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# A SIMULATION OF THE INSTRUMENT POINTING SYSTEM FOR THE ASTRO-1 MISSION

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# TABLE OF CONTENTS

## LIST OF ILLUSTRATIONS

## LIST OF TABLES

# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ACP | accelerometer package |
| ADF | attitude determination filter |
| arcs | arc seconds |
| arcs/s | arc seconds per second |
| ASTRO | astronomical observatory |
| CDMS | command and data management system |
| cg | center of gravity |
| CTA | contingency target acquisition |
| DCM | direction cosine matrix |
| DCU | data control unit |
| DOF | degree of freedom |
| EC | experiment computer |
| EDU | elevation drive unit |
| EL | elevation gimbal angle |
| FHST | fixed head star trackers |
| FO | functional objectives |
| FOV | field-of-view |
| GP | gyro package |
| GSA | gimbals structure assembly |
| HUT | Hopkins ultraviolet telescope |
| Hz | Hertz |
| IDIN | star acquisition operation |
| IDOP | operational identification procedure |
| IPS | instrument pointing subsystem |
| LKF | linearized Kalman filter |
| LOS | line-of-sight |
| MDP | mission dependent parameter |
| ms | milliseconds |
| MSFC | Marshall Space Flight Center |
| NASA | National Aeronautics and Space Administration |
| NASTRAN | finite element computer code |
| N·m | Newton meter |
| OSP | optical sensor package |
| PERFSIM | Dornier performance simulation program |

| | |
|---|---|
| PID | proportional-integral-derivative |
| rad/s | radians per second |
| RDU | roll drive unit |
| RL | roll gimbal angle |
| RSLEW | slew trajectory software |
| s | second |
| SDAP | simplified digital autopilot |
| SDF | software development facility |
| SSC | subsystem computer |
| TDPO | desired platform attitude DCM |
| UIT | ultraviolet imaging telescope |
| UV | ultraviolet |
| VRCS | Vernier reaction control system |
| WD | desired platform rate |
| WUPPE | Wisconsin ultraviolet photopolarimetry experiment |
| XDU | cross-elevation drive unit |
| XL | cross-elevation gimbal angle |

TECHNICAL MEMORANDUM

# A SIMULATION OF THE INSTRUMENT POINTING SYSTEM FOR THE ASTRO-1 MISSION

## I. INTRODUCTION

In recent years, the National Aeronautics and Space Administration (NASA) has developed a shuttle-borne astronomical observatory known as Astro. The first Astro mission began at 1:49 a.m. e.s.t. on Sunday, December 2, 1990, and returned after an 8-day, 23-hour duration. The mission of Astro was to study celestial objects in the ultraviolet (UV) spectrum more extensively than had been done previously. Astro utilized three unique astronomical instruments: the Hopkins ultraviolet telescope (HUT); the ultraviolet imaging telescope (UIT); and the Wisconsin ultraviolet photopolarimetery experiment (WUPPE). Astro observed planets, stars, star clusters, galaxies, supernovae, nebulae, and other objects that are bright in the UV spectrum. During the 8-day mission, an ambitious schedule of more than 200 observations was performed with 135 targets acquired (some targets were observed more than once) [1].

Whereas the UV astronomy data collection is made possible with advanced science instruments, observing numerous science objectives during the 8-day mission required a high performance pointing control system. To this end, the Spacelab instrument pointing subsystem (IPS) was employed.

The IPS, developed by Dornier System, is a three-axis stabilized platform designed to point observation instruments with stability and accuracy requirements beyond the capability of the NASA shuttle. It is a multipurpose pointing instrument with the capability of accommodating scientific instruments of various masses and configurations. During Astro-1, the IPS quiescent pointing performance for a typical stellar target was measured to be less than 1 arcsecond standard deviation in line-of-sight (LOS) [2]. In July and August of 1985, the IPS was flown aboard the shuttle to observe solar phenomena as part of the Spacelab-2 (SL-2) mission. The IPS quiescent performance during SL-2 was comparable to that during Astro-1 [3].

### A. Motivation for TREETOPS IPS Simulation

Astro-1 was a stellar astronomy Spacelab mission with several unique aspects when compared to the SL-2 solar astronomy mission. The ambitious schedule of observation required the IPS to point at many successive targets without interruption. This in turn required precise slewing and pointing of the IPS. Since the IPS is a multibody configuration subject to large-angle, nonlinear motion, the need exists to accurately model the dynamics of the IPS in a framework suitable for control system design, analysis, and verification. The TREETOPS IPS simulation provides this capability.

The impetus for developing the TREETOPS IPS simulation originated from a Tiger Team investigation at the Marshall Space Flight Center (MSFC) Spacelab Software Development Facility (SDF). In the SDF, flight-type hardware is used to implement and verify flight software for Spacelab missions. The Tiger Team was commissioned to assess and correct the cause of an attitude error accumulation during IPS slews [4]. During these maneuvers, the cumulative attitude error was such that a time-consuming star acquisition operation (IDIN) was needed after the maneuver. If this procedure were to be required after every slew in flight, science observation time would be greatly impacted. Furthermore, due to hardware limitations in the SDF, the SDF model of the orbiter and IPS dynamics is somewhat simplified. The SDF model does not accurately simulate the true large-angle, multibody dynamics of the IPS.

Therefore, the need existed to verify the pointing control system in a simulation that accurately represented the nonlinear, multibody dynamics of the IPS and orbiter in the flight configuration. Thus, the TREETOPS IPS simulation was developed and used to independently evaluate IPS performance to aid in the successful completion fo the SDF Tiger Team investigation.

Several other interesting aspects of IPS performance may be investigated utilizing the features of the TREETOPS IPS simulation. The TREETOPS IPS simulation provides the capability to model the dynamics of the IPS and analyze the performance of the pointing control system using flight system parameters in realistic mission operation scenarios. An orbiter attitude control system introduces disturbances into the fine-pointing of the IPS via simulated thruster firings. Also, an orbital environment is included in the simulation. To summarize, the applications of the TREETOPS IPS simulation are fourfold:

- Verify pointing control system design
- Predict on-orbit performance
- Trouble-shoot and correct in-flight anomalies
- Aid in postflight data analysis.

## B. Introduction to TREETOPS

TREETOPS is a time history simulation developed for analysis of the dynamics and control-related issues of multibody structural systems. The name "TREETOPS" is indicative of the tree topology of linked multiple bodies, each of which may be rigid or flexible, with translations and large angle rotations between each body. Kane's method is employed in the derivation of the equations of motion, which are numerically integrated to generate the time history response of the system. Extensive control system modeling capabilities are incorporated in TREETOPS including a host of active sensors and actuators along with controller models in the form of block diagram (transfer function), state space (matrix), and user-defined continuous or discrete controllers. An interactive setup program allows a convenient, easy to use interface with the simulation for model definition, input data editing, and error checking. For more detailed information on the analytical formulation and modeling aspects of TREETOPS, the reader is referred to the user's guide [5].

This report is written to document the development of the TREETOPS IPS simulation as used in support of the Astro-1 mission. Section II describes the IPS flight system whereas section III is a parallel description of the simulation implementation of the IPS flight system. The results of representative simulation runs are discussed in section IV, and the report concludes with remarks in section V.

## II. DESCRIPTION OF INSTRUMENT POINTING SUBSYSTEM

### A. Hardware

The IPS is a complex inertial pointing mount. Its support structure has integrated actuator and sensor hardware along with the necessary electronics, data processors, and software to allow pointing to, and tracking of, a variety of astronomical targets such as stars, gas clouds, planets, and comets. It uses a unique three-axis gimbal design which allows scientific instruments to be attached to the extremities of payloads, as opposed to the typical gimbal design which attaches to the center-of-gravity (cg) of the payload. The IPS gimbal configuration is often referred to as an "inside-out" configuration and can result in non-orthogonal gimbal geometry for some IPS attitudes. The IPS gimbal structure design allows for a large range of motions and for a variety of payload masses and inertias. An exploded view of the IPS components, taken from reference 6, is presented in figure 1.

The primary hardware component which makes a three-axis pointing mount possible is the IPS gimbals structure assembly (GSA). The GSA contains three identical torque drive units whose outer housings and inner shafts form the gimbals mechanism which allow one rotational degree of freedom (DOF) each [6]. The first rotational DOF is provided by the elevation drive unit (EDU) with the shaft attached to the Spacelab support structure and the EDU housing connected to the cross-elevation drive unit (XDU) shaft. A yoke structure, connecting the XDU and the roll drive unit (RDU) housings, was designed to produce a gimbal geometry with the three axes of rotation intersecting at a point on the elevation shaft. The RDU shaft is then connected to the equipment platform and is free to rotate the payload about the IPS LOS. Resolvers are associated with each torque motor to provide relative attitude measurements for control system inputs and commutation of the torque motors. With this gimbal configuration, the IPS is constrained to a 30° half-cone angle and is capable of ±180° roll orientations.

Various sensors are located on the GSA to provide measurements for control system inputs. Mounted on the IPS lower support framework is an accelerometer package (ACP) consisting of three analog force pendulums in an orthogonal configuration. ACP outputs are filtered, sampled, and held at a 50-Hz frequency before being acquired by the control unit. Acceleration measurements are utilized in a feed-forward path to stabilize the pointing platform with respect to orbiter vibrations and disturbances.

A three-axis strap-down inertial reference unit, manufactured by Feranti, is mounted on the underside of the equipment platform above the RDU. The gyro package (GP) uses four single DOF pulse-balanced rate integrating gyroscopes in the rate mode. In order to provide redundancy in case of a single wheel failure, the fourth wheel is skewed with respect to the remaining three orthogonally mounted wheels. The delta angle outputs by the GP are read by the digital controller every 10 milliseconds and are the primary inertial reference measurements.

