5.6. The Onboard Computer.

The onboard computer (OBC) maintains attitude control and controls the scientific experiment operation. Because it is so vital to spacecraft operation, the OBC must be highly reliable. The general characteristics of the Advanced Onboard Processor (AOP) are presented below.

- Power consumption. 15 watts maximum while computing (including power converter and full memory complement). 9 watts when halted.

- Speed. Add time, 5 microseconds. Multiply time, 38 microseconds. Divide time, 75 microseconds.

- Memory. 3 modules of 4K by 18 bit word (each 4K module incorporates cycle by cycle power switching).

- 55 Instructions.

- Simple to Program: one double length accumulator (36 bits), one index register, smooth handling of interrupts by hardware, powerful bit manipulating instructions and direct addressing of all 4096 words in any page.

- Multilevel Interrupts. 16 priority interrupt levels with program control over lock-out status and interrupt disable.

- Direct Memory Access (DMA). Up to 16 independent cycle steal operations time share one DMA channel. Maximum I/O rate of 100 k words per second.

- Memory Write Protection. In orbit reprogramming dictates that storage limits must be modifiable. Storage areas can be assigned in increments of 128 word blocks.

- System utilizes a bus concept so that unpowered spare memory modules or processors may be flown. An automatic switch over control for real-time repair can be readily implemented.

- Any spare memory bank may be used to functionally replace any other bank. The memory bank used for fixed (Interrupt and I/O) locations can be reassigned by command.

The OBC consists of several modular components, a central processing module (CPM, which contains a central processing unit, CPU, and a special input/output, SIO, unit integrated into a single package), memory modules and a power converter. Redundant modules are used to ensure that there is no individual component failure. There are two CPM’s, two power converters and three 4K 18-bit word memory units. These units are interconnected so that any remaining component can be connected to the functioning counterparts to create a whole system. Two data buses are used to ensure data flow between any combination of memory units and CPM’s. Operating software systems requiring 8K and 4K are used.

- **Central Processing Unit (CPU).** The CPU uses large-scale integration and transistor-

transistor logic. The processor employs a fully parallel adder and parallel data transfers between registers and at the Processor/Memory interface. 16 individually armed priority interrupts are used, which allow asynchronous spacecraft events to gain access to computer operation at event dependent intervals. The interrupt handling logic is designed so that when an interrupt is honoured, three critical registers are automatically saved and initialized to new values from fixed memory locations. These are the instruction counter, the interrupt lockout registers and the storage limit register. The hardware handling of these registers is important in providing security of program execution in a long term unattended environment.

- **Special Input/Output Unit (SIO).** The SIO handles all communication between the CPU and the spacecraft (e.g., command, attitude control and scientific instrument). These events are asynchronous, relative to regular computer operation, and must be introduced so they will not disturb normal CPU operations. Program independent data transfers are accomplished by the AOP through the use of buffered I/O channels, operated in a cycle steal mode similar to the priority interrupt technique. These channels time-share a single set of Direct Memory Access (DMA) hardware.

  The SIO receives data from the DMU and converts it from serial to parallel format for the CPU. It also receives digital data from the CPU and coverts them to the proper multiplexer format. The SIO converts signals from the DMU level to transistor-transistor logic and vice versa.

  The command system accepts commands from both the computer and the command receiver on a time-shared basis. Therefore, the OBC can control any commandable system if it is programmed to do so. This includes the capability of issuing stored commands on a time delayed or event dependent basis. Commands related to the computer's basis task of attitude control are computed, formatted, and sent to the reaction wheels or jets via the command system.

- **Memory Units.** The OBC has three 4096 by 18-bit word plated wire memory units. These memories feature cycle-by-cycle power switching which reduces the power dissipation in the nonaddressed memory units from 4 watts to 150 milliwatts. They are nonvolatile and readout is nondestructive. The access time is 500 nanoseconds and cycle time is 1 microsecond.

- **Power converter.** All components of the OBC operate on a power supply of 5 volts direct current. Since the spacecraft main power bus is 28 volts direct current, a direct current-direct current power converter is provided for the OBC. Two 28 volt to 5 volt converters are used; the second unit being redundant. The power converters have an efficiency of 70% and have power clear circuitry, which anticipates power shutdown and causes a graceful shutdown of the processor when power is interrupted. The power converter units also contain the control circuits for selecting the redundant CPU and SIO and memory unit combinations.

Flight Software.

The OBC 8K flight software provided for attitude control, camera exposure control, station keeping maneuvers and other vital functions. It was contained in banks 0 and 2 memories. The flight software was divided into two categories: the Flight Executive and the Workers.

The Flight Executive program performed specific tasks mainly dealing with I/O functions, controlled time-critical operations, scheduled and initiated the application programs (Workers), and performed the following tasks:

- Initialized the flight software.
- Real-time interrupt services and processor schedules.
- Saved and restored critical registers.
- Accepted and stored OBC and ground telemetry data.
- Accepted commands and data blocks to the OBC.
- Generated OBC status words which indicate current errors, operational modes and software selected options.
- Issued OBC telemetry to the DMU.
- Issued commands to any subsystem including itself in response to software or hardware generated interrupts.
- Controlled the start of hold/slew algorithm.
- Issued stored or uplinked command groups (delayed commands).
- Controlled any automatic mode sequencing.

There were 16 interrupts available. The Flight Executive code used 8 spacecraft initiated (int. 4, 5, 9, 11, 12, 14, 15 and 16) and 4 ground initiated interrupts (int. 0, 1, 8 and 10), the other ones were not defined. An interrupt was a software service routine called by external devices handled on a time dependant basis. A priority decoder ensured that only one interrupt was selected at a time, and interrupts were serviced in order of priority. If an interrupt occurred during the execution of an instruction, it was not honoured until that instruction was completed. If several allowable interrupts occurred at one time, there was one CPU instruction executed before each interrupt was serviced. The following list is a summary of the OBC interrupts along with their functional description.

