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IN-19-CR
7985
P. 12

NASA-CR-200148

AIAA 95-3686
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(NASA-CR-200148) ASTRO-2 SPACELAB INSTRUMENT POINTING SYSTEM MISSION PERFORMANCE (McDonnell-Douglas Aerospace) 12 p

N96-18524

Unclas

G3/19 0099869

AIAA 1995 Space Programs and Technologies Conference
September 26-28, 1995/Huntsville, AL

ASTRO-2 SPACELAB INSTRUMENT POINTING SYSTEM MISSION PERFORMANCE

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Abstract

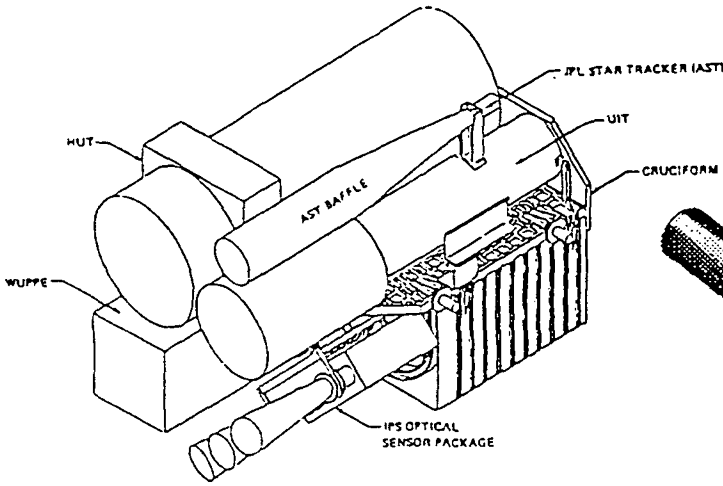
This paper reports the performance of the Instrument Pointing System (IPS) that flew on the National Aeronautics and Space Administration (NASA) ASTRO-2 Spacelab mission aboard the Space Shuttle Endeavour in March 1995. The IPS provides a stabilizing platform for the ASTRO-2 instrument payload complement that consists of three main experiments (telescopes). The telescopes observe stellar targets in the universe within the ultraviolet portion of the electromagnetic spectrum that must be observed from beyond the earth's atmospheric filtering effects. The three main experiments for observation are the Hopkins Ultraviolet Telescope (HUT), the Ultraviolet Imaging Telescope (UIT), and the Wisconsin Ultraviolet Photo-Polarimetery Experiment (WUPPE). The HUT uses spectroscopy to obtain the structure and chemical makeup of ultraviolet targets. UIT is responsible for wide field photographing to capture the hidden view of the ultraviolet universe. The WUPPE gathers data on the polarization of the ultraviolet electromagnetic energy coming from the astronomical targets. The capability of IPS enables the experiments to "see" faint celestial objects. A brief explanation of the IPS is given followed by a review of engineering efforts to improve IPS performance over the ASTRO-1 mission. The main focus of improvements was on enhancing the star acquisition capability through improved guide star selection, lab simulations, computer upgrades, data display systems improvements, and software modifications. A star simulator was developed in the lab to enable IPS to be simulated on the ground pre-mission with flight hardware and software in the loop. The paper concludes with results from the ASTRO-2 mission. The number of targets acquired and the IPS pointing accuracy/stability is reported along with recommendations for the future use of the Instrument Pointing System.

IPS

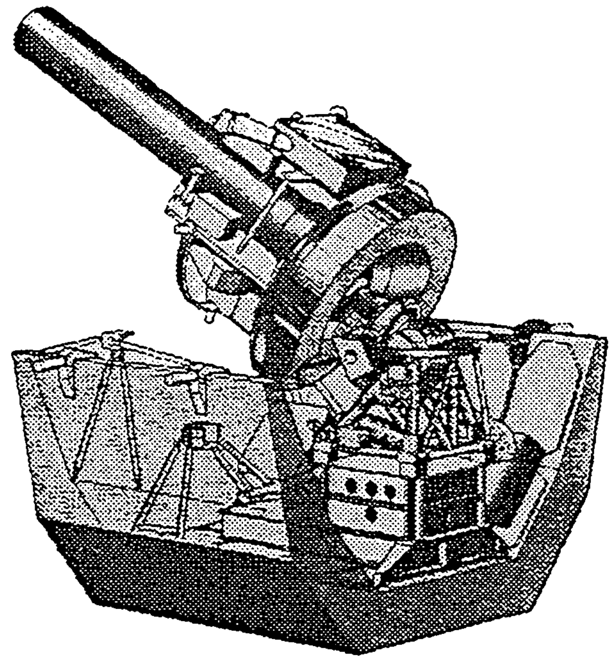
IPS is basically a 3-axis gyro-stabilized and controlled platform on which scientific instruments are mounted for pointing to inertial targets. For ASTRO-2, the scientific instruments were ultraviolet telescopes (HUT, WUPPE, and UIT). To meet science data gathering requirements during the mission, IPS inertial attitude (orientation) needed to be known and stabilized precisely (within arc-seconds) because gyro drifts cause the IPS attitude to get corrupted. An Optical Sensor Package (OSP), consisting of three star trackers, was provided to track stationary stars and compensate for gyro drifts.