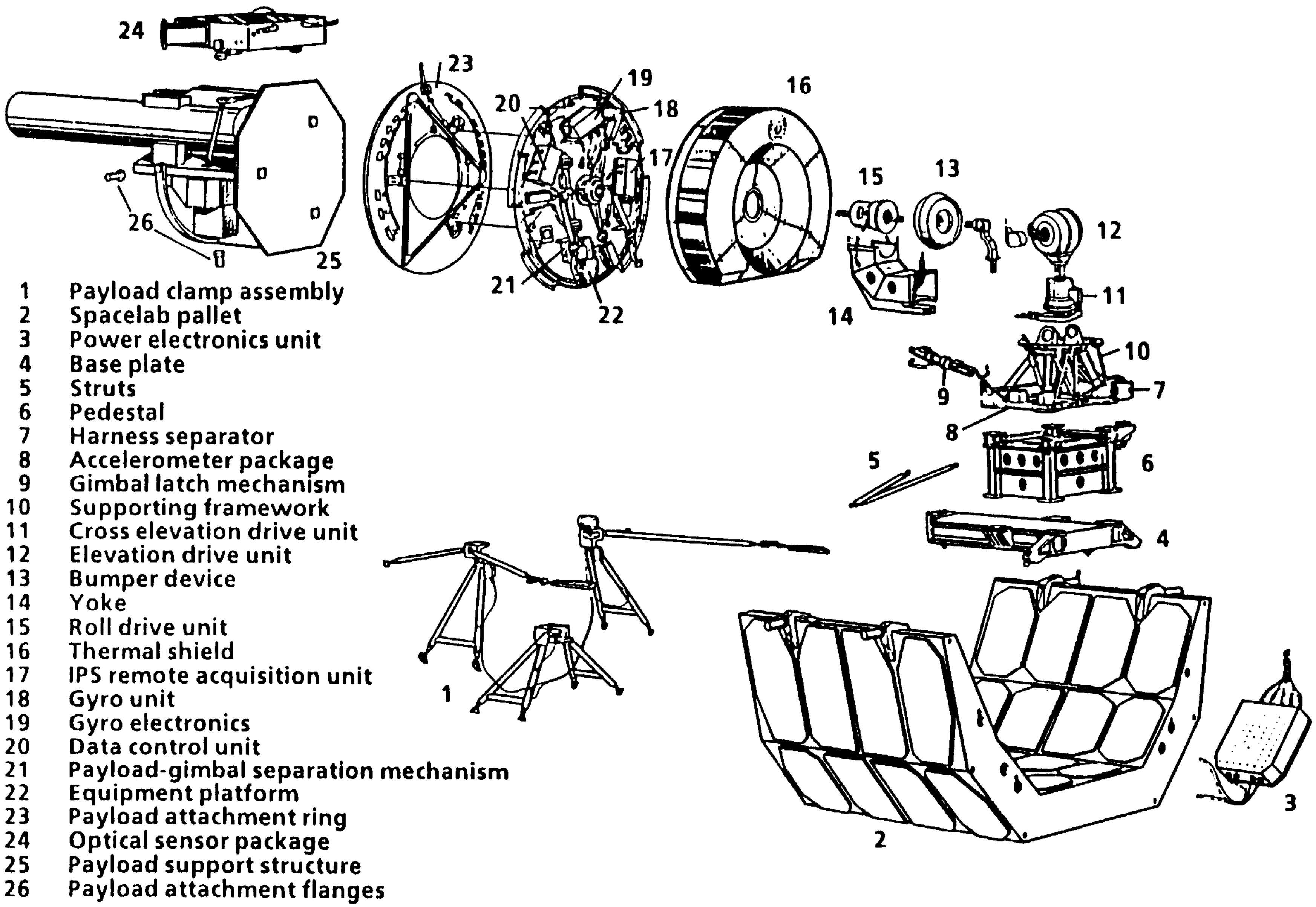

Figure 1. Exploded view of IPS components.

The final inertial sensing element is the optical sensor package (OSP) which consists of three fixed head star trackers (FHST). The longitudinal axis of each FHST lies in a plane with the boresight FHST aligned along the IPS LOS, and the two remaining trackers skewed ±12° with respect to the boresight tracker. Each FHST is capable of outputting a *y* and *z* focal plane coordinate for one or two stars. Over a 1-second interval, the FHST measurements are averaged 18 times before being sent to the control unit to be processed by the attitude determination filter (ADF). Use of skew trackers is important for determining the IPS roll attitude and roll drifts.

Another important element of IPS hardware is the data processing system. Three computer systems and their respective interfaces comprise the IPS automatic data processing system,

**Data Control Unit (DCU):** A 16-bit fixed-point processor which performs the primary 25-Hz control computations.

**Command and Data Management System (CDMS):** IPS operational mode definition, IPS command generation, and telemetry operations are provided by the CDMS. A subsystem computer (SSC) of the CDMS performs the 1-Hz ADF processing.

**Experiment Computer (EC):** Provides data processing for the scientific instruments and also processes FHST measurements which are provided to the SSC during sensor substitution.

## B. Software

A critical element of the IPS is the pointing control system. This system consists of several elements which generate pointing commands, maintain a knowledge of IPS inertial orientation, perform slewing maneuvers, and reject disturbances so that the IPS points precisely at each specified target. The IPS uses a multirate, multivariable digital pointing control system to accomplish these objectives. Platform attitude and attitude rate commands are generated at 5 Hz by software known as RSLEW. A 25-Hz control loop (fast loop) in the DCU utilizes gyro feedback in a proportional-integral-derivative (PID) structure for coarse pointing and an accelerometer feed-forward loop for base motion isolation. In addition to the fast loop, during fine-pointing operations, the 1-Hz ADF in the SSC may be used. The ADF processes inertial measurements generated by OSP to estimate gyro drifts and star tracker misalignments to compensate for errors accumulated during slewing and gyro-only pointing. Once every second, the ADF provides the DCU with IPS attitude updates and system drift estimates. These elements of the IPS pointing control system are described in the remainder of this section.

### 1. DCU

Figure 2 shows a simplified block diagram of the DCU fast loop configuration implemented in flight software. The DCU contains the fast loop software that generates torque command outputs to the EDU, XDU, and RDU for pointing the IPS. Two loops comprise the fast loop controller. A gyro feedback loop utilizes rate gyro measurements to determine the inertial attitude and rotational rates of the pointing platform. These measured quantities are

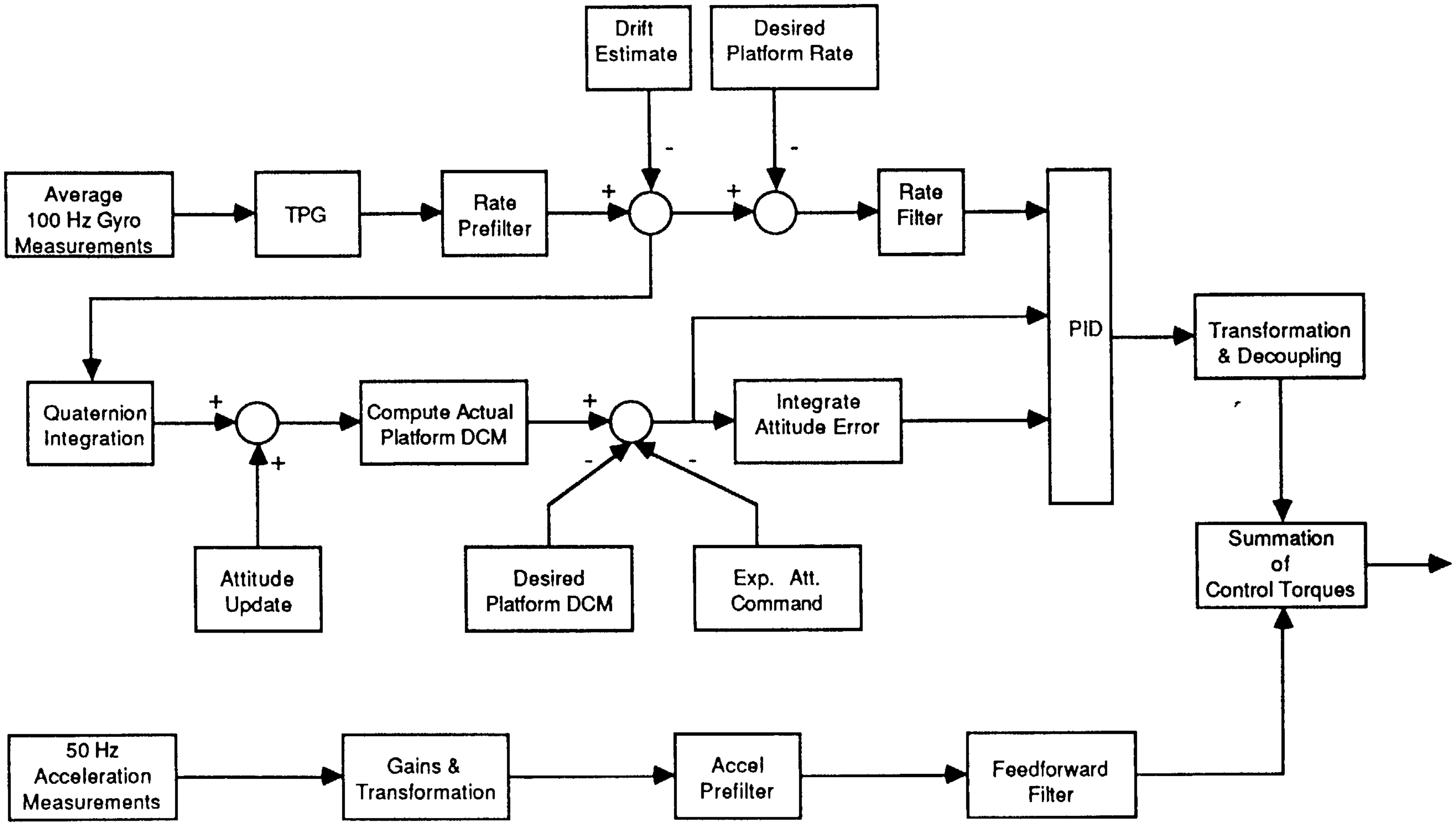

Figure 2. IPS fast loop controller.

compared to the commanded platform attitude and platform rates generated by RSLEW to form the pointing error signal. A second loop of the fast loop is the accelerometer feed-forward loop which utilizes orbiter acceleration measurements to stabilize and isolate the pointing platform from base motion (orbiter) induced disturbances.

