequence. This rules out problems with the mechanical or electrical scanner drive components, command path, loading of the power bus, or loss of the spacecraft clock.

In addition it permits a possible explanation for the temperature rise noted following the initial malfunction and the absence of this temperature rise in subsequent tests. This temperature rise phenomena has been observed and documented as part of the ERBE Scanner Instrument Anomaly Investigation (Reference 2). The scanner drive has two power modes, high and low, which are autonomously selected on the basis of the error signal presented to the driver. Power dissipation in high power mode is 4 times higher than for low power mode. During nominal operation, high power mode is activated for only a small fraction of total scan time. Since the initial failure occurred with the scan head in mid-scan and all indications are that the scanner drive was faithfully executing the last received velocity command, the scanner drive would have continued to drive the scan head at continuous velocity until the head impacted the mechanical stops. With the scanner drive executing a velocity drive command, and the head mechanically restrained the error signal to the motor drive would have saturated and forced the driver into continuous high power mode. This has been shown to result in temperature rises similar to those observed following the malfunction. In the subsequent tests, following CPU-Reset commands, no heating would be expected as the head was locked at the space-look position, and motor power was removed.

SWICS Commands and Internal Calibration Sequence Command

Individual Short Wave Internal Calibration Source (SWICS) commands were issued for modulated levels 1, 2 and 3, and the instrument performed nominally. This verified that the instrument was capable of executing SWICS commands for each of the 3 levels.

The internal calibration sequence command normally executes a series of SWICS modulated level commands from level 1 to level 3 at preset time intervals to create a profile as shown in figure 2a. However, when the internal calibration sequence was issued to the NOAA-10 scanner following the malfunction, a sequence of SWICS level 3 and SWICS off commands were executed with a radically different time sequence as shown in figure 2b. The total number of SWICS commands was the same as for a normal sequence, and following the completion of the sequence the scanner returned to its "standby" mode. Primary instrument data (DIG A) remained valid throughout and following the internal calibration sequence.

Program Memory Considerations

The fact that the only commands which produced anomalous or failure condition were internal sequence commands, prompted a review of the manner in which these commands were executed and their relative location in memory. The routines responsible for execution of these commands showed no apparent unique common code or instructions, but the tabular information used by both of these routines was determined to be the sole contents of the high ROM chip (A2A1-U50).

A comparison of the internal calibration SWICS commands, and the erroneously executed SWICS commands, shown in table 4, suggested some interesting failure mechanisms. The internal calibration table consists of twenty-five bytes of information which define twelve internal instrument command events, and a sequence stop byte, shown in table 5. Each event is defined by an event time relative to the major frame counter, which is reset when the internal calibration command is received, and an internal SWICS command to be executed at the prescribed time. The stored commands are same as the lower byte of the instrument level commands. As an example, execution of the internal table hex value 97H causes the same SWICS function as the instrument level hex command 897H. Note that the command sequence Level 1 (97H), Level 2 (95H), Level 3 (93H), and SWICS Off (91H) are repeated three times; that the Level 3 and SWICS Off commands can be derived from the Level 1 and Level 2 commands respectively by clearing a single bit (b2); and that the Level 1 and Level 2 commands are offset from the Level 3 and SWICS Off commands respectively by 4 counts which can be achieved by setting a single address bit (b2).

The SWICS internal calibration sequence became the Rosetta Stone for the remaining trouble shooting and analysis which was performed almost exclusively by analysis and simulation of the microprocessor and high ROM program code interaction.

To execute the internal calibration sequence the processor loads the first event time and first command from the table, then on each subsequent major frame interrupt (32 sec) it compares the major frame counter to the first event time, and if the event time matches the major frame counter it issues the first internal SWICS command. Once the sequence commands are issued the software and hardware mechanism for their execution is identical