The three trackers were mounted as follows: One tracker was designated as boresight (tracker 1), and defined IPS line of sight. Two skew trackers were designated right (tracker 2), and left (tracker 3) respectively, with lines of sight pointing nominally 12 degrees (for stellar missions) on either side of the boresight. A payload provided Astros Star Tracker (AST) served as back-up for the OSP boresight tracker in sensor substitution mode. The AST was the primary star tracker for Image Motion Compensation System (IMCS) which was a part of the payload.

IPS platform is dynamically isolated from the orbiter by three torquer controlled gimbals. The torquers are commanded by a control system that maintains IPS inertial attitude while the orbiter moves during disturbances such as crew motions, and orbiter thruster firings. In addition to the gyros, an Accelerometer Package (ACP) provides feed forward signal to the control loop. The ACP compensates for IPS rotations caused by linear motions (linear accelerations) of the orbiter. IPS maneuvers are accomplished by a control system residing in the Data Control Unit (DCU). Control system sensors are: Gyros, ACP, star trackers, and resolvers. The Control system actuators are torquers. Figure 1 shows the IPS.

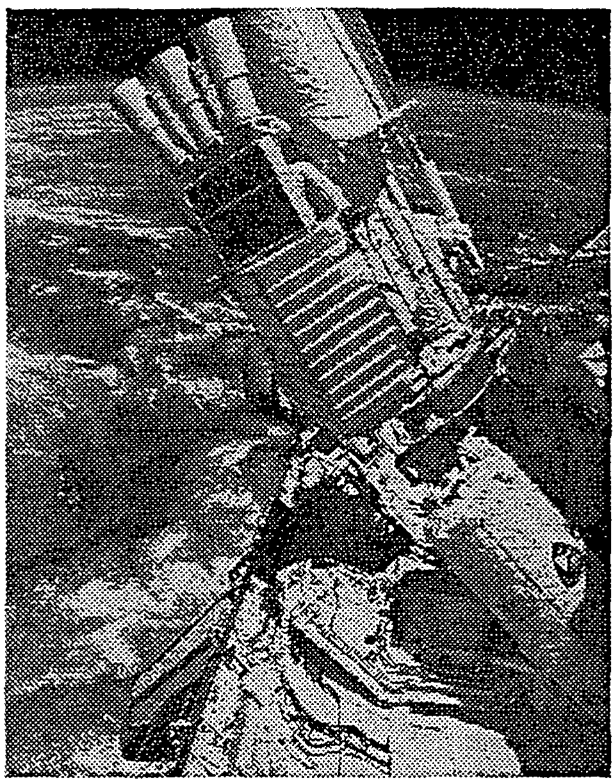


ASTRO-2 Payload, by Mike Lowery

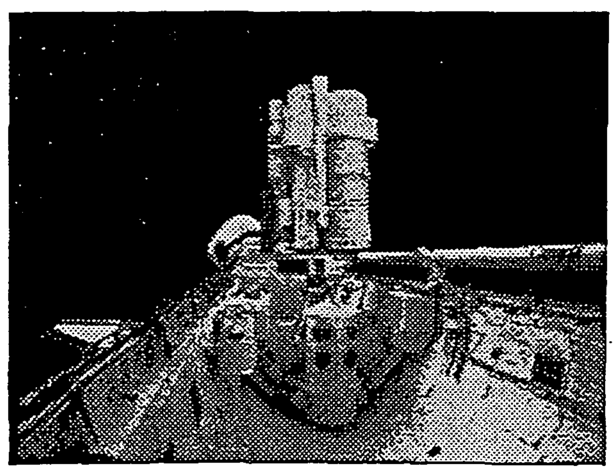


Generic IPS supplied by DORNIER

Photos supplied by NASA



IPS on ASTRO-1, STS -35



IPS on ASTRO-2, STS -67

Figure 1. Instrument Pointing System

The discussion of the IPS may be based on seven areas. These areas are the Gimbal Structure Assembly, Payload Retention Latch Assembly, Power Electronics Assembly, Data Electronics Assembly, Attitude Measurement Assembly, Thermal Control Assembly, and System Software. Each area is responsible for specific functions that allow the IPS to operate successfully.