The fast loop controller, both the gyro and accelerometer loops, is divided into two 50-Hz minor cycles. The gyro loop begins each minor loop with two sequential delta angles, measured at 100 Hz by the GP, being averaged and divided by 20 milliseconds to obtain the gyro rate measurement. The 50-Hz rate measurements are then transformed from the gyro coordinate system to the IPS platform coordinate system. In order to eliminate aliasing effects due to high frequency signals not suppressed by the averaging process, the 50-Hz rate measurements are processed by a normalized second-order prefilter with a 4-Hz bandwidth. The output equation of the prefilter is computed every other minor cycle, resulting in a 25-Hz prefilter output. However, the prefilter states are preserved between the two minor cycles of prefilter processing. Once the 25-Hz rate measurements are obtained, the signals are compensated by a system drift estimate, which is an output of the ADF. The desired rates generated by RSLEW are compared to the rate signal to produce rate error signals. Rate error signals for the elevation (EL) and cross-elevation (XL) channels are then processed by a seventh order digital rate filter. The filtered EL and XL and the unfiltered roll (RL) rate error signals form the derivative input to the PID controller.

The IPS inertial attitude quaternion is determined by numerically integrating Euler's kinematic differential equation which is a relationship between the derivative of the attitude quaternion and the body rates (gyro measurements). An attitude error signal is obtained by computing the actual platform attitude direction cosine matrix (DCM) from the inertial attitude quaternion and comparing this DCM with the desired platform attitude DCM generated by RSLEW (section II-3). The resulting attitude error DCM is input to the PID proportional channel and is also summed to form the integral channel input to the PID controller. To facilitate this processing of the rate information, the DCU is designed with a 40-millisecond delay in the proportional and integral channels. Hence, the most recent derivative signal is combined with integral and proportional signals from the previous minor cycle as inputs to the PID controller. Outputs of the PID controller are then transformed into the gimbal system and are decoupled to produce torque commands in the individual gimbal axes.

Inputs to the acceleration feed-forward loop of the fast loop controller are acceleration measurements from the ACP (located on the IPS support structure). Acceleration measurements sampled at 50 Hz are transformed to the IPS platform coordinate system before the signal in each axis is processed by a 50-Hz prefilter with a 2-Hz bandwidth. The acceleration prefilters are of the same form as the rate prefilters, where a 50-Hz signal is processed in both minor cycles with a 25-Hz output from the first minor cycle only. The acceleration prefilter serves to prevent aliasing when the 50-Hz acceleration measurements are processed by the controller at 25 Hz. Acceleration signals in each axis are then processed by three second-order filters and summed with the PID torque commands to generate the torque commands from the fast loop controller.

## 2. Attitude Determination Filter

A desire to view different astronomical bodies and the occultation of objectives due to the shuttle's orbit require the capability to perform IPS and/or orbiter inertial attitude maneuvers. In order to minimize the time between astronomical observations, the maneuvers are performed at rates which exceed the original tracking capability of the IPS optical sensors. Therefore, the inertial attitude is maintained by the gyros and the attitude calculations are performed in the DCU. Both the unknown gyro drift and DCU numerical errors result in an accumulated attitude error unobserved by the IPS control system. To imporove the IPS pointing performance, an estimation filter is implemented using the optical sensor to determine the system drifts and the attitude errors accumulated during gyro-only control. Use of the optical sensor requires that the estimation filter be executed during fine-pointing operations, when the IPS platform inertial rates are expected to be within the optical sensor tracking capability.

The estimation filter, referred to as the ADF, is a linearized Kalman filter (LKF) executed at a 1-Hz rate by the SSC. An LKF linearizes the IPS system about a nominal state trajectory, which allows the generation of preflight computed gains. Gyro measurements are used to calculate a state transition matrix, which is necessary to propagate the estimated states.

A 10-state ADF was designed and implemented for the IPS system. The first three terms of the estimation filter are the inertial attitude of the IPS. System drifts comprise the next three elements of the filter states, while misalignments of the skew FHST (with respect to the boresight FHST) complete the final four ADF states.

## 3. RSLEW

RSLEW is a subroutine in the subsystem computer software which computes the desired platform attitude DCM (TDPO) and the desired platform rate (WD). At a 5-Hz rate, TDPO is sent to the proportional/integral (attitude) channel while WD is sent to the derivative (rate) channel. In this manner, TDPO and WD serve as attitude and rate commands when the IPS is slewing in one of two modes, inertial slew or gimbal angle command. When IPS is not slewing or is in gimbal hold, TDPO is set to identity and WD is set to zero.

When performing inertial slews, the IPS is commanded to slew to a position specified in inertial space. In this mode, RSLEW computes TDPO and WD without accounting for orbiter motions. When slewing in gimbal hold command mode, the IPS gimbals are commanded to a particular orientation with respect to the orbiter. In this mode, RSLEW uses information from the orbiter state vector to compute TDPO and WD such that a particular attitude with respect to the orbiter is achieved and maintained.

RSLEW operates by computing an optimal desired slew trajectory based on the "Pontryagin" principle for an eigenaxis rotation. The following is a brief outline of the methodology of RSLEW. For more detailed information, the reader is referred to reference 7.

RSLEW begins by constructing a platform attitude error DCM based on the current and desired platform attitudes. The construction of the DCM varies, depending on whether IPS is in inertial slew or gimbal angle command mode.

Slew trajectories are computed separately for the lateral (elevation and cross elevation) and roll axes. The trajectories are updated every 5 seconds. First, the respective lateral and roll errors are extracted from the attitude error DCM. Rate gyro measurements are then used to initialize the actual platform rates (which is limited by a mission dependent parameter (MDP)), and the actual lateral and roll Euler angles are initialized to zero. Next RSLEW checks to see if the IPS will hit the roll-stop at ±180° and makes a correction to the roll trajectory to avoid hitting the roll-stop. If IPS is in gimbal angle command mode, RSLEW will transform the orbiter rates (obtained from the orbiter state vector) from the orbiter coordinate (By) system to the platform system. If IPS is in inertial slew, the orbiter rates are set to zero. This series of operations is performed every 5 seconds as an update or correction to the slew trajectory. Otherwise, these operations are bypassed, the trajectory is integrated, and TDPO and WD are computed every time through the loop.

The next phase is the integration of the slew trajectory in the lateral axis and the roll axis at 5 Hz. The acceleration switching curve is first evaluated and then the Euler rates are integrated and limited by an MDP. Euler angle integration is performed, and a lateral DCM and a roll DCM are computed based on the resulting Euler angles. Next, the orbiter rates are integrated to obtain a set of quaternions from which an orbiter DCM is obtained. Finally, TDPO and WD are computed based on the lateral, roll, and orbiter DCM's. RSLEW continues to compute TDPO and WD at 5 Hz until the slew end condition is satisfied.

## III. DESCRIPTION OF TREETOPS IPS SIMULATION

In order to verify the design and implementation of the controller, predict the performance, and assess flight data, a full nonlinear simulation of the IPS system has been developed. For a direct comparison of simulation results with flight data, this simulation must replicate many of the operational aspects of the Astro-1 mission. The TREETOPS IPS simulation accounts for the dynamics of the multibody system by modeling the IPS hardware as independent bodies connected in a tree topology, originating from the payload bay of the orbiter. Not only is an accurate model of the IPS hardware essential, but in addition much of the flight software and models of the accompanying sensors and actuators must be incorporated in the simulation. The flight software implemented includes the fast loop controller, ADF, RSLEW, and a simplified digital autopilot (SDAP) for orbiter attitude control. With these features, the simulation has the capabilty of executing realistic mission scenarios, demonstrating pointing performance in the anticipated disturbance environment, and slewing and pointing at multiple successive targets. The following sections discuss the TREETOPS model of the IPS hardware, the user-defined control software, and the IPS operational scenario as implemented in the simulation.

### A. TREETOPS IPS Model

#### 1. Bodies

In TREETOPS, a dynamic system is modeled as a collection of independent bodies interconnected in a tree topology. Each body is an independent element that can be modeled as rigid or flexible with each body having its own mass properties. Once the topology of the structure is determined, sensor and actuator models are added, a control system is defined, and the interconnections between the elements are specified.

A five-body model of the IPS and orbiter is used to analyze stellar pointing operations during the Astro-1 mission. The first body is an on-orbit model of the shuttle orbiter *Columbia* with the payload bay doors open and the payload excluding the IPS. Constituting the second body is the Spacelab pallet and IPS gimbal support structure. The elevation torque motor housing and cross-elevation torque motor shaft form body 3. Body 4 includes the cross elevation and roll torque motor housings and the yoke. The last body, body 5, consists of the roll torque motor shaft, IPS instrumentation, and science equipment. The current version of the IPS TREETOPS simulation consists of rigid bodies with mass and inertia properties of each body obtained from test verified NASTRAN simulations.

## 2. Hinges

Interconnections between bodies are referred to as "hinges" in TREETOPS terminology and serve to define the topology of the structure as well as the kinematic variables of the system. The first hinge must connect the first body to the inertial reference system, so for the IPS simulation, hinge 1 connects the orbiter to the spacecraft centered inertial frame allowing the orbiter 6 DOF. The "gimbal" option is selected for hinge one which implies that an Euler rotation sequence is used for orbiter attitude parameterization. A standard pitch-yaw-roll (2-3-1) sequence specifies the orbiter attitude for this simulation. Hinge 2 rigidly attaches the pallet to the orbiter. Hinge 3 is a 1-DOF connection between the gimbal support structure and the elevation torque motor housing that allows elevation rotations. Cross elevation motion is accomplished with the 1-DOF hinge 4 which connects the cross elevation torque motor shaft and the roll torque motor housing and the yoke. The roll torque motor shaft and payload are attached to the roll torque motor housing by hinge 5 which allows the 1-DOF roll motion.