Table 5
Comparison of Calibration Command Tables Before and After Malfunction

(a) - Internal Calibration Sequence

Step	Before Malfunction (Normal)			After Malfunction		
	Command Code	Time Code Hex (Dec)	Description	Command Code	Time Code Hex (Dec)	Description
1			Int Cal Seq			Int Cal Seq
2	97	01 (1)	Lev #1 Mod	93	**01** (1)	Lev #3 Mod
3	95	04 (4)	Lev #2 Mod	91	00 (0)	SWICS Off
4	93	07 (7)	Lev #3 Mod	**93**	00 (0)	Lev #3 Mod
5	91	0A (10)	SWICS Off	**91**	**0A** (10)	SWICS Off
6	97	10 (16)	Lev #1 Mod	93	**10** (16)	Lev #3 Mod
7	95	13 (19)	Lev #2 Mod	91	02 (2)	SWICS Off
8	93	16 (22)	Lev #3 Mod	**93**	10 (16)	Lev #3 Mod
9	91	19 (25)	SWICS Off	**91**	08 (8)	SWICS Off
10	97	3D (61)	Lev #1 Mod	93	10 (16)	Lev #3 Mod
11	95	40 (64)	Lev #2 Mod	91	**40** (64)	SWICS Off
12	93	43 (67)	Lev #3 Mod	**93**	**43** (67)	Lev #3 Mod
13	91	46 (70)	SWICS Off	**91**	**46** (70)	SWICS Off

(b) - Solar Calibration Sequence

Step	Before Malfunction (Normal)			After Malfunction		
	Command Code	Time Code Hex (Dec)	Description	Command Code	Time Code Hex (Dec)	Description
1			Solar Cal Seq			Sol Cal Seq
2	24	01 (1)	Short Scan	04	**01** (1)	Invalid Cmd - Hex 804
3	11	02 (2)	Azimuth to 0	**11**	00 (0)	Azimuth to 0
4	14	03 (3)	Azimuth to A	04	**03** (3)	Invalid Cmd - Hex 804
5	25	12 (18)	MAM Scan	**25**	00 (0)	MAM scan - Fail after init.
6	15	22 (34)	Azimuth to B			
7	14	34 (52)	Azimuth to A			
8	24	44 (68)	Short Scan			
9	11	45 (69)	Azimuth to 0			
10	22	54 (22)	Normal Scan			

Notes: (1) Stored commands do not contain the high byte "8".
(2) Bold type indicates correct command or event time.

to that for SWICS commands issued by the spacecraft. The internal calibration sequence continues issuing SWICS commands at the prescribed intervals until it encounters the stop byte, an interval time of 255 (FF Hexadecimal).

An understanding of the major frame counter is essential to understanding the extremely long internal calibration sequence intervals observed for the malfunctioning scanner instrument. The major frame counter is a byte wide and thus acts as a modulus 256 counter. Thus, if the succeeding event time which the processor receives from the ROM data table is the same or less than the present major frame value the major frame counter will have to cycle through zero to match the counter with the event time.

SWICS Internal Calibration Implementation

Analysis of flight data from the malfunctioning scanner instrument indicated the number of major frame intervals which occurred between SWICS commands. From these intervals and the fact that the first command was issued on the first major frame the assumed event time codes shown in table 5 were derived.

First Failure Hypothesis

A failure in the microprocessor, address bank decoding circuits, address buffers, or high ROM is causing one or more address and/or data bits to be cleared or set when reading data and code from the high ROM memory. This erroneous data and code is in turn producing the observed system malfunction.

First Hypothesis Testing

The cross mapping of high memory addresses into low memory was rejected as a probable cause of the failure when the low memory data in either of the 2 low ROMs could not support the SWICS Level 3 and SWICS Off sequence. This eliminates the bank decoding circuitry as a likely cause of the malfunction.

A computer program generated and tested thousands of combinations of address and/or data bits set or cleared in an attempt to match both the SWICS and event time sequences observed in the flight data. Hundreds of combinations were generated which produced the proper command sequence, but none of the event time sequences were even close to the sequence derived from the flight data. For this reason it is considered unlikely that a combination of address and data bits set or cleared is a likely cause of the problem. This eliminates the microprocessor and bus drives as a likely cause of the malfunction.

Further comparison of internal calibration data table commands and event times with the commands and event times derived from the flight data, indicated that there were 2 blocks of table data which could have been read normally. These blocks (addresses 10D4H-10D7H & 10E4H-10E7H) are each 4 bytes long and separated by a span of 12 bytes. This address pattern suggested a revised failure hypothesis.