- **Int 0.** Initiate the OBC program.
- **Int 1.** Command input for OBC software load.

- **Int 4.** Ground Telemetry Data in.
- **Int 5.** Computer Data in.
- **Int 8.** OBC software dump.
- **Int 9.** Command out to command decoder.
- **Int 10.** Ground command to OBC (executive request handler).
- **Int 11.** Frame synchronization check for Ground and Computer Data in.
- **Int 12.** Direct Address to DMU.
- **Int 14.** OBC Data out.
- **Int 15.** Scheduler for Workers and Out-of-Limits handler.
- **Int 16.** Exit. Executive services (sets up Int 9).

A Worker was an OBC application program that performed a specific task. Workers were called by the flight executive. The following list explains the task performed by each Worker.

- **Worker 0 - Hold/Slew Algorithm.**
  This attitude control algorithm was the single most important routine on board the IUE. The purpose of this program was to provide a method by which the spacecraft might be slewed to a command region and/or hold an existing orientation for an extended period of time. The program integrated rate and position sensor data and calculated the reaction wheel commands necessary to hold or slew the spacecraft. Worker 0 used a set of variables, called Mode Bits, to select appropriate inputs to the operational mode (e.g. the sensor which were to be used on that iteration to calculate the three control variables). Worker 0 also checked for violations on axis/sensor configurations and changed the configuration as necessary. Worker 0 underwent periodic code changes to improve spacecraft pointing accuracy and slew control as well as to account for sensor failures. It was the most affected Worker when a new attitude control system was implemented.

- **Worker 1 - Maneuver Processor.**
  Worker 1 was a service routine. It processed the minimum time slew information (axes and angles) contained in a Datablock 11 and set telemetry flags to indicate the status of the maneuver. The processing of the information basically consisted of feeding the slew information to worker 0 one leg at a time.

- **Worker 2 - Exposure Control.**
  This service routine accurately timed to within 0.4096 seconds camera exposures for collection of scientific data. It used the information contained in a Datablock 14 to perform the exposures. The Datablock 14 indicated which camera was to be exposed and for how long. Worker 2 commanded the camera to “expose” mode, counts up from zero

to the indicated time in 409.6 millisecond ticks, and then issued a "standby" command to the camera.

- **Worker 3 - Cyclic Delayed Command Worker.**
  In 1988, Worker 3 was designed to use the DMU clock in conjunction with Interrupt 5's scheduled execution time to provide accurate cyclical executions of an uplinked block of commands (Datablock 18). It was intended to be used to "strobe" the spectroscopic cameras to obtain phase coverage of pulsar-like variables with very short periods. Worker 3 was never used because the rapid cycling on the cameras could damage them.

- **Worker 4 - Bright Light Protection.**
  This diagnostic algorithm checked star intensity. If it was too great, a command to shut down the FES, close the sunshutter and put the cameras in standby mode was given to protect the equipment from permanent damage. This Worker was only used early in the mission.

- **Worker 5 - Pointing Constraint.**
  Worker 5 was a diagnostic algorithm. If Worker 5 was active, it would command the FES to shut down and close the sunshutter, put the cameras in standby mode and the spacecraft in Sun acquisition hold-on-wheels mode whenever it sensed the absence of sunlight from the digital sun sensor. This worker was only used early in the mission.

- **Worker 6 - Memory Checksum.**
  This self-check algorithm performed an exclusive OR operation on the contents of the OBC memory banks, excluding variable data points. The result of the XOR was compared to a constant stored in memory. If the checksum failed, an error flag was set to indicate possible corruption of the OBC contents.

- **Worker 7 - Central Processing Unit Functional Test.**
  Worker 7 was a self-check algorithm. It checked the OBC logic and arithmetic instructions for correctness. A series of manipulations were done and compared to a set of constants in memory. If an unfavourable compare was found, an error flag was set.

- **Worker 8 - Attitude Control System Worker Timeout.**
  Worker 8 had top priority of the self-check algorithms. It performed a time limit check to verify that Worker 0 completed running within a prescribed time. If this condition failed, an error flag was set and Worker 0 was rescheduled.

- **Worker 9 - Rate Arrest.**
  This diagnostic algorithm monitored the wheel speeds when there were no slews in progress. An error flag was set when the absolute value of the wheel speed change was greater than a given threshold and a change was in the same direction on three consecutive iterations. This worker had a commandable option to allow the program to switch to the inertial (Worker 10) hold on wheels control mode when an error was detected.

- **Worker 10 - Wheel Speed Hold.**
  Worker 10 was an attitude control algorithm. It maintained the reaction wheel speeds at

a designated rate. The reference wheel speeds could be uplinked in a Datablock 16 or the current values could be captured as references at the time Worker 10 was turned on. Wheel hold was used for control in case of ACS sensor malfunctions and, sometimes, during shadow periods (Shadtrack mode).

- **Worker 11 - Safe Attitude Slew.**
  Worker 11 was a diagnostic algorithm. When enable, it allowed the OBC or user to have the spacecraft automatically slew from a constrained (violation of spacecraft orientation limits) to an unconstrained region. The safe attitude coordinates were stored in a Datablock 11.

- **Worker 12 - Shuts Down Fine Error Sensor, Camera and Shutter.**
  This diagnostic algorithm gave the user a quick way of protecting the spectrograph hardware and could be activated by ground command or by Worker 4 or 5. Worker 12 shut down the FES, closed the sunshutter and put the cameras in a standby mode.