Gimbal Structure Assembly

The Gimbal Structure Assembly (GSA) consists of a Static Structure, Moving Structure, Stow and Unstow Mechanisms, along with Special Devices. The Static Structure consists of a base plate, pedestal, and supporting framework. The base plate attaches the IPS to the Spacelab pallet within the Space Shuttle payload bay. Attached to the base plate is the pedestal and support structure that provides the required rigid base for IPS. The Moving Structure consists of the Drive Units, Yoke, Equipment Platform, Payload Attachment Ring, Payload Attachment Flanges, and Payload Support Structure. The Yoke houses the elevation, cross elevation, and roll drive units that allow IPS to point at targets. The Equipment Platform is used to mount different hardware components such as the gyros. The instrument payload, on the Payload Support Structure, attaches to the IPS through the use of the Payload Attachment Ring and Payload Attachment Flanges. The Stow and Unstow Mechanisms consist of the Gimbal Latch Mechanism and Gimbal Separation Mechanism. These mechanisms consist of motors, actuators, and shafts that are used to latch and unlatch the IPS. The Special Devices consist of bumpers, guide horns, plunger end-stops, Roll Drive Unit end-stop and Viewing Envelope Modifiers to keep the IPS in the proper operational cone so it will not impact other equipment.[1] Special devices also cover the Jettison Hardware that is used to eject the IPS from the Orbiter payload bay in case the IPS will not stow properly.

Payload Retention Latch Assembly

The Payload Retention Latch Assembly is responsible for securing the payload during the ascent and descent portions of the flight. This is accomplished through the Payload Attachment Ring being separated from the Equipment Platform and the payload being placed into the payload retention latches integrated onto a Spacelab pallet. The payload must be secured during the ascent and descent to avoid damage to the static structure of the IPS.

Power Electronics Assembly

The Power Electronics Assembly consists of the Power Electronics Unit (PEU) and the Contingency Control Panel (CCP). The PEU is responsible for distributing the power required by the IPS. The PEU drives the heater mats within the Thermal Control Assembly. The PEU also contains circuits for the torquers, stow and unstow hardware, and jettison hardware. The software obtains information about the PEU and other different systems through the use Remote Acquisition Units (RAU). The Contingency Control Panel is used if loss of software control occurs. The CCP can be used to stow the IPS or erect and jettison the IPS if it can not be properly stowed.

Data Electronics Assembly

The Data Electronics Assembly is composed of the Data Control Unit (DCU) the Data Control Unit Converter (DCUC) and the Accelerometer package. The DCU is a microcomputer that controls the data to the IPS subsystem computers. It accepts data from the Gyro Package, Subsystem Computer, and the Accelerometer Package to update the position of IPS. See Figure 2. IPS Control System Diagram. The control system is composed of two timing loops. The fast loop obtains gyro, resolver, and accelerometer data at 100 Hz to quickly correct for position drift while the slow loop obtains data through the subsystem computer from the Optical Sensor Package at 25 Hz to correct for gyro drifts within the system.[1] The DCUC provides the required regulated power to the DCU. The Accelerometer Package is mounted just above the pedestal and contains accelerometers in the orthogonal x, y, and z axis that provide fast loop data to the DCU.

Attitude Measurement Assembly

The Attitude Measurement Assembly consists of the Optical Sensor Package and the Gyro Package. The OSP contains three Fixed Head Star Trackers (FHST) that are used to acquire stars and report the IPS position to the subsystem computer through the IPS RAU. There is a