Revised Failure Hypothesis

A failure in the address decoding logic of the high ROM (A2 A1-U50), causing a logical ANDing of multiple memory locations, would result in erroneous data and code being executed by the microprocessor. Specifically, data output from the ROM is the logical ANDing of the data at the specified address with the data at the location with the specified address modified by setting bit 2 and clearing bit 3 as shown in table 6. This erroneous data and code processed by the microprocessor in turn produces the observed system malfunction.

Revised Hypothesis Testing

An Internal Calibration Sequence data table corresponding to this failure hypothesis was generated. The commands and event times from this table were compared with commands and event times apparently being executed by the flight instrument. The agreement was perfect.

Demonstrating the connection between the proposed ROM failure and scan mode command related failure required greater effort. The high ROM contains 2 type of "tables" which are used to produce the 5 scan profiles. There is a data table for each of the 5 scan modes, which contains a sequence of event times and code entry pointers, which in turn define the piecewise continuous scan profiles. The first byte contains the event time which is similar to the internal calibration event times except that they are referenced to the 33.3 ms (120 count) interrupt driven clock. The next two bytes contain the address of a block of code, also in the high ROM, which executes a scanner drive level command (e.g. slew clockwise in velocity mode at 66 degrees per second).

A complete high ROM data/code set corresponding to this failure hypothesis was generated, and used in a computer simulation of the microprocessor and associated circuits. A simulation of the normal scan command was performed, and the results account for the observed flight instrument behavior. The simulation indicated nominal performance through the initialization sequence. When the processor attempted to use data from the table, erroneous commands were issued including a command to

Table 6
Internal Calibration Sequence Table
Normal and Erroneous Data

Memory Address		Memory Data		Mask Data		Erroneous Data	
Hex	Binary	Hex	Binary	Hex	Binary	Hex	Binary
10CF	0001 0000 1100 1111	01	0000 0001	67	0110 0111	**01**	**0000 0001**
10D0	0001 0000 1101 0000	97	1001 0111	93	1001 0011	93	1001 0011
10D1	0001 0000 1101 0001	04	0000 0100	0A	0000 1010	00	0000 0000
10D2	0001 0000 1101 0010	95	1001 0101	91	1001 0001	**91**	**1001 0001**
10D3	0001 0000 1101 0011	07	0000 0111	10	0001 0000	00	0000 0000
10D4	0001 0000 1101 0100	93	1001 0011	93	1001 0011	**93**	**1001 0011**
10D5	0001 0000 1101 0101	0A	0000 1010	0A	0000 1010	**0A**	**0000 1010**
10D6	0001 0000 1101 0110	91	1001 0001	91	1001 0001	**91**	**1001 0001**
10D7	0001 0000 1101 0111	10	0001 0000	10	0001 0000	**10**	**0001 0000**
10D8	0001 0000 1101 1000	97	1001 0111	93	1001 0011	93	1001 0011
10D9	0001 0000 1101 1001	13	0001 0011	0A	0000 1010	02	0000 0010
10DA	0001 0000 1101 1010	95	1001 0101	91	1001 0001	91	1001 0001
10DB	0001 0000 1101 1011	16	0001 0110	10	0001 0000	10	0001 0000
10DC	0001 0000 1101 1100	93	1001 0011	93	1001 0011	**93**	**1001 0011**
10DD	0001 0000 1101 1101	19	0001 1001	0A	0000 1010	08	0000 1000
10DE	0001 0000 1101 1110	91	1001 0001	91	1001 0001	**91**	**1001 0001**
10DF	0001 0000 1101 1111	3D	0011 1101	10	0001 0000	10	0001 0000
10E0	0001 0000 1110 0000	97	1001 0111	93	1001 0011	93	1001 0011
10E1	0001 0000 1110 0001	40	0100 0000	46	0100 0110	**40**	**0100 0000**
10E2	0001 0000 1110 0010	95	1001 0101	91	1001 0001	91	1001 0001
10E3	0001 0000 1110 0011	43	0100 0011	FF	1111 1111	**43**	**0100 0011**
10E4	0001 0000 1110 0100	93	1001 0011	93	1001 0011	**93**	**1001 0011**
10E5	0001 0000 1110 0101	46	0100 0110	46	0100 0110	**46**	**0100 0110**
10E6	0001 0000 1110 0110	91	1001 0001	91	1001 0001	**91**	**1001 0001**
10E7	0001 0000 1110 0111	FF	1111 1111	FF	1111 1111	**FF**	**1111 1111**

Note: Bold print indicates commands or event times which are not modified by the fault.

remove power from the elevation drive motor. The processor then executed a command at location 1000 hex for which the erroneous value read from ROM was zero.