- **Worker 13 - Delayed Commands.**
  This service routine retrieved and processed stored commands contained in Datablock 17 and directed them out to the command decoder. Any type of command could be transmitted to the OBC via a Datablock 17 and then executed at a later time by commanding Worker 13 on. Camera preparation and wheel unloads were the most common uses for delayed commanding. When all the commands had been retrieved and sent to the command decoder, Worker 13 turned itself off.

- **Worker 18 - Software Loads.**
  Worker 18 was a service routine which handled all Datablocks and OBC patches. The first command in the load triggered Interrupt 10 and identified the number of commands to follow. The commands were then stored in one of two temporary storage buffers by the DMA. Worker 18 would then copy the commands to the final buffer or address in the OBC. After loading was complete Worker 18 would shut itself off. If Worker 18 remained on, software loads could not be processed until the Worker was turned off by a ground command.

- **Worker 19 - Rate+Position Hold / Delta-V.**
  This attitude control algorithm used much of the same sensor data used by Worker 0 to calculate and send commands to the HAPS jets. It was designed to provide control of the IUE during Delta-V burns. In the Rate+Position Hold mode, the three spacecraft axes were controlled by the low-thrust jets. Delta-V mode was similar to Rate+Position except that the yaw axis was controlled by high-thrust jets, which were being commanded to fire for the velocity correction burn. Datablock 19 contains the control information for Worker 19.

- **Worker 22 - Zero Out Gyro Bias Angles.**
  This service routine reset the pitch and yaw gyro measured body angles to zero.

In the course of operations many Workers were left inactive. The limited memory of the OBC became critical in the transition from the 3-Gyro to the 2-Gyro system and Workers 4, 5, 7, 9, 11, 12 and 22 were removed.

Commands and Datablocks.

The command structure was set up to achieve maximum flexibility and allowed the OBC to detect the various requests and process them properly.

Singles commands were used for different utilities, for example to start the OBC code, stop the OBC, select the memory banks, dump the memory contents to ground, load instructions from the ground to the OBC code, switch on/off the workers, select FES 1/FES 2 data and so on.

Datablocks were the most common type of software load sent to the OBC. They contained either commands that was issued to the spacecraft or operating parameters for a particular worker. Each Datablock had a specific function and carried specific types of commands or information within it. These five Datablocks were used in everyday operations:

- Datablock 11 - Minimum Time Maneuvers. It contained the slew leg angles and the axes to be slewed for minimum time slews (long maneuvers were performed one axis at a time).

- Datablock 14 - Camera Exposure. It contained the identification of the camera to be exposed and the length of the exposure.

- Datablock 15 - Attitude Readout. It placed the ground generated Right Ascension, Declination and Roll angles into the OBC telemetry stream.

- Datablock 17 - Delayed Commanding. It could store any set of commands in the OBC to be sent at a later time. This Datablock was most often used for wheel unloads and camera preps.

- Datablock 21 - Worker 0 Configurations. It was a versatile Datablock that handled Mode Bit configurations, gyro trims and fixed rate slews (usually short slews in both pitch and yaw axis). This Datablock was labelled Datablock 10 under the 3 Gyro system.

There were also other Datablocks used in special circumstances like Datablock 12 (used to sequentially define the desired order of the OBC telemetry frames for ground inspection), Datablock 13 (used to define the content of 6 OBC programable addresses contained in OBC telemetry), Datablock 16 (used to provide reference wheel speeds for OBC Worker 10) or Datablock 19 (used to uplink information needed by Worker 19).

Datablocks were uplinked to the spacecraft and handled by Worker 18 which was controlled by Interrupt 1, the software load Interrupt. Worker 18 verified that each Datablock was built correctly and then stored the data in a buffer set aside for particular datablock, each datablock had its own storage area. The data contained in the datablock was then available for its associated worker to use.

Error Flags.

An error flag was a status bit set by OBC Workers or Interrupts to indicate some parameter violation or the identification of a specific condition. Error flags came down in OBC telemetry to be displayed at the control consoles and to alert the analyst of a potential problem.

Memory Dumps.

The contents of the OBC memory banks could be examined by dumping the contents into the telemetry stream and reconstructing them on the ground. This was often done after an anomaly involving the OBC to pin-point the cause and to ensure that no part of the memory has been corrupted. Dumps were also done whenever software changes were made to improve or correct the OBC workers to verify the patch were properly stored in memory.

Temperature Limits.

The OBC required that certain temperature limits be maintained to ensure proper and reliable operation. The prelaunch maximum predicted value was 35°C, but soon after launch it was apparent that this early prediction could not be met. The operational temperature limit for the OBC was raised over the spacecraft lifetime and reached 58.3°C. At elevated temperatures the OBC might begin taking “hits” and cease to operate, resulting in an OBC crash and a loss of attitude control.

On January 10,1995 the OBC temperature upper limit was reduced from 58.3°C to 56.4°C due to the DMU anomaly (see section 4.4.1.).

4K Operational System.

OBC memory bank 1 contained a complete operating system that only occupied 4K of space. This system was developed as a backup in case of an anomaly with the 8K system. The 4K system was also used during spacecraft tests for attitude control while the other two memory banks were being loaded with test software. In order to make the system small enough to fit in 4K, many workers had to be eliminated.

For the first 3 years of the IUE mission, the OBC 4K operational system was used strictly as an emergency backup to the 8K operational system. It could not support science operations, but was used to recover attitude and monitor spacecraft telemetry until the 8K operational system was operational again.

During 1981, a new 4K operational system was developed which could be used to support science operations.

After the third gyro failed, science operations could not be supported by the new two-Gyro-FSS 4K operational system, it had no Worker 13, so delayed commanding via Datablock 17 could not be performed and no Worker 14, so no exposures could be taken. Also, it had only Worker 0 for attitude control.

5.6.1. OBC Patches.

OBC patches were used to introduce new values or instructions to the existing OBC code. These modifications were realized in a attempt to improve the OBC control or to solve a new problem. The list below explains the main patches introduced to the OBC code and, also, the different system versions used in the 4K and 8K code.