IPS CONTROL SYSTEM DIAGRAM

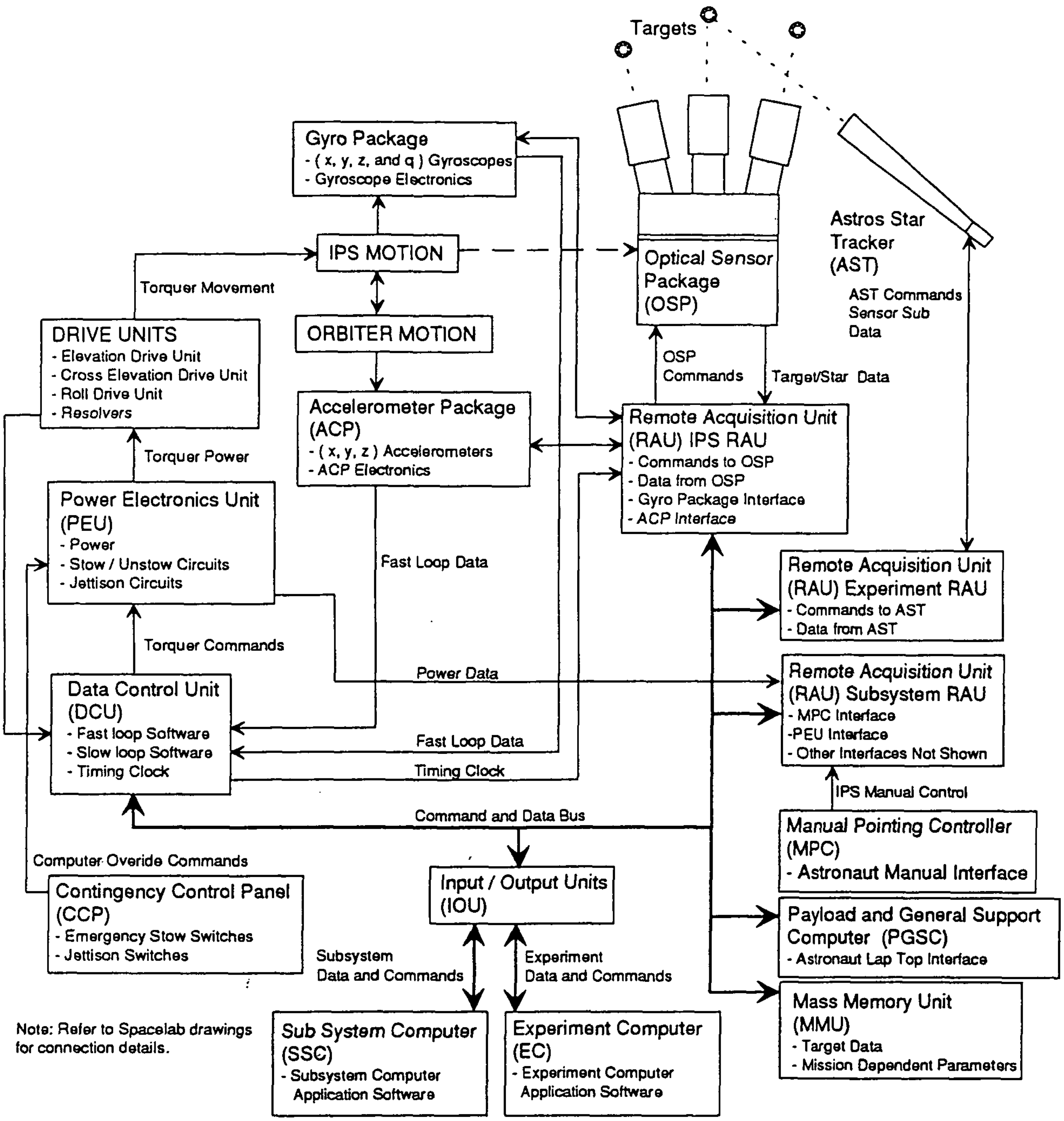


Figure 2. IPS Control System Diagram

boresight FHST that is positioned along the line of sight of the experiments along with a right and left FHST that are positioned at a 12° separation to the left and right of the boresight FHST. The subsystem computer uses the OSP information to update the gyro drift factor. The Gyro Package contains gyroscopes that are positioned in the orthogonal x, y, z, and skew "q" axes and electronics required for communication to the DCU. The fourth gyroscope (q) acts as a backup in case of an x, y, or z gyroscope failure.

Thermal Control Assembly

The Thermal Control Assembly consists of passive and active thermal devices. The thermal protection is required due to the extreme temperature variations of space. The Passive Thermal Control System consists of multilayer insulation blankets, second surface mirrors, emissive coatings, and thermal standoffs. The active Thermal Control System consists of heater mats and the Spacelab Freon Loop. Temperature measurements are made through the use of thermistors that have conditioning circuits within the PEU or DCU. When a system needs to be heated the heater mats are switched on to raise the temperature of the hardware. The Spacelab Freon Loop is used to cool equipment.

IPS System Software

The IPS System Software consists of Status and Monitoring Software, IPS Applications Software, and Attitude Control Software. The Status and Monitoring Software monitors inputs from the hardware and alerts the astronauts if a parameter is out of nominal limits. The Applications Software is responsible for thermal control, memory access, DCU and SSC communication, and gimbal hold that keeps IPS in position using the gimbal angles received from the resolvers. The Attitude Control Software is the software that is responsible for the pointing, tracking and slewing of the IPS.[1] The Attitude Control Software is divided into the fast loop software and slow loop software as discussed earlier. IPS motion is controlled by the software using drive units in the elevation, cross elevation, and roll axis. The software obtains data from the gyros and accelerometers to issue torque commands to the drive units to keep the IPS pointing on target. The optical sensor package is used to obtain position information of stars for the software to update the drift factors within the gyros. A mode of operation called sensor substitution is also available. Sensor substitution uses the experiment star tracker called the Astros Star Tracker (AST) to replace the data coming from the boresight FHST.

IPS Target Acquisition and Fine Pointing Modes

Target acquisition and fine pointing by IPS is accomplished using one of three modes: Operational Identification (IDOP -- automatic mode), Manual Target Acquisition followed by Lock On (any) Target (MTA/LOT), and Sensor Substitution. During IDOP, IPS software determines if one of pre-selected guide stars has been acquired. This mode of acquisition, when successful, is fast and accurate. During MTA/LOT, the crew manually acquires a target using HUT video, maneuvers IPS using Manual Pointing Controller (MPC), to place the target at the center of instrument field of view, and commands IPS to lock on any acceptable target in the field of view.