Figure 3 depicts the above description, showing the orientation of the local reference frame for each body, hinge interconnections, and local coordinates (in meters) of each hinge attach point with respect to the body cg.

## 3. Sensors and Actuators

Various sensors and actuators are used by the pointing control system of the IPS. These elements have been included in the TREETOPS simulation in an attempt to replicate the flight hardware to the greatest extent possible. The ACP has been modeled by three accelerometers attached to body 2, the gimbal support structure. Whereas the GP consists of four rate gyroscopes mounted to the payload mounting plate, only three gyro models are attached to body 5 in the IPS model. Since the fourth (skew) gyro is not included in the model, the three gyro models are oriented orthogonally and aligned such that no gyro transformation is needed in the simulation. To account for measurement noise, a constant rate drift of 3 arcs/s is added to the gyro measurements as well as a random noise quantity of ±1 arcs/s. Three star trackers comprising the OSP are modeled and used to sense pointing error for the ADF. A random noise contribution of ±1 arcs is added to corrupt the star tracker measurements. As with the torque drive units of the EDU, XDU, and RDU, resolver models are attached to the elevation, cross-elevation, and roll hinges. The only sensors used in the IPS

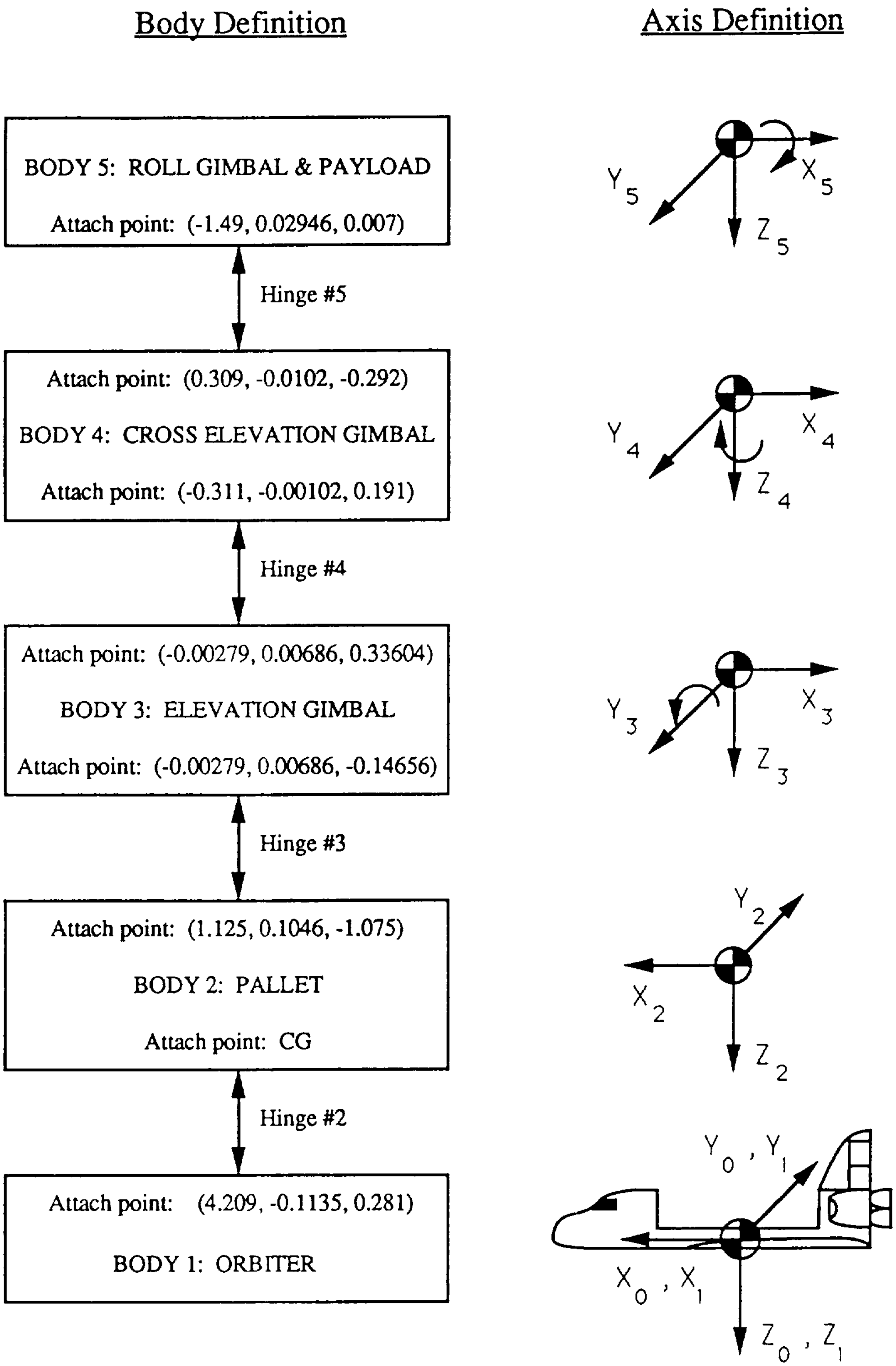

Figure 3. IPS body orientations.

simulation that do not have a direct physical analog are the rate gyros and resolvers mounted on hinge 1 (which does not physically exist) between the orbiter and the inertial reference frame. These sensors are needed to measure the orbiter rates and attitude for use by SDAP and RSLEW. These sensors are summarized in table 1.

Table 1. TREETOPS sensor definition.

| Type | Measurement Quantity | Measurement Location |
|---|---|---|
| Rate Gyro | IPS RL Rate | CG, Body 5 |
| Rate Gyro | IPS EL Rate | CG, Body 5 |
| Rate Gyro | IPS XL Rate | CG, Body 5 |
| Accelerometer | –Z Orbiter Acceleration | Pallet |
| Accelerometer | –X Orbiter Acceleration | Pallet |
| Accelerometer | Y Orbiter Acceleration | Pallet |
| Resolver | IPS RL Gimbal Angle | Hinge 5 |
| Resolver | IPS EL Gimbal Angle | Hinge 3 |
| Resolver | IPS XL Gimbal Angle | Hinge 4 |
| Star Tracker | Boresight Star Tracker | Body 5 |
| Star Tracker | Left Skewed Star Tracker | Body 5 |
| Star Tracker | Right Skewed Star Tracker | Body 5 |
| Rate Gyro | Orbiter Roll Rate | Hinge 1 |
| Rate Gyro | Orbiter Pitch Rate | Hinge 1 |
| Rate Gyro | Orbiter Yaw Rate | Hinge 1 |
| Resolver | Orbiter Roll Angle | Hinge 1 |
| Resolver | Orbiter Pitch Angle | Hinge 1 |
| Resolver | Orbiter Yaw Angle | Hinge 1 |

Actuators modeled in TREETOPS are the IPS gimbal torque motors and a set of thrusters used for orbiter attitude control by the vernier reaction control system (VRCS). The VRCS thrusters used by SDAP are by no means representative of the entire VRCS flight system, but are sufficient for this simulation. One thruster from each VRCS cluster is included in the simulation with the notation used in table 2 indicating to which cluster each actuator belongs. For example, "F5R" indicates the fifth thruster in the forward end (F), right side (R) cluster. Similarly, L denotes left side and D denotes downward orientation. These six thrusters are defined with the output axis oriented so that various combinations can produce positive and negative pitch, roll, and yaw motion. These actuators are summarized in table 2.

## B. Software Description

A FORTRAN subroutine is incorporated in the TREETOPS IPS simulation as a user-defined, discrete time controller. Like the flight system, the user controller implements the DCU fast loop controller, ADF, RSLEW, and SDAP for orbiter attitude control. The simulation implementation of these routines is designed to replicate the flight software versions, thus their descriptions closely follow the description of flight system software in section II.2.

Table 2. TREETOPS actuator definition.

| Type | Output Quantity | Actuator Location |
|---|---|---|
| Torque Motor | IPS RL Torque | Hinge 5 |
| Torque Motor | IPS EL Torque | Hinge 3 |
| Torque Motor | IPS XL Torque | Hinge 4 |
| VRCS Thruster | F5R | Body 1, node 4 |
| VRCS Thruster | F5L | Body 1, node 5 |
| VRCS Thruter | R5R | Body 1, node 6 |
| VRCS Thruster | L5L | Body 1, node 7 |
| VRCS Thruster | R5D | Body 1, node 8 |
| VRCS Thruster | L5D | Body 1, node 9 |

## 1. DCU

The fast loop portion of the user controller is divided into two 50-Hz minor cycles. Two sequential rate gyro measurements, sampled at 100 Hz, are averaged to obtain 50-Hz rate gyro measurements for the gyro feedback loop. Three gyro measurements are processed by the three-axis, second-order prefilter which outputs the filtered rate signals every other minor cycle. Prefilter states are computed and stored each minor cycle with the output equation computed every other minor cycle, resulting in a 25-Hz prefilter output. Drift extimates, computed by ADF, and desired platform rates, computed by RSLEW, are subtracted from the filtered rate signal to form the rate error signal. Filtered EL and XL and unfiltered RL rate error signals are the derivative channel inputs for the PID controller.

Outputs of the rate prefilter, after being compensated by the drift estimate are integrated and renormalized to form the inertial attitude quaternion. The inertial attitude DCM is computed from the quaternion and compared to the desired attitude DCM, computed by RSLEW, to obtain the attitude error DCM. This attitude error is then limited. The attitude error and the integral of the attitude error are inputs to the proportional and integral channels of the PID controller, respectively.