- On November 4, 1979 two changes were introduced in the 4K system. The first one was to introduce a new gyro matrix with gyros 2, 4 and 5. So, it would be used in the event of gyro 1 or 3 failure or a failure of the 8K system. The second one consisted of a “hit” protection to automatically restart the OBC.

- On November 8, 1979 some patches were applied to the 8K system to prevent a missing interrupt from halting the OBC, eliminate the static OBC telemetry problem and store the contents of certain registers to aid in later analysis in the event of an OBC crash.

- On January 29, 1980 the “NO-OP” instruction in the idle loop was replaced by the “HALT” instruction to permit the memory power to cycle. The “HALT” instruction was expected to save power and reduce the OBC temperature by a couple of degrees.

- On March 31, 1980 the “NO-OP” instruction was again inserted in place of “HALT” instruction. The “NO-OP” instruction greatly reduced bus noise and the change did not reduce the power or temperature.

- On May 20, 1980 a new sequence was introduced to automatically restart the OBC in the event of a crash.

- On June 16, 1980 the Interrupt 9 was modified to improve its command capability.

- On August 31, 1981 a new 4K system was uplinked and successfully tested, which was capable of supporting science operations. In order to squeeze this much into 4K, many programs were deleted or changed. The following workers were deleted: worker 4, 5, 7, 9, 10, 12 and 19. Worker 8 and 18 no longer existed as separate workers, their functions still existed, however, and were included in Interrupts 15 and 1. The Worker 0 was slightly changed from the 8K version.

- On August 18, 1985 the 2 Gyro/FSS system was uplinked to the spacecraft. It required a great amount of changes with respect to the previous system. Datablock 10 was replaced by Datablock 21. The Workers 4, 5, 7, 11 and 12 were deleted to gain memory. The Workers that had to do with slewing and attitude control were substantially changed and, also, the Mode Bits were redefined.

- On April 25, 1986 the roll control law was completely changed from the original 2 Gyro/FSS code to do a much better job of controlling large oscillations at low beta angles. Some attempts to improve the roll control were made during the previous with minimal improvement. The new law improved the roll control by holding the sun centred on the edge between two FSS buckets.

- On October 17, 1990 a new 4K system was developed. Only basic hold/slew capabilities were provided by the available Workers 0 and 1. Worker 1 was essentially identical to the current version used in the 8K system. Worker 0 was greatly reduced in size and capabilities (no FES processing, no filtered modes, no low gain option). Worker 18's function was still included in the flight executive code but it was not distinguished as a separate Worker.

- On December 21, 1990 a patch was implemented to effectively correct the roll FSS data used by the OBC when course bit 5 had dropped out. Because of the current control algorithm and the symmetry of the FSS, the patch simply reset the bit when it dropped out. An error flag was set by the patch simply reset the bit when it dropped out. An error flag was set by the patch when the bit was reset by the code to enable the ground controllers to keep track of this anomaly.

- On May 6, 1991 a patch was introduced to the OBC code to correct another FSS anomaly. When an erroneous beta value greater than 136° was measured, the value was ignored and the patch set an error flag. Worker 9 had to be deleted to implement this correction due to a lack of available memory.

- On July 8, 1991 a patch was uplinked to enhance Worker 0 control during minimum time slews. It also improved Worker 19 control. The new law produced a better roll angle control. The roll angle was corrected on each worker iteration to be always as close to zero as possible during slews. This resulted in smaller maneuver errors.

- On July 19, 1991 a patch was uplinked to prevent a complete loss of attitude control in the event that track was accidentally broken during an eclipse. If a loss of star occurred, the spacecraft attitude control was automatically switched to Worker 10, which provide control independent of the FES and FSS. The patch was made to allow Worker 0 to perform its calculations even if a no sun presence condition existed. So, control was returned to Worker 0 at the end of the eclipse and it could zero out the net errors accumulated while under Worker 10.

- On September 9, 1992 a patch was introduced to the OBC to correct all code inconsistencies that produced a discrepancy between the decoder used by the OBC and the telemetry point indication of the decoder being used.

- On July 1, 1993 a patch was developed to detect most incidents of the FES tracking on scattered light and automatically placed the spacecraft in a stable hold mode.

- On March 11, 1996 the 1 Gyro system was loaded into the OBC. The primary change in this system was the attitude control Workers. The Mode Bits also had to be redefined.

- On March 26, 1996 the yaw axis control was improved after several attempts. Also, the FES scattered light check had to be changed and the error threshold adjusted to compensate for the relatively larger errors experienced during fixed rate slews when using the FES.

5.6.2. Three-Gyro System.

The three-Gyro system was the original control mode. It was used until the forth gyro failed. In this system, there were two basic ways of controlling the pointing of the spacecraft:

- Gyro mode. The gyros sensed motion in three axes (pitch, yaw and roll) and this information was used to control the spacecraft.

- FES mode. “Put track on” meant that the FES and filtered gyro data were used to control the pitch and yaw, while roll was controlled using filtered gyro data. The attitude sensor data coming to the OBC could also be filtered.

The normal sequence of events from preparing for a maneuver to starting an exposure proceeded as follows:

- The maneuver was computed by the ground system.

- Before and during the slew, the spacecraft remained in Gyro mode. The minimum time maneuver was done slewing one axis at a time, pitch, yaw and roll.

- After the maneuver, the star field was identified and a wheel unload performed (if needed). Some fixed rate slews were performed in Gyro mode to acquire the target and put it into the aperture.

- Once the star was in the aperture, a guide mode (FES mode) was chosen and the exposure started.

