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# INDOSTAR-1 EARLY ORBIT OPERATIONS

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Launched in November, 1997, Indostar-1 is the Orbital Sciences Corporation's first geosynchronous satellite and ushers in the beginning of a new era in smaller, less expensive geosynchronous spacecraft. The state-of-the-art momentum-bias attitude control system design is based on Princeton Satellite Systems' commercially available SPACECRAFT CONTROL SYSTEM and represents the first spaceflight of this package.

This paper describes the in-orbit operations of the Indostar-1 communications satellite attitude determination and control system (ADACS) in the first few months following its launch. Prior to launch, the ADACS flight software was tested and verified on two simulators. The performance predicted by these simulators matched the actual spacecraft response during transfer orbit, acquisition, and nominal on-orbit operations. Anomalies were discovered, however, when the spacecraft attempted its first stationkeeping maneuver and during the unloading of the momentum wheel. This paper describes the ensuing anomaly investigations and discusses the lessons learned during early orbit operations.

## INTRODUCTION

PT Media Citra Indonesia of Jakarta, Indonesia, contracted with DSI (later acquired by CTA International which has since been acquired by the Orbital Sciences Corporation - Space Sciences Group) for the provision of a turnkey Direct Broadcast Satellite system covering Indonesia, called Indostar. The Indostar system was designed to provide the first digital direct-to-home broadcast television service (32 channels) and one analog television channel to the entire Indonesian archipelago.

Indostar-1 was launched in November, 1997 aboard an Ariane rocket from Kourou, French Guinea. For the next two weeks, the spacecraft underwent transfer orbit operations which placed it into a geosynchronous orbit at 106 degrees East longitude. Check out of the spacecraft then took place and commercial operations commenced in June, 1998.

A considerable amount of time during spacecraft check out was spent verifying the performance of the Indostar-1 attitude and determination control system. The state-of-the-

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art momentum-bias attitude control system design is based on Princeton Satellite Systems' commercially available SPACECRAFT CONTROL SYSTEM and represents the first space-flight of this package.[1] Prior to launch, the ADACS flight software was tested and verified on two simulators. The performance predicted by these simulators matched the actual spacecraft response during transfer orbit, acquisition, and nominal on-orbit operations. Anomalies were discovered, however, when the spacecraft attempted its first stationkeeping maneuver and during the unloading of the momentum wheel. The simulators were then employed to assist in the anomaly investigations.

The first section of the paper presents an overview of the Indostar-1 satellite and its attitude control system. The second section briefly describes the simulators used to verify the flight software. A description of the transfer orbit operations is given in the third section. The fourth section compares the pre-launch predicted behavior during stationkeeping with the actual response during the first maneuver. A discussion of the anomaly investigation and the subsequent control loop recompensation is included. The fifth section describes the redesign of the roll/yaw controller for momentum unloading and the effect of the implementation of the new gains on the operation of the satellite. The conclusion summarizes the lessons learned, including the desired modifications to future ADACS designs to further simplify operations.

## INDOSTAR-1 SPACECRAFT

Indostar-1 is the first application of Orbital's StarBus satellite platform. The StarBus is a fully redundant, Delta-class spacecraft bus designed for geosynchronous missions and adaptable to other missions from low-Earth orbit to sun synchronous trajectories. The spacecraft's unique, lightweight design results in significantly reduced manufacturing and launch costs compared to other spacecraft in the same class.

Figure 1 shows the Indostar-1 spacecraft. The core structure is approximately a 6-foot cube. The articulated sun tracking solar arrays are deployed in two wings from opposite sides of the spacecraft. Each wing consists of three 5-foot long solar panels for a total power generation of 1500 W at end of life (EOL). The launch weight of the spacecraft was 3054 lbs and the spacecraft is designed for a 7-year lifetime with sufficient propellant loaded for 12 years of operation. Based on the success of the initial design, Orbital is already developing a next-generation StarBus spacecraft platform that provides up to 5000 W (EOL) and has a 15-year design life.

### Attitude Determination and Control System

The Indostar-1 Attitude Determination and Control System is a 3-axis stabilized, pitch momentum bias system, chosen for its inherent capability to satisfy pointing requirements using a minimum complement of reliable sensors and actuators. The ADACS provides all of the functionality necessary to bring the satellite from the post injection transfer orbit to a geosynchronous orbit at the desired longitude and controls all phases of the spacecraft life. This includes Geostationary Transfer Orbit (GTO), Geostationary Drift Orbit, and all On-Station modes including Fault Detection and Backup Safehold modes. A

**Figure 1 Indostar-1 Spacecraft**

brief summary of the ADACS functionality for each of these mission phases is given in the following sections. Table 1 then summarizes the commandable ADACS modes.