The user controller also includes an implementation of the feed-forward (accelerometer) loop of the fast loop controller. ACP measurements are multiplied by the ACP gain matrix, and then processed by the three-axis, second-order acceleration prefilter. Outputs of the prefilter are computed at 25 Hz and processed by three second-order filters in each axis to complete the feed-forward loop of the fast loop controller. Outputs of the two loops, the gyro feedback and accelerometer feed-forward loops, are summed to generate the torque command output of the fast loop controller.

Certain aspects of the DCU, as implemented in the TREETOPS IPS simulation which differ from the flight system, should be addressed. The flight DCU hardware is a 16-bit machine, although some computations performed by the flight DCU do not use the full 16-bit capability of the DCU hardware. Thus, some computations performed by the flight DCU are not as accurate as the computations performed in the TREETOPS IPS simulation which is implemented on a 32-bit machine. As mentioned previously, only three orthogonal rate gyros are used in the simulation, neglecting the skew gyro of the gyro package. In the flight system, gyro measurements must be transformed from the gyro system to the platform system prior to prefiltering since the two systems are not aligned. However, since the gyros in TREETOPS are oriented to coincide with the platform system (body 5 system), no gyro measurement transformation is needed. Similarly, the controller torque commands do not need to be transformed in the simulation since they are input directly to the torque motor actuators on the EL, XL, and RL hinges.

### 2. RSLEW

The source code for RSLEW was obtained from Dornier's performance simulation program (PERFSIM). The FORTRAN subroutine RSLEW was modified and incorporated into the DCU emulator (user controller) in TREETOPS. Most modifications involved computing the numerous transformation matrices and restructuring common blocks.

Input variables passed into RSLEW consist of: rate gyro measurements, resolver angles, current (actual) quaternions, orbiter rates, desired angles, and various flags indicating the type of slew maneuver to be performed. In the TREETOPS model, there is no skew gyro, and the gyro inputs are defined in the platform system; thus, RSLEW was modified to require only three gyro measurements, and the gyro to platform transformation in RSLEW was set to identity. Also, the desired angles are computed within the DCU emulator such that for inertial slew the desired angles are the differences between the destination and current resolver angles. For gimbal angle slews, the desired angles are the actual destination resolver angles.

## C. Implementation of IPS Operations

### 1. Operational Modes

In an effort to closely emulate on-orbit operations of the IPS, a mission timeline is executed in the simulation. The simulation has the capability for both slewing and pointing to allow successive target pointing scenarios involving both orbiter and IPS attitude maneuvers between targets. Four modes of operation for the IPS are executed in the simulation:

a. Optical hold

b. Inertial slew

c. Gimbal angle command

d. Inertial hold.

To specify the sequence of operations, the timeline data consists of the time to begin a new mode, IPS operational mode, commanded IPS hinge (gimbal) angles, and orbiter mode and attitude. SDAP may operate in one of two modes such that the orbiter attitude can be maintained within a deadband or allowed to drift.

In the TREETOPS IPS simulation, the IPS performs pointing operations in either inertial hold or optical hold. When either mode is active, RSLEW commands the desired platform attitude DCM to be identity and the desired platform attitude rates to be zero, thus maintaining inertial orientation. Whereas inertial hold operates with only gyro rates as feedback measurements, optical hold mode also uses inputs from the ADF. The ADF utilizes inertial attitude measurements from the OSP to estimate gyro drift and the resulting accumulated attitude error. Optical hold is the mode used during periods representing scientific observation in the TREETOPS IPS simulation.

IPS slews may be accomplished in the simulation by either a gimbal angle command or an inertial slew. When in inertial slew mode, the desired attitude DCM for the new inertial attitude is updated by RSLEW at a rate of 5 Hz and compared to the actual platform attitude DCM in the feedback loop to obtain an attitude error DCM. In flight software, the commanded attitude for an inertial slew is specified in right ascension/declination coordinates, but for an inertial slew in this simulation, the gimbal angles are specified that result from a slew through the desired inertial angles. Gimbal angle command mode performs slews by integrating gimbal (relative) rates to generate the attitude DCM. The relative rates are obtained by subtracting the orbiter rates from inertial rates, which is similar to tachometer feedback. Gimbal angle command mode will cause the IPS to slew to the commanded gimbal angle configuration and then maintain that gimbal angle configuration (which is not an inertial hold if the orbiter is moving).

### D. IPS Operational Sequence

The operational sequence in the user controller is written with the objective of investigating IPS performance during multiple target pointing operations. The sequence begins with the orbiter in deadband control and the IPS in inertial hold. When a new target objective is specified, a gimbal angle slew of the IPS (as well as an orbiter slew, possibly) is required to point the IPS at the new target. If the IPS slew is completed while the orbiter is still slewing, the IPS maintains its gimbal orientation in gimbal angle command mode. When the orbiter enters the 2° attitude deadband for the commanded attitude and the IPS has completed the gimbal angle command slew, SDAP maintains orbiter attitude within the deadband, and the IPS enters inertial hold mode. Although the IPS gimbals are in the desired orientation, the IPS is not in the desired inertial orientation since the orbiter has not completed its maneuver. Thus, the target is not in the center of the field-of-view (FOV) of the star trackers. Since the IPS slew rate is approximately ten times faster than the rotation rate of the orbiter, an inertial slew of the IPS is used to move the IPS to the proper inertial orientation instead of waiting until the orbiter completes its maneuver. At the completion of this small IPS inertial slew, the IPS enters inertial hold mode, and the operational identification procedure, or IDOP [4], is performed. After a successful IDOP, the period representing scientific observation commences with the IPS in optical hold mode. It should be pointed out that in this simulation, it is assumed that the target of observation is always centered in the FOV of the IPS (the capability for offset pointing has not been incorporated in this simulation).

## IV. SIMULATION RESULTS

To demonstrate the capabilities of the TREETOPS IPS simulation, three representative operational scenarios are executed and the results presented in this section. These example cases demonstrate: (1) disturbance rejection, (2) fine-pointing operation, and (3) successive target pointing and slewing. These example cases are representative of functional objectives (FO's) scheduled during the Astro-1 mission to demonstrate slewing, pointing, and disturbance rejection performance of the IPS. Whereas these examples are presented for illustrative purposes only, the TREETOPS simulation has been used to predict on-orbit performance of the IPS performing specific FO's [8].

## A. Disturbance Rejection

The first example case demonstrates the ability of the IPS to reject disturbance during fine-pointing operation. The largest typical disturbance source is thruster firings from the VRCS, which is used for orbiter attitude control. It has been shown that during the Astro-1 mission, VRCS thruster firing was a larger disturbance (in terms of attitude error) than crew exercise on the treadmill [9].

This example is patterned after the functional objective FO-17, "IPS VRCS Response Test." In this test, the IPS is in the 90/0/0 gimbal configuration in inertial hold with the orbiter in free-drift mode. VRCS thruster pulses are applied in one axis for a minimum duration of 320 ms. Pulses are applied successively in the positive and negative directions for orbiter roll, pitch, and yaw with a 30-s pause between firings. Note that by defintion, when the IPS is in the 90/0/0 gimbal configuration, orbiter roll corresponds to (negative) IPS cross elevation, orbiter pitch corresponds to (negative) IPS elevation, and orbiter yaw corresponds to IPS roll.

When the IPS is in gimbal hold at the beginning of a simulation, an initial rotation rate is measured by the gyroscopes that is due to the initial conditions of the simulation. This initial rate error is due to the orbiter having a constant rotational rate due to the orbital environment which is not assigned to the hinges attaching each body of the IPS. Thus, the IPS is inertially fixed while the orbiter is rotating, and this rate must be compensated for by the IPS controller to maintain gimbal angles.

Thruster pulses are applied only in the positive sense for this example. The first disturbance is a 320-ms thruster firing in the positive orbiter roll axis occuring at 30 s, followed by 320-ms thruster pulses in the orbiter pitch and yaw axes at 60 and 90 s, respectively. Figure 4 shows the torque commands (in N-m) produced by the IPS controller to suppress the disturbance, figure 5 shows the rate gyroscope measurements (in rad/s), and figure 6 presents the attitude error (in rad) computed by the fast loop controller. The largest torque command occurs in the cross-elevation axis for the orbiter roll thruster pulse, which saturates the torque motor at 27 N-m. Similarly, the largest rate measurements, 42 arcs/s, and attitude error computation, 7 arcs, occurs at this time in the cross-elevation axis. Cross-coupling between axes is evident in the accompanying plots. Due to asymmetry in the force vector and varying moment arms to the VRCS clusters, some cross-coupling between axes occurs. Thus, this nonuniformity complicates a direct comparison between axes.