Special techniques were used for certain types of observations:

- Blind offsets were slews from a visible target or guide star to non-visible target (those targets which could not be seen by the FES). Accurate coordinates for both the target and the visible reference star in the FES field of view were needed. Then, the guide star was placed at computed FES (X,Y) coordinates so that the target fell in the aperture. This required an accurate FES geometric calibration.

- Moving targets were performed under Gyro control. The spacecraft was made to follow the star motion by changing the gyro drifts.

- Trails were exposures taken of a star while the spacecraft moved such that the aperture crossed the target. Trails were performed under Gyro control.

The failures of the gyros and the reconfiguration of the gyro heaters resulted in a degradation in maneuver accuracy. New gyro scale factors corrections were calculated monthly based on the month’s observed maneuver errors. Plots were created showing the actual observed maneuver errors and what they would have been had new gyro scale factors been uplinked. The figure 5-68 shows this comparison (maneuver length and error the square root of the squares, only pitch and yaw errors included) with data from 1981. When large variations began appearing, the new gyro scale factor corrections were uplinked to the spacecraft (see section 5.5.1.2.).

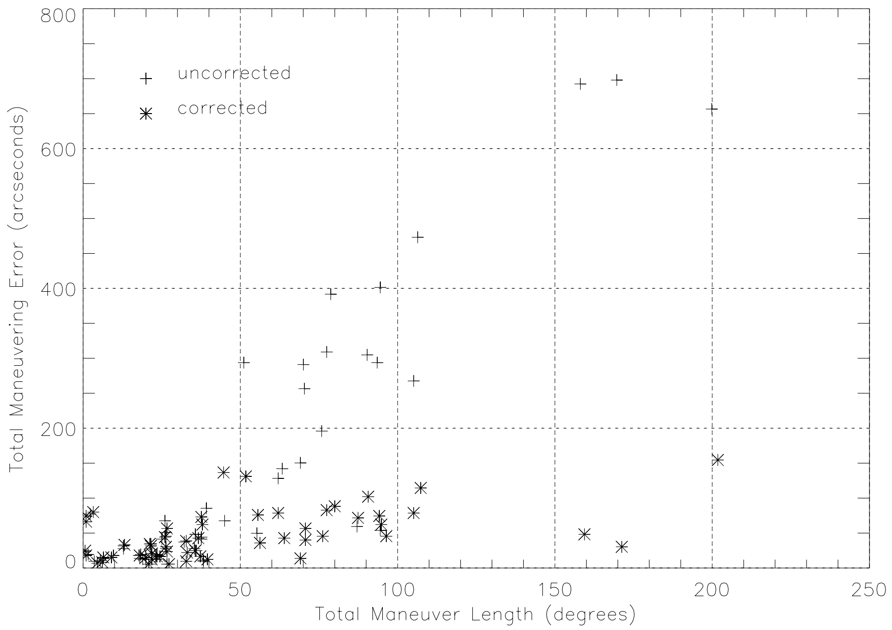

Figure 5-68. Comparison of errors with derived correction, 3-Gyro system.

5.6.3. Two-Gyro/FSS System.

The basic idea of this system was to use the FSS data to provide attitude information in place of a gyro. The FSS can sense both pitch and roll motions, but not yaw motion directly. Also the FSS control was cruder than gyro control, around 15 arcsecond instead of 1 arsecond accuracy. The motion in pitch and yaw axes could be measured from the gyros, while the roll angle was maintained as close to zero as possible based on the FSS measurements.

In the two-Gyro system, the OBC could use several different combinations of the 2 gyros, the FSS and the FES to monitor spacecraft motion in the three axes. The following modes were the more used ones:

- Default mode (pitch on FSS + gyro, yaw on gyro, roll on FSS). This was the mode normally used for minimum time slews.
- Acquisition mode (pitch and yaw on gyros, roll on FSS). This was the mode normally used to set up on the star or target and to perform all fixed-rate slews.
- Tracking mode 1 (pitch and yaw on FES + gyro, roll on FSS). This mode was normally used during the exposures.

- Tracking mode 2 (pitch and yaw on FES, roll on gyro). This is the only sun independent mode. So, this mode was normally used during the shadow periods.

During daily operations, the normal sequence of events was carried out as follows:

- The maneuvers were computed as usual, but there were no longer any allowed constrained maneuvers (e.g. it was not possible to slew to beta angles of less than 13°, because the FSS would loss sun presence).

- The spacecraft had to be prepared for the maneuver, which was performed in default mode. There were two types of slews: pitch and sunline. The sunline was actually a combination of a yaw slew and a roll slew, balanced so that a constant beta was maintained.

- After the minimum time slew was completed, the control mode was changed from default mode to acquisition mode. It was important to get out of the default mode, in which pitch was controlled through the FSS, quickly. As the sun moves slowly through the sky, the beta angle of a given star changes slightly. If the spacecraft was maintained at a fixed beta angle, then the star would appear to move across the FES field.

- The star field was identified and a wheel unload performed (if needed). Some fixed rate slews were performed to acquire the target and put it into the aperture.

- Once the star was in the aperture, a guide mode (Tracking mode 1) was enabled and the exposure started.

The special types of observations were achieved in a similar way to the three-gyro system. Blind offsets, moving targets and trails were performed while the spacecraft was under acquisition mode.

After the FES streak light anomaly appeared, the blind offset started to be used very frequently. Many stars were hidden by the streak light. So, a lot of times, fixed rate slews were to be performed from far (not included in the same FES field) bright stars. Sometimes, it also implied that there was not any available star to guide, so, the exposure had to be taken while the spacecraft was controlled in acquisition mode. As this mode was strongly dependent of the gyro drift (pitch and yaw were controlled on gyros) , the exposure time could not be very long (up to 40 minutes). Long exposures were performed divided in segments. At the end of each segment, the target (or another bright star close to the target) position was checked and the gyro drift measured from the position errors. From these drift measurements corrections to the gyro drift bias were calculated and uplinked to the spacecraft (see section 5.5.1.2).