The successful operation of the IPS requires the functionality of the Gimbal Structure Assembly, Payload Retention Latch Assembly, Power Electronics Assembly, Data Electronics Assembly, Attitude Measurement Assembly, Thermal Control Assembly, and System Software. Each portion of the IPS has its own unique responsibilities that allow for the IPS to maintain a stable platform for the experiments.

IPS Improvements

Following ASTRO-1, McDonnell Douglas made several improvements to IPS. They upgraded the Spacelab subsystem computer to an IBM AP101, developed a Star Simulator in the Software Development Facility (SDF) that enabled pre-mission IPS simulations with the flight star trackers in the loop, added the capability of Manual Target Acquisition (MTA) followed by Lock On (any) Target (LOT), improved Sensor Substitution mode, improved Objective Loads generation performance to provide superior guide star targets, enhanced the Attitude Determination Filter (ADF) gain sets, optically calibrated the star trackers using ASTRO-1 data, and supported star tracker alignment measurements and payload instrument alignments prior to the mission. In addition, a generic Spacelab change was made with the replacement of the Data Display System (DDS) with the Payload General and Support Computers (PGSC) -- laptop computers.

SDF Simulations

The Software Development Facility (SDF) provides a test bed for IPS simulations. A mathematical model of IPS is used with flight type hardware in the loop to verify the flight hardware and software functions prior to the mission. The star simulator enabled the flight Optical Sensor package consisting of three star trackers, and the experiment optical sensor, Astros Star Tracker (AST), to be in the loop for IPS simulations.

Star Simulator

The star simulator proved to be a valuable tool that contributed to the success of the ASTRO-2 mission and is discussed further.

The Star Simulator was designed to provide a laboratory testbed for the check-out of a newly developed communication and commanding mode of the Optical Sensor Package (OSP) for use on the ASTRO-2 Spacelab mission. The ASTRO-1 experience revealed the need for a manual commanding technique for the searching and tracking of stars. The star fields were to be realistic, generated from a star catalog, or manually created to perform specific functions in the testing and checkout of the new flight software.

The Star Simulator provides three independent star fields measuring approximately 2.5 x 2.5 degrees. The star fields are displayed on three extremely high resolution monitors. The spectral output of the monitors was designed to coincide with the spectral response of the Fixed Head Star Trackers in the OSP. The relative visual magnitude (Mv) range required by the Fixed Head Star Trackers is 2 to 8 Mv, which is accomplished by a mutual calibration and adjusting software brightness settings. The Star Simulator is driven in a closed loop mode by a dynamic simulation of the Instrument Pointing System and the star field generation system based on a 486DX 66 MHz personal computer.

The Star Simulator Setup consists of three monitors for star generation, a monitor controller to interface the monitors to a 486DX 66 MHz personal computer (PC), collimating optics to make the pixels (stars) appear at infinity, an optical bench for vibration isolation, and a 100K clean room to keep the area clean and dark. Figure 3 shows the layout of the Star Simulator Test Setup.

Each monitor provides an extremely high resolution of 4096 x 4096 pixels. A *single* pixel produces a simulated star with a radial size less than 100 arc seconds. To maintain a near steady light source the pixel update rate is 1000 Hz where 50 stars (pixels) maximum are output on each monitor at a given time. These high speeds are obtained by using a vector monitor where the electron gun jumps from point to point as opposed to a raster scan monitor. Each addressable point has a wavelength output of approximately 550 nm by using a P44 phosphor. This wavelength was chosen to match the center of the spectral response of the FHST. The pixel output intensity is controllable and mutually calibrated with the FHST to obtain a relative output over the range of 2 to 8 visual magnitudes. The position control allows a pixel movement of less than 5 arc seconds between adjacent points and the overall position tolerance is less than 50 arc seconds. Each monitor combined with a collimating lens provides a 2.55 x 2.55 degree field of view input to a FHST.

The monitor controller directly interfaces to the monitors. For each monitor the monitor controller receives horizontal position, vertical position, brightness, and monitor blank/unblank commands from the 486DX 66 MHz PC. The monitor controller converts and transports these signals to each monitor through coaxial cables. Changes in the horizontal and vertical position data move a pixel. Changes in the brightness data change the apparent visual magnitude of the star. The blank/unblank command enables and disables output on the monitor screen.

The 486DX 66 MHz personal computer contains the Star Simulator software. The software allows for calibration and simulation control. The optical system can be aligned using the calibration software. Optical field of view alignment consists of first manual and then fine adjusting of the line of-sight, followed by fine adjustment of the rotation, and size parameters. Calibration also consists of changing the intensity of pixels to