## B. Fine Pointing Operation

The next example case demonstrates the performance of the IPS for a typical fine-pointing operation. This example is patterned after the Astro-1 functional objective FO-12, "ADF Test." An offset of 0.3° (0.005 rad) is specified in the initial condition of the IPS

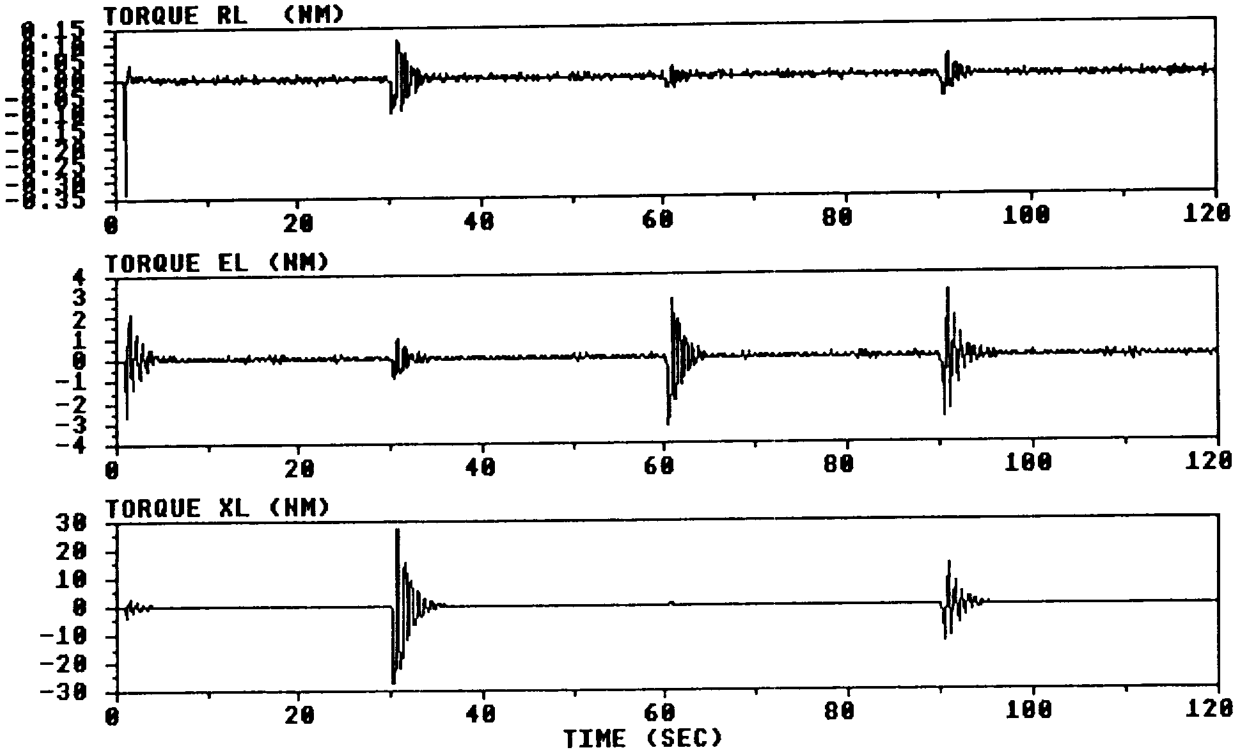

Figure 4. VRCS test: controller torques.

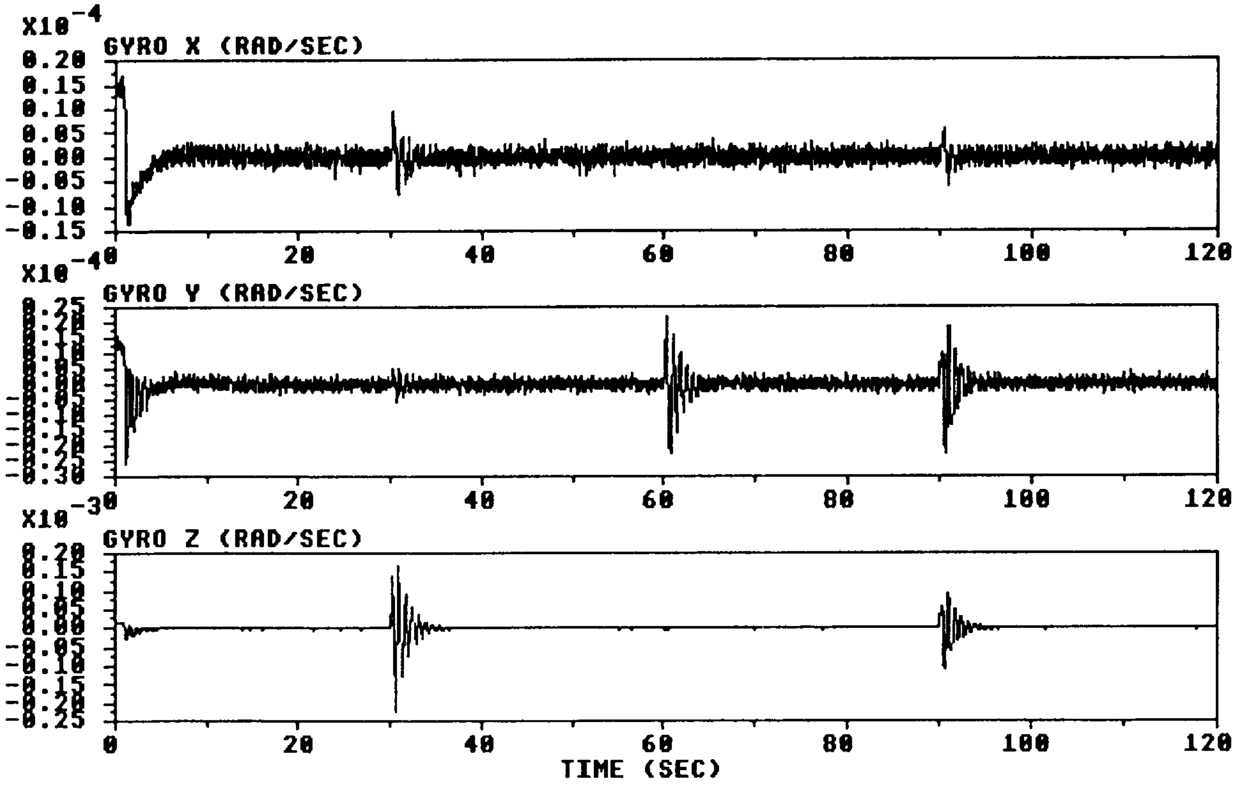

Figure 5. VRCS test: rate gyro measurements.

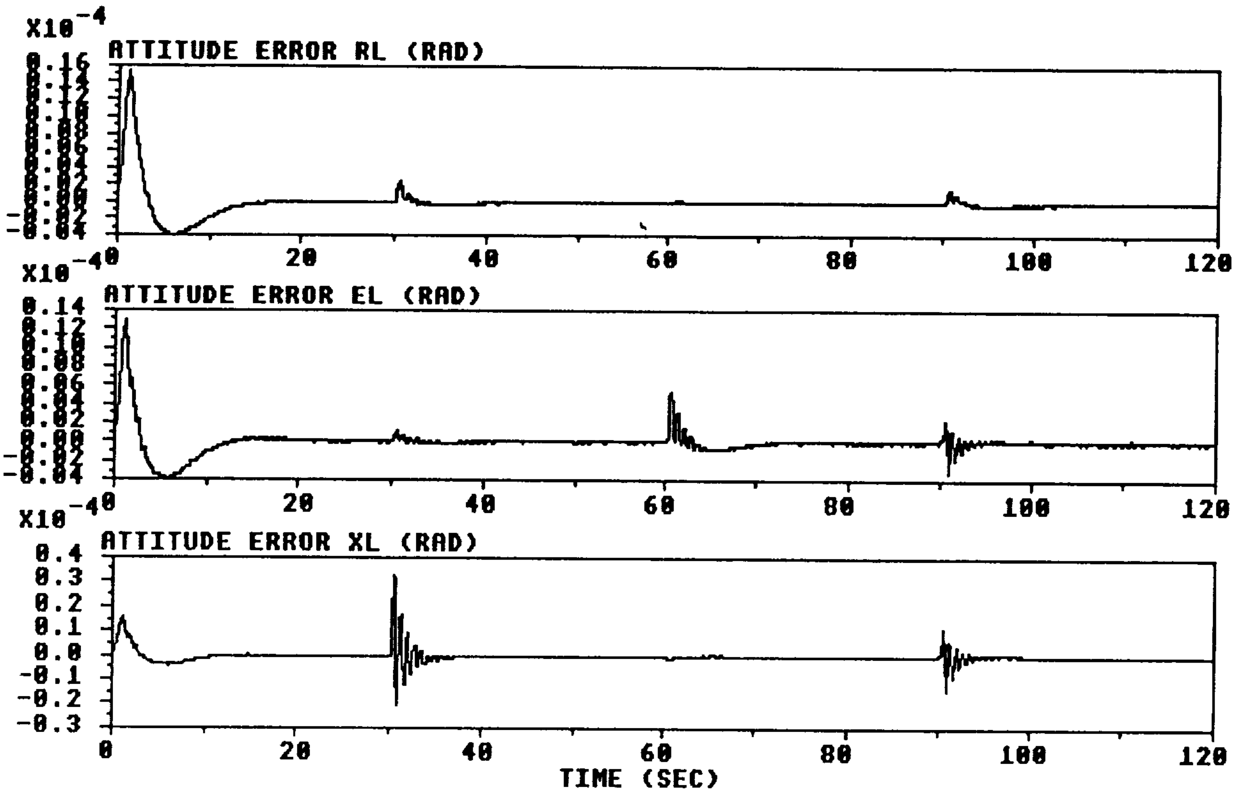

Figure 6. VRCS test: attitude errors.

elevation, cross-elevation, and roll-hinge angles. The offset represents attitude errors accumulated from system drifts and numerical errors during slews and gyro-only control.

During fine-pointing operation, the ADF utilizes optical sensor measurements to estimate the accumulated errors and update the control system knowledge of its attitude. Figure 7 presents the LOS measurements from the boresight optical sensor for the IPS fine-pointing simulation. The nominal position of a guide star for the boresight sensor is centered at the origin of the tracker during fine-pointing in this simulation (the capability for offset pointing has not been incorporated), and accumulated error is represented by the 0.005 rad $y$ and $z$ measurements when the ADF is initialized. After approximately 10 s, the attitude errors are removed, and after approximately 20 s, the ADF is completely settled. Figure 8 shows the torque commands generated by the controller to remove the pointing offset. Note the large initial starting torques that saturate each axis and the smaller oscillations at approximately 10 s to null the rate when the error is removed. It is clear from the plots of rate gyro measurements (fig. 9) that there is no rate error initially, only the attitude error sensed by the star trackers. Thus, the ADF is needed to compensate for this type of pointing error which would not be removed with gyro-only control.