The spacecraft appeared to maneuver better under the 2-Gyro/FSS control mode than under the 3 Gyros control mode. In the 2-Gyro/FSS system, pitch slew errors were not usually greater than ±2 arcseconds. Sunline slew trends are shown in the figure 5-69. The FSS resolution was rather poor at low betas, so this fact increased very much the final errors.

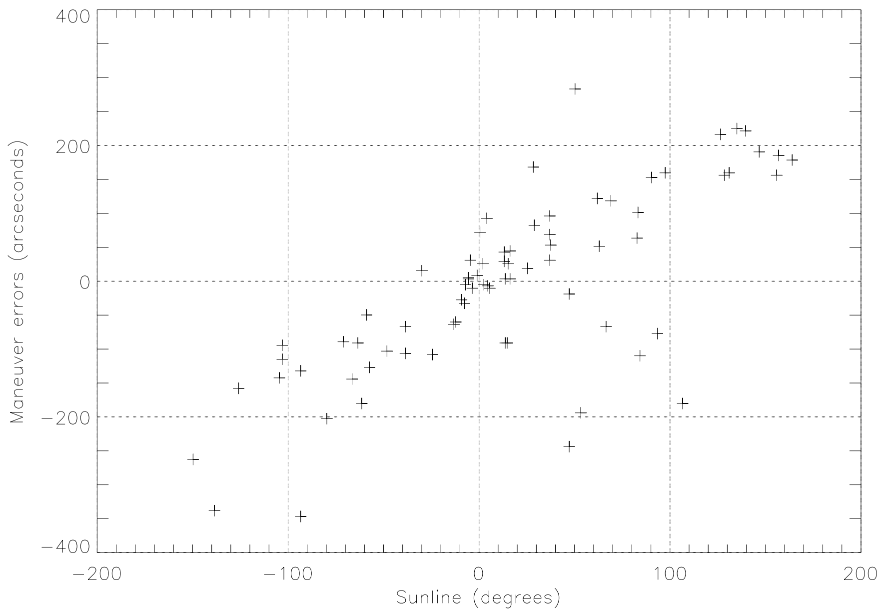

Figure 5-69. Sunline slew errors, 2-Gyro/FSS system.

5.6.4. One-Gyro System.

The one-Gyro flight code processed information for 2 axes from the FSS or the FES and the one remaining gyro to provide 3 axes control. Having one operational gyro required that this gyro be used as a sensor for only one axis at a time. This was necessary because the gyro's input axis was equivalent to having one equation with three unknown variables, which could not be solved. In order to derive useful single axis information from the gyro, the motion sensed from the other 2 axes was removed from the gyro data. Information from the FSS and/or the FES provided the necessary information to solve the equation.

The following modes were the most used ones:

- FSS default mode (pitch and roll on FSS, yaw on gyro). This control mode provided the most robust control and was used for minimum time maneuvers and wheel momentum unloads. It was the only FES independent mode and provided a coarse control. The accuracy in the pitch axis was around 15 arcseconds (the FSS resolution changes with beta) and in yaw axis around 1 arcminute (it was strongly dependent of beta angle).

- Tracking mode 1 (pitch and yaw on FES, roll on FSS). This mode provided the fine pointing control to perform fixed rate slews and exposures. FES 1, FES 2 or both FES's data could be used, but, due to thermal and power constrains, the FES 2 data was actually the only one used.

- Tracking mode 2 (pitch and yaw on FES, roll on gyro). It was the only sun independent mode and was used during the shadow periods.

The normal sequence of events from preparing for a maneuver to starting an exposure was carried out as follows:

- The maneuver was computed as usual.

- The spacecraft had to be prepared for the maneuver, which was performed in FSS default mode. As in the two-Gyro/FSS system, there were two types of slews: pitch and sunline.

- After the minimum time slew was completed, an FES image was taken and the star field identified.

- The tracking mode 1 was put on the guide star. It was important to get off the FSS default mode as quickly as possible. As the sun moves slowly through the sky, the beta angle of a given star changes slightly. This apparent sun motion produced spacecraft motion in both pitch and yaw axes.

- Some fixed rate slews were performed to acquire the target and put it into the aperture. As the fixed rate slews were done in tracking mode, they had to be performed inside the FES field.

- Once the star was in the aperture, an exposure was started. The only mode to have fine pointing control was to use a guide star, so, each target needed a bright enough start to be used as a guide star.

Blind offsets could be performed in FSS default mode or in tracking mode. The first mode had to be used when the initial star and the target were not in the same FES field, but the accuracy was very poor.

Moving targets and trails could be performed using a guide star in tracking mode 1. An exception was the observation of Comet Hyakutake from March 23 to 27, 1996. At this time, no moving target procedure had been developed for the one-Gyro control system (gyro 5 had been lost on March 6, 1996). The operational mode chosen was to follow the comet in FSS default mode by direct commanding of drift rates to the OBC. On the one hand, these rates compensated for the spacecraft drift following the solar motion and, on the other hand, brought the comet into the aperture by introducing the same comet motion in the spacecraft reference system.

The figures 5-70 and 5-71 show pitch and sunline errors at different beta angles.