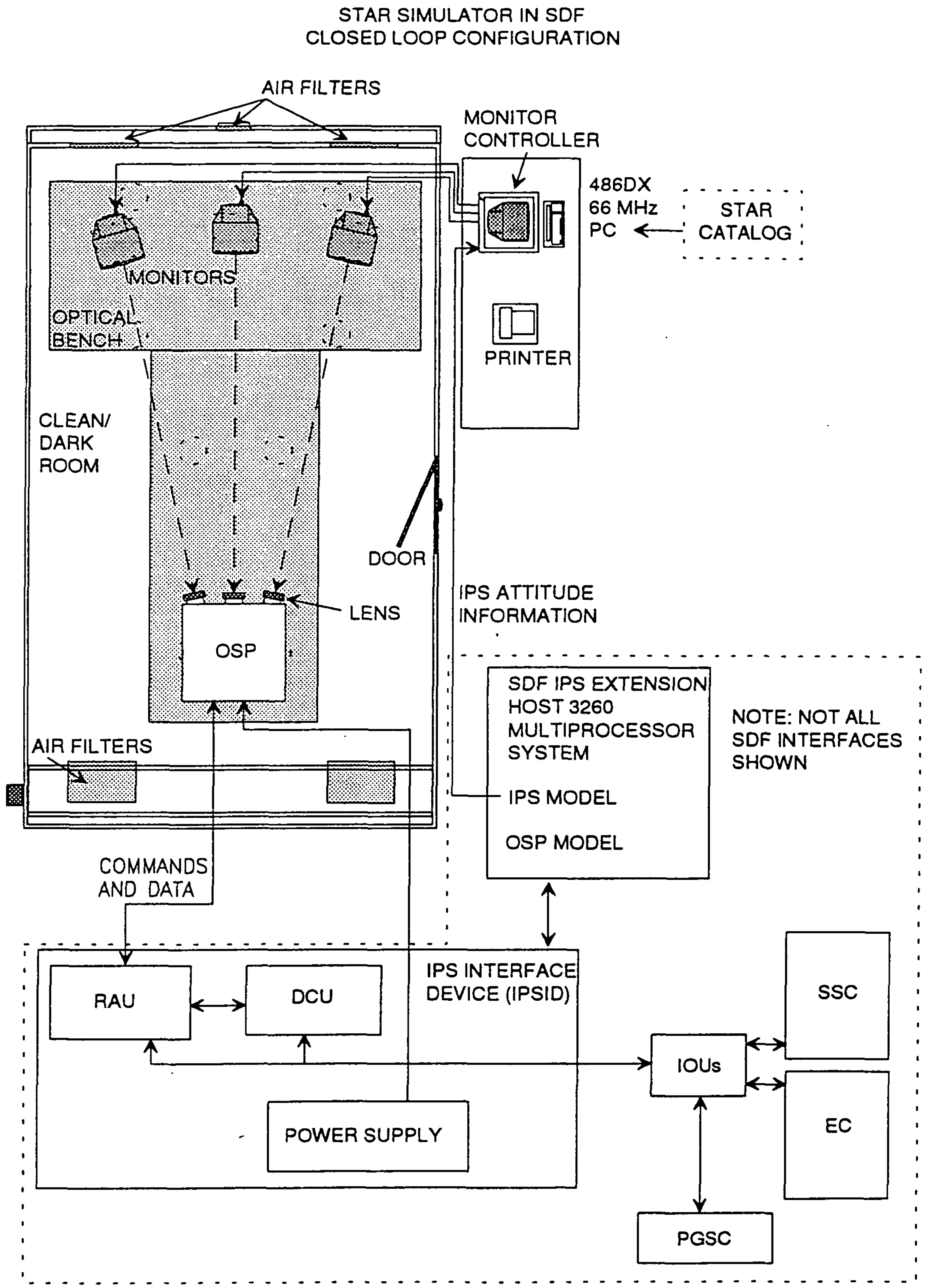


Figure 3. Star Simulator Test Setup

match the output expected from the FHST over the intensity range of 2 to 8 visual magnitudes. After the system is calibrated a simulation can begin. The simulation software uses a subset of the star catalog (star database) generated off line. This subset of stars defines the available stars during the simulation and is called the Sky Map. The stars displayed on the monitor are a subset of the available stars in the Sky Map and is called the Viewport. During simulation the position data changes causing the output (Viewport) on the monitor to change. The software either receives position information by an external source through an RS-232 link or the simulation operates in an open loop fashion and produces a fixed position. The pixel movements make the FHST respond as if it were being moved and the stars (pixels) were stationary as on orbit. The output of the monitors are sensed by the FHSTs through the collimating optics.

The collimating optics make the pixels on the monitor appear as if they were at infinity. This is required to simulate the stars at a far off distance as on orbit. The collimation is achieved by placing a monitor in the focal plane of a lens. Each FHST requires its own collimating lens. The lens used in the system is a 150 mm diameter achromatic lens with a 3000 mm focal length. The system was defocused using a dim pixel (8th magnitude). The distance between the FHST and the monitor was adjusted until the dim pixel was stable to approximately 1 arc second. The final distance between the monitor and FHST was measured at approximately 3060 mm.

To obtain a near 1 arc second stability, vibration isolation had to be provided. The optical vibration/isolation bench isolates the system from external disturbances to allow the simulated stars to remain stable. The bench uses an 8 leg system where each leg has a piston that is driven with compressed air to support the table. The compressed air in the legs causes the optical bench to 'float'. The optical bench is contained in a clean/dark room.