The CDP-1802 machine instruction corresponding to the value zero is the IDLE instruction which is somewhat unique to the 1802 processor family. The function of the instruction is to place the processor in a kind of "suspended animation" until it receives a hardware signal in the form of an interrupt or a Direct Memory Access (DMA). The DMA function is not implemented in the ERBE instruments, so the only means of exiting from an IDLE condition is via a hardware interrupt. Interrupts are implemented in the ERBE Scanner Instrument for 33 ms clock, the major frame clock, and azimuth drive. However, the processor will not respond to these hardware signals if the interrupt enable flag is not set.

In the fault mode simulation the processor executed the IDLE instruction with the interrupt enable bit cleared. Execution of this instruction effectively killed all microprocessor controlled instrument functions including the issuing of scan drive commands, acquisition of data, and transmission of DIG A data to the spacecraft interface. The only possible exit from this condition is a CPU-reset.

A Solar Calibration Sequence data table corresponding to this failure hypothesis was generated. The commands and event times from this table were used to predict the behavior of the flight instrument. A Solar Calibration Sequence command was issued to the instrument on September 15, and the flight data was in complete agreement with the predictions.

Conclusions and Recommendations

The simulation results and the ability to predict the behavior of the instrument when issued a solar calibration sequence strongly support the conclusion that the cause of the NOAA-10 ERBE Scanner malfunction is traceable to a failure of the internal address decoding circuitry of the high ROM memory chip A2 A1-U50. The failure causes a logical ANDing of multiple memory locations, and the resulting erroneous code and/or data. When the erroneous data and/or code is executed by a normally functioning microprocessor, it produces the anomalous behavior and malfunctions which have been observed in the flight instrument.

Since there is no method of reprogramming the processor, and there are no alternate scan modes which are functional, the only course of action which remained was to power-down and then power-up the instrument on the chance that the failure in the ROM would be self healing. The probability of this being successful was low as the ROM memory chip (generic part S82S191) is a bipolar fusible link device. When this was tried on October 17 and failed to produce any change in instrument performance, no further tests were recommended.

There are some similarities between failure of the ERBE Scanner instruments on NOAA-9 and NOAA-10. However, since the scanner on NOAA-9 would not respond to a CPU-Reset attributing the failure to a memory failure would be speculative at best.

Although the cause of the failure can not be determined from available data, some comments can be made about the suspect part. The 21002BJX ROM devices (generic part S82S191) is on the MIL-38510 parts list and has been used extensively in military and spaceflight hardware, including a total of eighteen devices installed on the 6 ERBE Scanner and Nonscanner Instruments. Records indicate that no failures have been recorded in commercial, military or space use of the part due to manufacturing defects. Some ionizing radiation testing has shown, however, that this part is susceptible to single event upset (SEU). Charge build-up within the device due to gamma ray or high energy ion bombardment could cause bit latch-up and failure. The excess parts lists from ERBE instrument fabrication have been reviewed, and it has been determined that there are no remaining ROM chips from the flight lot on which further tests could be performed.

It is strongly recommended that Langley Research Center require the CERES instruments and any other extended mission instrument to be built with the capability of reprogramming the instrument in flight. Since a ROM failure in the bootstrap program is just as likely as in any other portion of code, it is further recommended that instrument designs have redundant bootstrap ROMs, direct RAM access from the spacecraft data bus, or redundant processors.

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16. Abstract
The Earth Radiation Budget Experiment (ERBE) scanner instrument on the NOAA 10 spacecraft malfunctioned on May 22, 1989, after more than 4 years of in-flight operation. After the failure, all instrument operational mode commands were tested and the resulting data analyzed. Details of the tests and analysis of output data are discussed herein. The radiometric and housekeeping data appear to be valid. However, the instrument will not correctly execute operational scan mode commands or the preprogrammed calibration sequences. The data indicate the problem is the result of a failure in the internal address decoding circuity in one of the ROM (Read Only Memory) chips of the instrument computer.

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