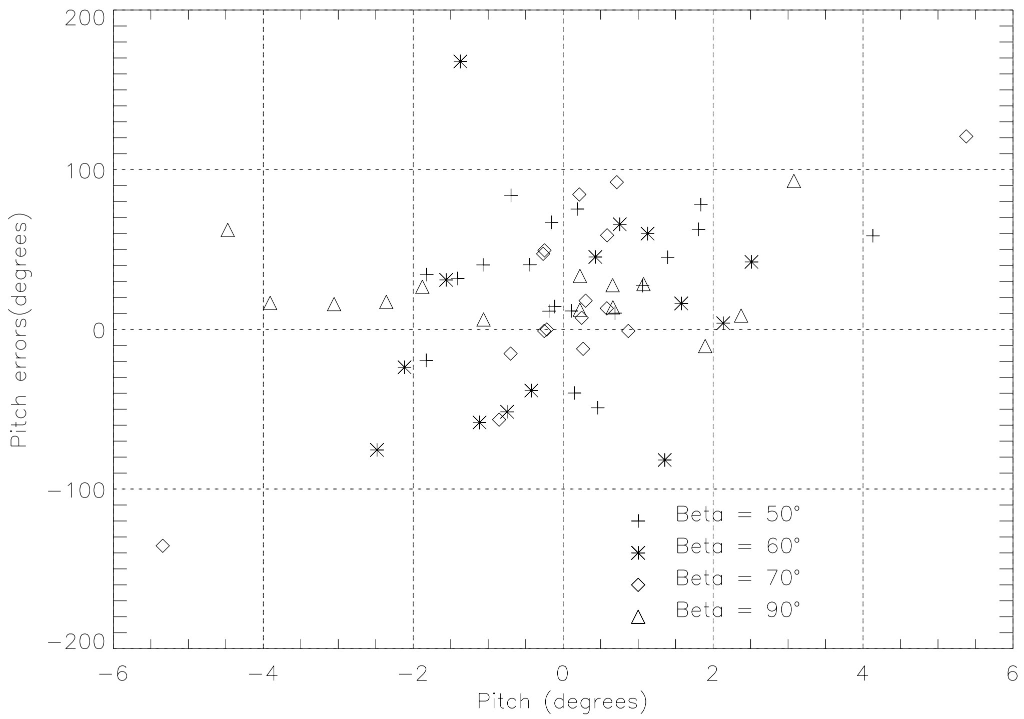

Figure 5-70. Pitch slew errors, 1-Gyro system.

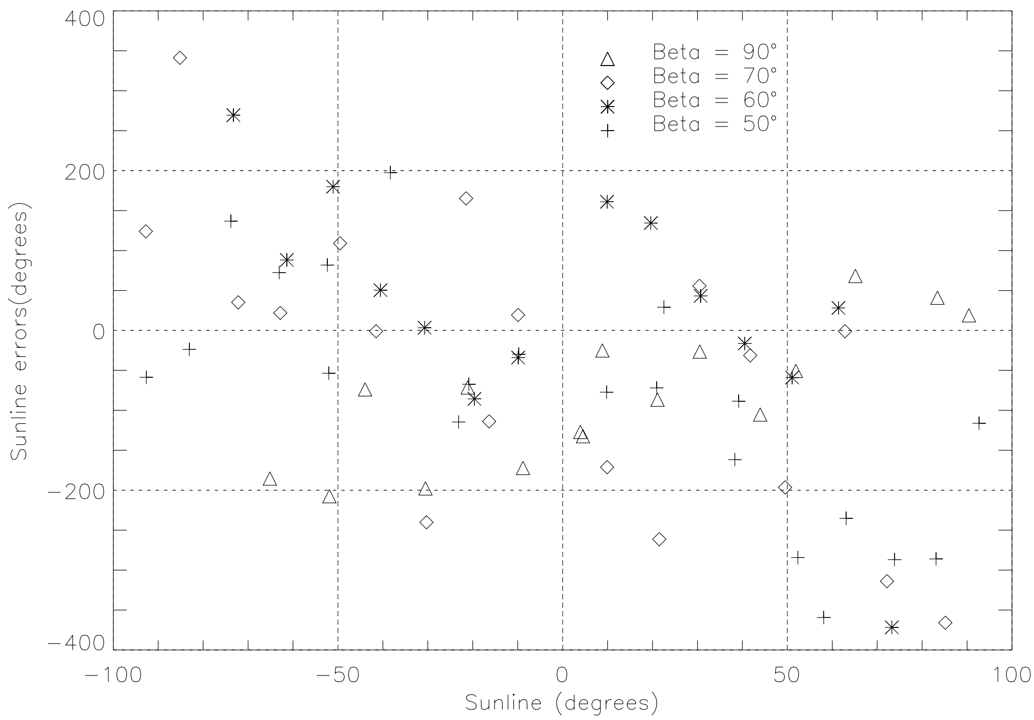

Figure 5-71. Sunline slew errors, 1-Gyro system.

5.6.5. Attitude recovery procedures.

During the IUE's mission, the spacecraft experienced several losses of attitude due to an OBC crash or other spacecraft problem. The primary symptom of loss of attitude was the inability of identify the star pattern in the current FES field-of-view. Following these events, an attitude recovery was necessary. The following attitude recovery procedures were available.

- **Attitude recovery at beta = 0°.**
  At beta = 0°, the spacecraft pointing was towards the anti-sun position at a given time, which right ascension and declination could be interpolated from the solar ephemeris (to the nearest minute of time). The spacecraft maneuvered to this position, where the north direction on the finding chart and the north arrow on the identified FES field-of-view were compared. From the difference, a correction to the roll attitude currently in the system was estimated.

  The attitude should be verified to eliminate small pointing errors, and to improve the accuracy of the spacecraft roll determination. Before going to beta equal 0°, a maneuver to beta equal 20° was usually performed to optimize the FSS before the sun was lost. This maneuver also introduced errors from optimum roll of no more than a few arcminutes.

- **Course attitude recovery.**
  This procedure provided a deterministic 3-axes attitude using FSS and PAS data. The course attitude recovery had to be performed at beta equals 90°. A ground program provided a list of the time intervals during which the Earth may be target by the PAS (it viewed the Earth twice a day at a time span of 12 hours between the viewing slots). If the Earth path was due within the next hour or two, one should take into consideration to recover attitude using this method.