The monitors, monitor controller, 486DX 66 MHz PC, Star Simulator software, and collimating optics are the core of the Star Simulator. These items form the stand alone portion of the entire system. The core components of the Star Simulator could be transported to another facility and integrated with user supplied trackers, optical bench, and clean/dark room. This would provide a hardware in the loop test bed for other trackers. A user supplied computer could transmit the attitude information data stream to the Star Simulator and receive the data output from the user supplied trackers to create a closed loop test bed.

The two primary design concerns were the correct simulation of the star movement and its associated brightness. The Star Field Stimulator had to produce simulated stars that were within the position tolerance and brightness range of the FHST. In brief, the simulated stars had to have a movement capability down below 5 arc seconds and position accuracy on the order of 50 arc seconds. The simulated stars had to have a visual magnitude range spanning three visual magnitudes (Mv) in the range from 2 to 8 Mv. The Star Simulator exceeded the requirements for movement, position, and brightness control. The Star Simulator produced simulated stars that allowed the FHST to behave as if it were in orbit observing actual stars. The Star Simulator has proven to be a valuable tool in determining the response of the Fixed Head Star Trackers to both normal and extreme operational scenarios. Tests allowed for the fine tuning of the application software. This tool proved its usefulness over that of a mathematical model of any fidelity because of the invaluable hardware-in-the-loop testing capability. This was particularly evident during the ASTRO-2 mission when it showed a software patch for moon operations would not have worked if it were uplinked to the crew.

The use of the IPS Star Simulator during the mission allowed the engineers in the lab on earth to verify procedures before being uplinked to the crew of Endeavor. Specifically, during the earth moon observations, the brightness of the moon would damage the boresight Fixed Head Star Tracker. As a result, alternatives were eliminated by testing in the lab using the spare flight OSP integrated with the IPS Star Simulator in the SDF. Tests showed that turning down the high voltage, instead of closing the shutter by tracker reset, resulted in a reduction in the count rate from only 4500 to 2900 counts. Thus, the tracker would still be damaged by the moon. As a result of testing in the lab, the decision was made to turn off the boresight tracker during the remaining moon observations.

Mission Performance Results

Targets

The ASTRO-2 scientists made over 300 observations of 236 targets in the ultra-violet, range of the electromagnetic spectrum. This included distant quasars, stars, super novas, and galaxies. The planets Jupiter, Mars, and Venus were observed. In addition, Jupiter's moon Io, and our own Earth's moon were viewed.

Lunar Observations

IPS was designed to point to inertially fixed targets, but during ASTRO-2, the capabilities of IPS were stretched. It was used to track a moving target.

During the ASTRO-2 mission, four lunar observations were made. Observing the moon is different from observing stellar targets because the moon's inertial attitude changes continuously due to its relative nearness (parallax) to earth, while stellar targets are inertially fixed. Also, the moon is too big for an IPS tracker to acquire and hold optically. Furthermore, the moon is too bright for the IPS trackers, and its light could damage the image dissector tube (IDT) of the tracker.

These considerations resulted in the following:

1. IPS attitude would need to change to stay pointed at the center of the moon. IPS has been designed to fine-point to inertially fixed targets. If IPS attitude was held fixed, the moon would appear to streak across the instrument fields of view. To keep the observing telescopes pointed to the center of the moon, IPS would need to track the center of the moon.

2. The moon could not be used as a guide star because it projects too big of an image on the tracker's IDT. To point to the center of the moon with the desired pointing accuracy, a two-skew-tracker IDOP would have to be performed.

3. The boresight tracker's shutter would need to have been closed prior to the slew to the moon attitude, to protect the boresight tracker from possible damage to its image dissector tube.

The method chosen for moving IPS may be thought of as a two-step process. The first step was to command IPS to point to an inertially fixed attitude. The commanded inertially fixed attitude was along the vector joining the center of the moon to the center of the earth at the start of moon tracking. The second step was to add a time varying experiment bias command to move IPS to point to and stay pointed at the center of the apparently moving moon. The initial value of the time-varying bias pointed the IPS line-of-sight to the center of the moon and the subsequent values maintained the track.

This method was chosen because IPS software does not have a provision to continuously change the commanded attitude parameter. The commanded attitude and changing experiment bias together brought about the desired change.

The high voltage for the IPS boresight tracker must be turned off to avoid damage to the tracker due to moonlight. For the first observation, this was accomplished by issuing a reset of the tracker that puts the tracker in an unloaded state. For subsequent observations, the procedure was changed to power off the boresight tracker.

Moon attitude was achieved as follows: A two-skew-tracker IDOP was performed at the moon attitude. When the filter settled, optical hold was turned off (IPS was put under gyro control), target-track bias was enabled, and the moon was tracked.