## C. Multiple Target Operations

The last example case demonstrates the versatility of the TREETOPS IPS simulation by performing realistic mission scenarios. In this slew test, the TREETOPS IPS model will execute multiple successive pointing operations: pointing in inertial hold at a target, slewing

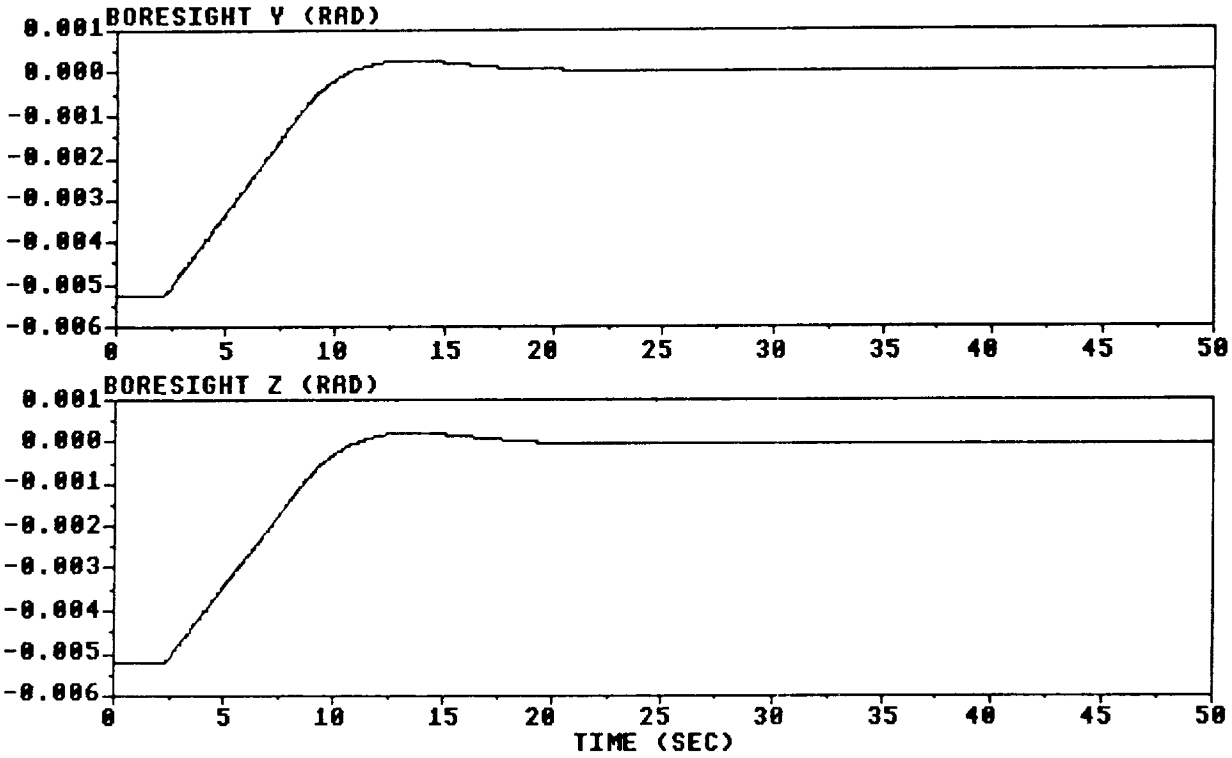

Figure 7. ADF test: star tracker measurements.

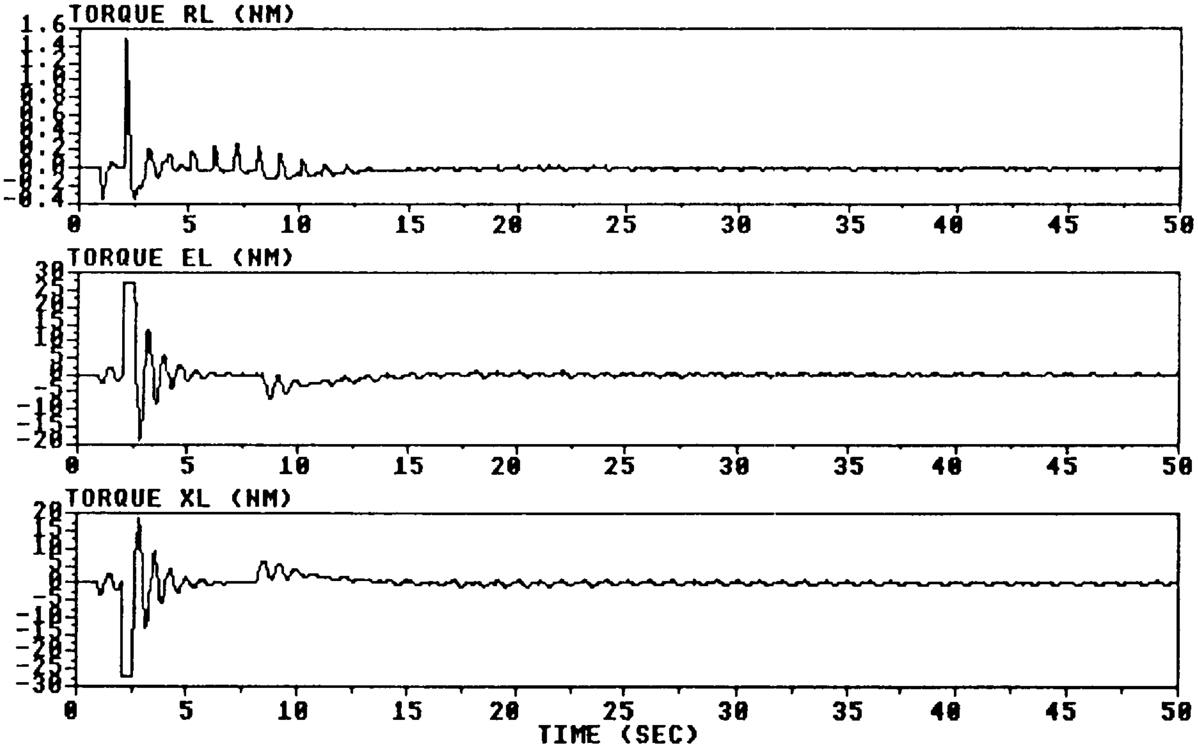

Figure 8. ADF test: controller torques.

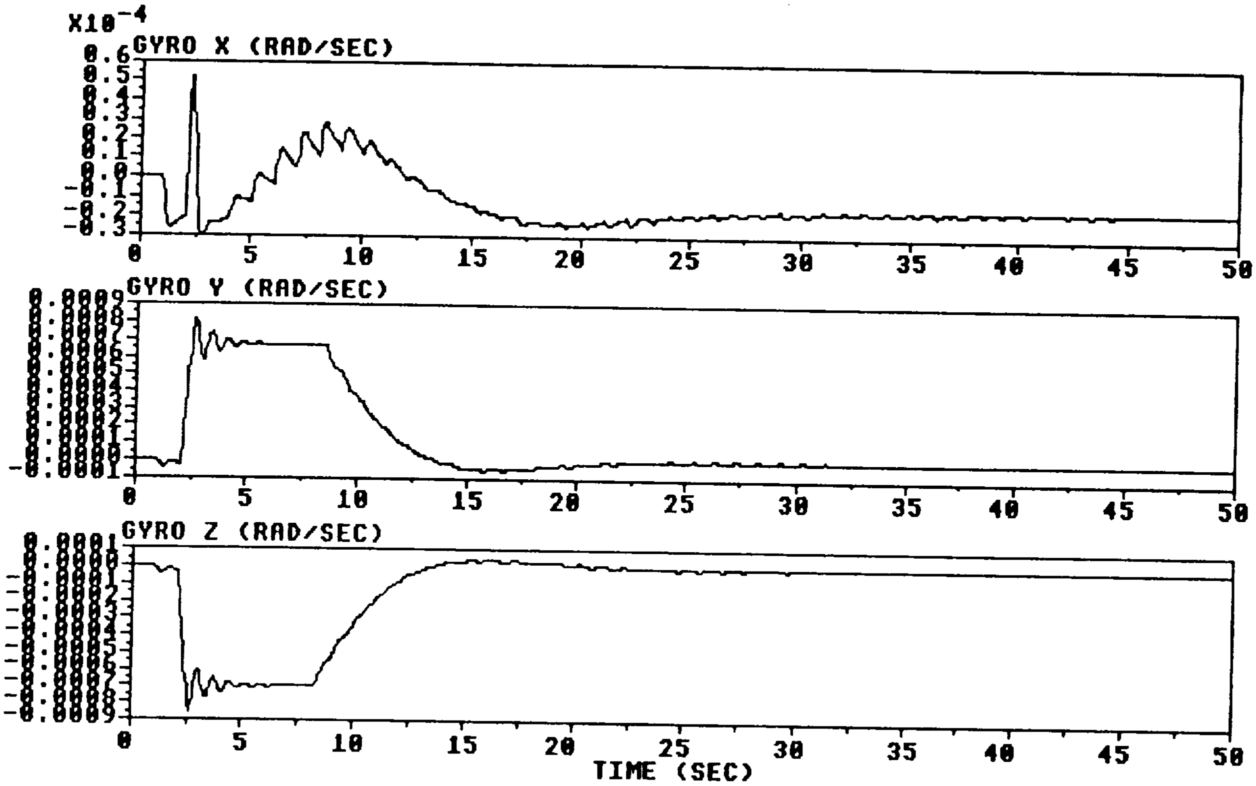

Figure 9. ADF test: rate gyro measurements.

to a new target, centering the new target in the FOV, and commencing with observation of the new target in optical hold. Representative plots of simulation data are presented to complement the description of key events in this example case. Figures 10 and 11 show the time response of the IPS hinge angles and boresight star tracker measurements, respectively.