  Experience showed an error of ± 0.5 degrees in spacecraft attitude using this procedure.

- **Attitude recovery using wheel speeds.**
  This procedure was valid only if no external sources of momentum had been introduced onto the spacecraft, such as haps jet firing. The wheel speed data was used to calculate how much movement the spacecraft had experienced about a selected axis combining this with the relative sun spacecraft angles. A pitch-yaw-pitch maneuver was calculated from the wheel speeds, and the yaw leg is calculated at beta equals 90°. The pitch legs of the maneuver were determined solely by the initial and final betas, while the yaw leg depended on the wheel speed change.

  The new attitude could be derived to an accuracy of about two degrees in each axis. The primary source of errors was in the inaccurate wheel speed telemetry and the resolution of the speeds (average resolution was 9 rpm / telemetry count).

- **Beta-dot.**
  The beta-dot (β-dot) procedure was based on the effect of the daily solar motion as seen by the FSS. It was measured by the movement of a star in the FES field-of-view. For beta equals 90°, the next equation shows the relation between beta-dot and the ecliptic latitude.

$$\beta\text{-dot} = \lambda\text{-dot} * \cos(\varepsilon)$$

Where λ-dot was the sun's movement at the time of the recovery. There was also a sign ambiguity which was resolved by measuring the roll-dot (the sign of the ecliptic latitude is the same as the sign of the roll variation).

The accuracy of this procedure did not seem to be much better than 3 degrees. Beta 90° was the best beta to apply it not only because it simplified the original equation, but also because the beta variation was maximum at this beta angle.

5.6.6. OBC anomalies.

The OBC experienced different malfunctions which had repercussion on IUE operations. These anomalies could affect the scientific experiment operations or the spacecraft control, which had to be rapidly identified and corrected. A list of the OBC anomalies experienced by the IUE during the mission are detailed in Appendix C.

OBC crashes.

When the OBC halted, it ceased issuing wheel control voltages and a loss of attitude control resulted. Because of this, quick recognition and recovery were essential.

Switching to the 4K backup system was the normal mode to recover the attitude control. If this failed to stabilized the spacecraft, Sunbath mode could be entered. Sometimes, the Sunbath mode was extremely important since it was the only mode available to stabilize the spacecraft when the 8K system halted. There was not a 4K backup system available at the beginning of the two-gyro/FSS control mode (from August, 1985, to October, 1990) and under the one-gyro control mode.

Following stabilization of the spacecraft after an OBC crash, the 8K memory was dumped and compared to its expected contents. If 8K corruption was found, the memory banks were reloaded with the proper OBC load tape.

Most of the times, the OBC crashed without a known reason although it could be associated with high OBC temperatures, unusual bit rates, etc. In other cases, some telemetry parameters helped in understanding the cause of the crash, as was the case with the hit counter (HITCTR) and the synchronization counter (SYNCTR).

- An OBC hit was a specific type of corruption to the data stored in the registers called the "Interrupt Return Vector". This corruption had detrimental effects to the proper functioning of the OBC programs (usually resulting in an OBC crash). The OBC included a hit analysis code to detect this problem and avoid the usage of the corrupted values.

- The SYNCTR value was incremented each time the Direct Read Table was out of sync (the OBC and the DMU were out of sync). During normal operations, the only time the SYNCTR was expected to increase was during a bitrate change. When a large increase in the SYNCTR occurred, there was the potential risk of an OBC crash.

Worker failures.

A brief explanation of the worker failures experienced is given below.

- Worker 22 was cycled on and off to zero out the ABG's were not zeroed.

- Worker 18 was turned on to load a Datablock but, for some reason, it was not scheduled to run. This resulted in the Datablock being lost and Worker 18 being unable to turn itself off. It had to be switched off manually to avoid all subsequent Datablocks being rejected. The majority of these cases were identified as resulting from two programs (Interrupt 15 and Interrupt 1) messing with Worker 18's downcounter at the same time. Also the Worker 22 and 13 failures can be explained in a similar way.

- Worker 13 failed to execute the commands in the Datablock 17 and remained on. It had to be switched off by ground command.

- Worker 2 did not work properly terminate an exposure, ending it early by two Worker 2 counts. This anomaly seems to be data dependent.

Command and Datablock skipped.

On several occasions, a single command or a Datablock was uplinked and received by the spacecraft but not executed. The commands were verified by the ground system and the spacecraft command decoder but there was not any action related with them. In general, it did not produce a great impact on operations. The command or Datablock had to be retransmitted and the operations resumed.

Beta 75° anomaly.

On November 28, 1988 the spacecraft attitude control degraded into oscillations, as a result of the beta 75° crossover point of the FSS. As the sun's apparent position drifted to a point near the spacecraft referenced beta angle of 75°, the misalignment of the FSS system's head caused the control algorithm to produce oscillations. A switch between the two system heads at beta 75° was accompanied by a roll axis correction due to the sensor misalignments. This roll axis rotation affected the beta angle, giving it a valve that indicated the other FSS system, head combination should be used. Thus, while the sun angle remained within a region close to beta 75°, the control algorithm continually cycled between the two FSS system/head combinations. On every FSS system/head switch the s/c rolled to some degree to account for the misalignment of the FSS system/head, resulting in the observed s/c oscillations. With sufficient time elapsed the sun angle moved far enough from beta 75° so that the Roll motion resulting from the switch in FSS system, heads did not indicate that the other FSS system, head should be used, and the oscillations ceased.

The OBC changes the FSS system/head at beta 75°, which did not produce any problem until the spacecraft began to be controlled under the two-gyro/FSS system. It was decided that no normal operations would be conducted around this beta (±5 arcseconds) due to the misalignment of the FSS systems and heads. The margin around beta 75° had to be increased (around ±1 arcminute) with the one-gyro control mode.