IPS Pointing Performance - Accuracy and Stability

IPS pointing performance was evaluated for a few typical observations. A visual output of the IPS line of sight is shown in Figure 4.

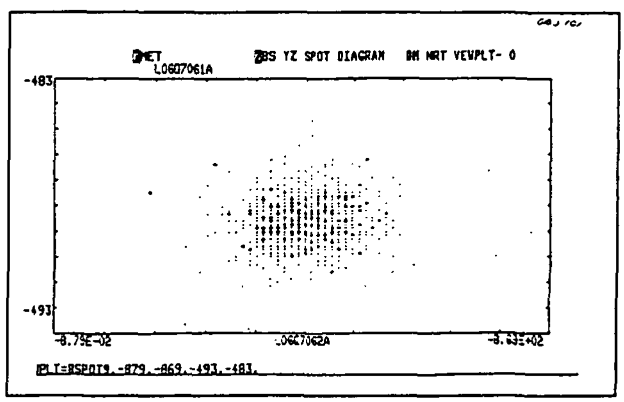


Figure 4. Boresight YZ Spot Diagram

Each spot on Figure 4 represents a data sample taken from the y and z coordinate position data reported from the boresight Fixed Head Star Tracker. The horizontal and vertical scale is 1 arc second per division. Pointing accuracy measured as the mean pointing error from commanded attitude was 0.85 arc seconds.

The stability of the IPS is evaluated using the Optical Sensor Package (OSP) coordinate measurements during periods of optical hold. Table 1 gives the standard deviations of OSP line-of-sight (LOS) measurements over several 200 second quiescent periods. The quiescent periods were selected to occur between orbiter thruster firings. A sub-arc second quiescent LOS pointing performance was typically maintained, and often exceeded the 0.75 arc second quiescent pointing goal.

Sensor substitution was only employed on a few occasions, but the LOS pointing performance appears to show a slight improvement as expected due to the lower noise characteristics of the AST compared to the FHST. Table 2 gives the standard deviations for the sensor substitution utilizing the Astros Star Tracker (AST) measurements in the Attitude Determination Filter (ADF). A definitive statement of the improved performance would have required more sensor substitution operations.

ASTRO-2 IPS QUIESCENT POINTING PERFORMANCE **Standard Deviation (arc seconds) (Between thruster firings)**						
GMT (Relative Seconds)	Boresight tracker y-axis	Boresight tracker z-axis	Right tracker y-axis	Right tracker z-axis	Left tracker y-axis	Left tracker z-axis
0.66:14:10 (350-500)	0.71	0.67	0.71	0.68	0.80	0.83
066:14:40 (1400-1500)			0.64	0.66	0.65	0.65
066:19:10 (100-300)	0.83	0.77	0.72	0.69	0.76	0.71
068:04:40 (1200-1400)			0.61	0.63	0.73	0.67
069:06:40 (100-200)	0.85	0.68	0.83	0.72	0.88	0.70

Table 1: ASTRO-2 IPS Quiescent Pointing Performance

ASTRO-2 SENSOR SUB PERFORMANCE Standard Deviation (arc seconds) (Between thruster firings)		
GMT (relative seconds)	Y	Z
070:18 (330-430)	0.65	0.50
075:20 (8,150-8,250)	0.89	0.91
073:11 (14,750-14,850)	0.42	0.43
072:11 (4,350-4,550)	0.42	0.48

Table 2: IPS Sensor Substitution Quiescent Pointing Performance

Summary

The Instrument Pointing System (IPS) performed superbly for the 14 plus days of IPS operations during the ASTRO-2 mission. IPS performed better than expected. The IPS control system functioned perfectly, and ADF performance was superior. The pre-flight predictions of alignment MDPs agreed closely with calibrations performed during the mission. The count rate predictions of guide stars for the IPS star trackers consistently matched the measurements observed during the mission. MTA/LOT was totally successful. IPS stability under optical hold was superior compared to ASTRO-1, as shown by a marked contrast with the one observation in which the crew performed manual hold. The pointing stability and accuracy were both less than 1 arc seconds.

NASA Headquarters, MSFC, Johnson Space Center, Principal Investigator (PI) teams, the press, general public, and MDA management expressed delight with the better than expected success of the mission. The PIs in particular were ecstatic. There was overwhelming response to internet coverage of the mission. There were over 2.6 million accesses of the home pages from about 200,000 individuals from 59 countries.

IPS is a versatile platform for fine-pointing at heavenly objects, and should be considered for future use.

ACKNOWLEDGMENTS

Our thanks to the National Aeronautics and Space Administration (NASA) Headquarters and the NASA Marshall Space Flight Center (MSFC) for their efforts that led to the successful ASTRO-2 flight. The authors acknowledge the contributions of TRW for software development, SODERN for the technical support, and Orwin Associates, Inc. for the development of the monitors and monitor controller. Thanks also go to McDonnell Douglas for giving the authors the freedom to get the job done.

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