At the beginning of execution for this case, the orbiter is maintaining a (0,0,0) inertial attitude with the IPS in optical hold at a (90,0,0) gimbal angle configuration. (The notation for orbiter attitude is (pitch, yaw, roll) and for IPS gimbals is (EL, XL, RL).) After 20 s in this mode, the orbiter begins a 10° pitch maneuver, and the IPS performs a gimbal angle command slew to the new target corresponding to a (75,-15,15) gimbal angle orientation. Note from figure 11 that when a new target is specified at 20 s, the star tracker is reset corresponding to the new target, resulting in a jump discontinuity and large pointing "error." When the IPS and orbiter maneuvers are completed, the new target will be centered in the FOV of the star tracker. The IPS completes the gimbal angle command slew at 57.19 s and remains at these gimbal angles until the orbiter completes its attitude maneuver (entering the 2° deadband) at 78.18 s. It is apparent from figure 11 that the target is not centered in the IPS FOV when the orbiter enters the deadband, thus IDOP cannot yet be performed. Instead of waiting until the orbiter passes through the center of the deadband and centers the target in the FOV, a small IPS inertial slew is used to remove the remaining pointing offset. This inertial slew begins when the orbiter enters the deadband at 78.18 s and is completed at 85.78 s, at which time inertial hold is entered and IDOP is attempted. The different maneuvering rates of the IPS and orbiter are apparent from the "piecewise linear" slopes of the inertial measurement plots in figure 11, where the steeper portions correspond to IPS slews, and the portion from 57.19 s to 78.18 s represents the orbiter maneuvering with the IPS in gimbal hold. After successful IDOP, the IPS enters optical hold, removes residual pointing errors with the ADF, and commences observation of the new target.

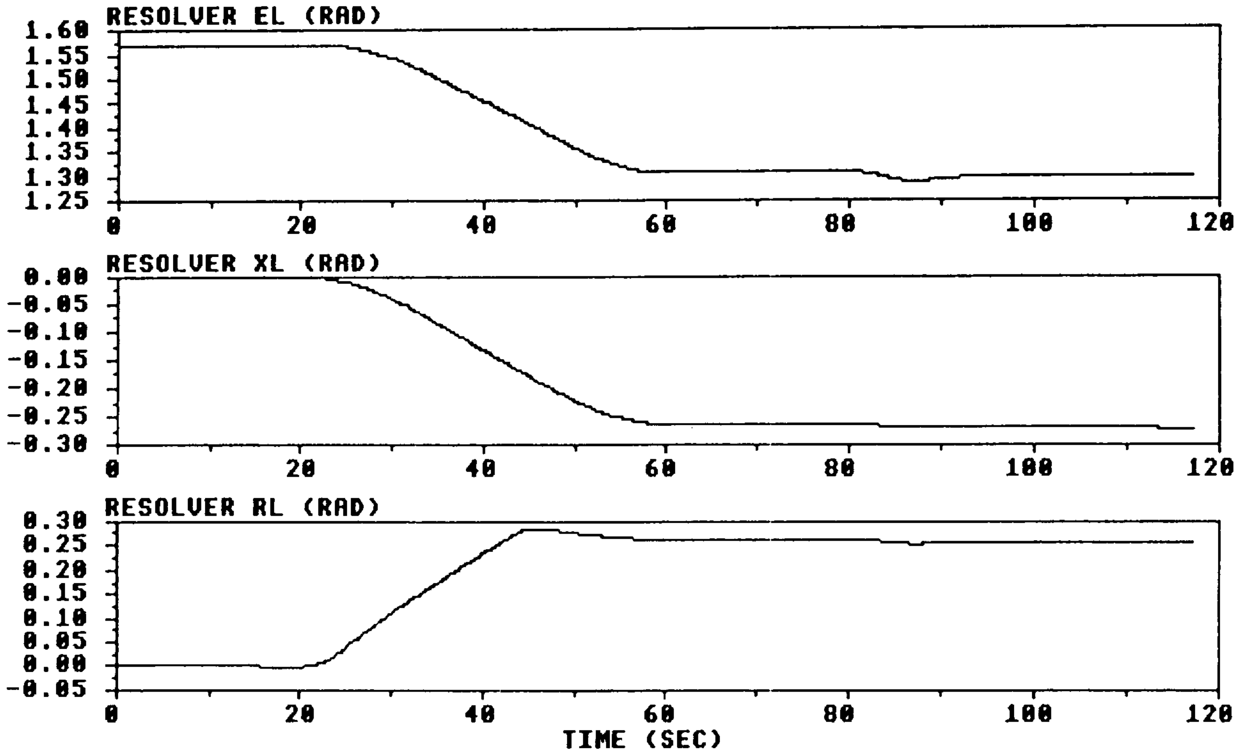

Figure 10. Slew test: hinge angles.

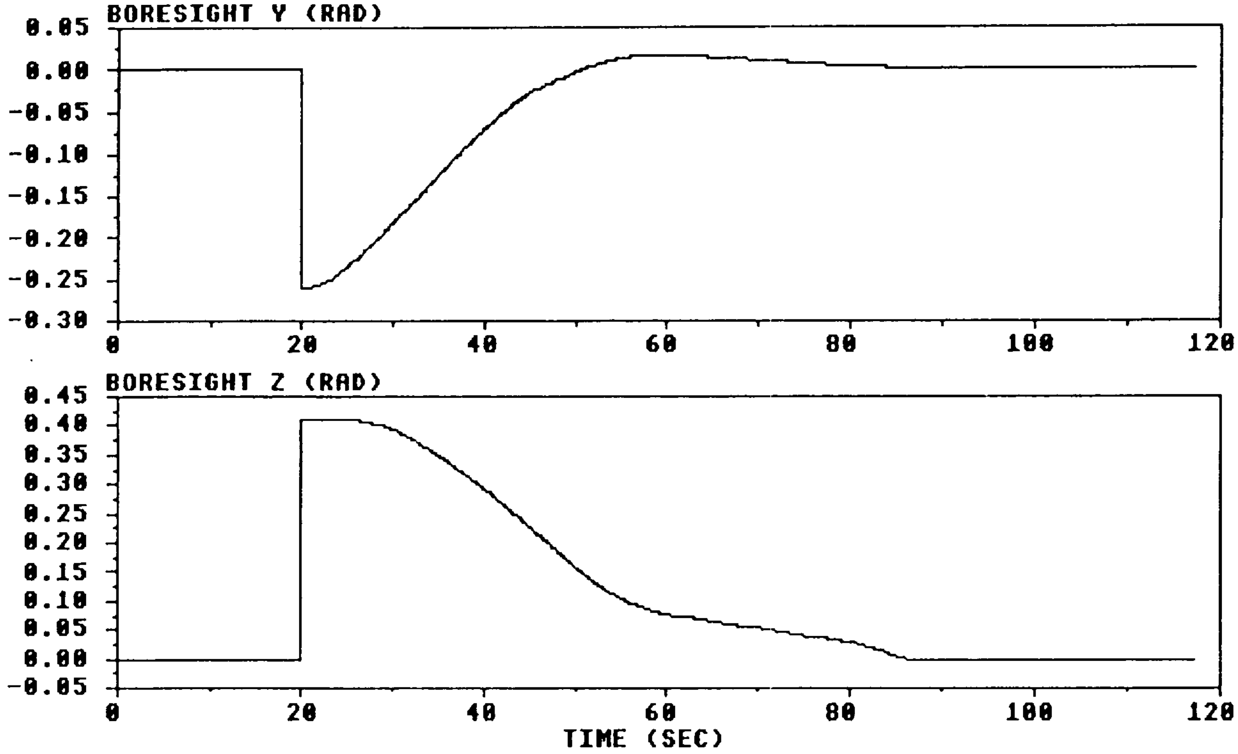

Figure 11. Slew test: boresight star tracker measurements.

# V. CONCLUSIONS

The TREETOPS IPS simulation provides the capabilty to model on-orbit operations of the IPS in a realistic mission scenario. The simulation accurately models the multibody IPS configuration subject to large angle, nonlinear motion, and is suitable for control system design, analysis, and verification.

The TREETOPS IPS simulation has been used by the Rate Drift Tiger Team in support of verification of the pointing control system design and implementation in the MSFC SDF. Additionally, with the capabilities demonstrated by the examples in section IV, the TREETOPS IPS simulation was used to predict the performance of the IPS during much of the Astro-1 mission and aid in post-flight data analysis.

Several factors degrade the performance of the IPS, including aerodynamic drag, cable torques, thruster disturbances, and extraneous noise sources. Of these, the removal of accumulated pointing error by the ADF and pointing performance in the presence of thruster disturbances were considered in this report. In each test case, a constant gyro drift as well as rate gyro and star tracker measurement noise was included in the simulation. The effect of these disturbances is to degrade pointing performance and results in pointing errors that must be removed by the ADF. The Astro-1 mission timeline was developed such that the procedure demonstrated in the multiple target operation example would be repeated frequently for observation of numerous successive targets. It was hoped that successful IDOP's would be performed after each slew; however, due to various complications, mission planners opted for operation in the contingency target acquisition (CTA) mode using manual pointing control inputs for removing bias pointing offsets. Since this simulation was developed to evaluate the IDOP process and since CTA is primarily inertial hold mode (which was simulated) with manual inputs, CTA was not simulated.

To support future missions utilizing the IPS, this simulation will be enhanced to include structural flexibility, aerodynamic drag, mechanical misalignments, and other mechanical disturbances such as cogging torque and cable torque.

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## APPROVAL

# A SIMULATION OF THE INSTRUMENT POINTING SYSTEM FOR THE ASTRO-1 MISSION

By M. Whorton, M. West, and J. Rakoczy

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

JMBlair

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Director, Structures and Dynamics Laboratory

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NASA has recently completed a shuttle-borne stellar ultraviolet astronomy mission known as Astro-1. A three-axis instrument pointing system (IPS) was employed to accurately point the science instruments. In order to analyze the pointing control system and verify pointing performance, a simulation of the IPS has been developed using the multibody dynamics software TREETOPS. The TREETOPS IPS simulation is capable of accurately modeling the multibody IPS system undergoing large angle, nonlinear motion. This report documents the simulation and presents example cases demonstrating disturbance rejection, fine pointing operations, and multiple target pointing and slewing of the IPS.

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