*Geostationary Transfer Orbit Modes*. During transfer orbit, the spacecraft is spin stabilized along its major axis of inertia. The ADACS controls the spin rate and enables spin axis precession maneuvers (SPM) to be performed. Sun and horizon sensor telemetry data are used for ground based attitude determination. The final ADACS goal in GTO is to point the spin axis to within 0.5 degrees of the desired apogee motor fire (AMF) attitude.

*Geostationary Drift Orbit Modes*. The ADACS controls all modes necessary to acquire the Earth and put the spacecraft in the correct orbital slot. Once in drift orbit, a Dual Spin Turn (DST) maneuver is performed to transfer momentum from the spacecraft Z axis to the momentum wheel assembly (MWA) along the Y axis and reorient the spacecraft. The ADACS algorithms enable thruster based Earth acquisition from any arbitrary pitch attitude. These modes can also be used for reacquisition should loss of Earth lock occur. Stationkeeping maneuvers are performed to position the satellite at the station and to correct the orbit period and eccentricity.

*On-Station Modes*. The ADACS is responsible for maintaining the antenna circular beam pointing error to less than 0.2 degrees at all times once the spacecraft is on-station. Earth sensor assemblies (ESAs) provide the roll and pitch errors used for closed loop control. Pitch control of Indostar-1 is provided by the MWA, whose momentum is managed to within ± 4% of nominal. Roll/yaw control and nutation damping is performed by magnetic torquer actuators (MTAs). Hydrazine reaction engine assemblies (REAs), or thrusters, are used for backup roll/yaw and pitch control.

During stationkeeping maneuvers, three-axis sensing is enabled. The Earth sensors are used for roll and pitch sensing while a gyro is used for yaw sensing. Prior to use, the yaw gyro must be initialized and its bias estimated. Attitude control is provided by the REAs which are off-pulsed if necessary. North/South maneuvers (orbit inclination control) use electrically heated thrusters (EHTs) as the primary maneuver thrusters and the control REAs as backups should the EHTs be unusable for any reason. East/West maneuvers are for orbit drift rate and eccentricity control and use the REAs.

*Failure Detection and Backup Safehold Modes*. These modes have been implemented to prevent loss of mission. Hardware failures are detected both on the ground and onboard the spacecraft. Processor failures are autonomously detected and switched over. Earth sensor failures are detected onboard and ground controllers are alerted. Failure of the momentum wheel must be detected on the ground. During thruster control, the allowable attitude range is limited and if the limit is exceeded, the thrusters are automatically shut off and control is returned to the momentum wheel and magnetic torquers.

The Attitude Safe Hold Mode is entered when the Earth sensors can not see the Earth. In this mode, the roll and pitch errors are set to zero. The Attitude Safe Hold Mode will result in a slow attitude drift and provide time for operations personnel to respond. If a disconnect is detected between the remote terminal and the flight computer, the Wheel Tach and Speed Clamp Mode is entered. In this mode, the remote terminal holds the momentum wheel speed constant.

**Table 1**
**ADACS FUNCTIONAL SOFTWARE MODES**

| Mission Phase | ADACS Mode | Description |
|---|---|---|
| Safehold | NoManeuver | Actuators disabled; GTO sensor data collected |
| Geostationary Transfer Orbit | SPM | Precesses the spin axis |
| | SpinChange | Changes the spacecraft's spin rate |
| Geostationary Drift Orbit | DualSpinTurn | Aligns the MWA axis along orbit normal after AMF |
| | PitchAcquisition | Acquire Earth after DST; uses REAs |
| On-Station | NormalModeMWA | Only pitch attitude controlled; can be used to acquire Earth or verify MWA pitch control |
| | NormalModeMWA/MTA | MWA for pitch and MTA for roll/yaw control |
| | NormalModeREA/REA | Pitch and roll/yaw thruster control; used after stationkeeping maneuver termination; unload pitch momentum |
| | NormalModeMWA/REA | MWA for pitch and REAs for roll/yaw control; used for large roll correction or to supplement magnetic control |
| | Stationkeeping | 3-axis thruster control during maneuvers; ESA for roll and pitch attitude; gyro for yaw attitude; |

## SIMULATORS

The Indostar attitude control system design was done by Princeton Satellite Systems and is based on their commercially available SPACECRAFT CONTROL SYSTEM. These algorithms were then validated using two different simulators. One of the simulators, INDOSIM, is a full software simulator. The other, CLSIM, is a hybrid. Figures 2 and 3 show the structure of the two simulators.

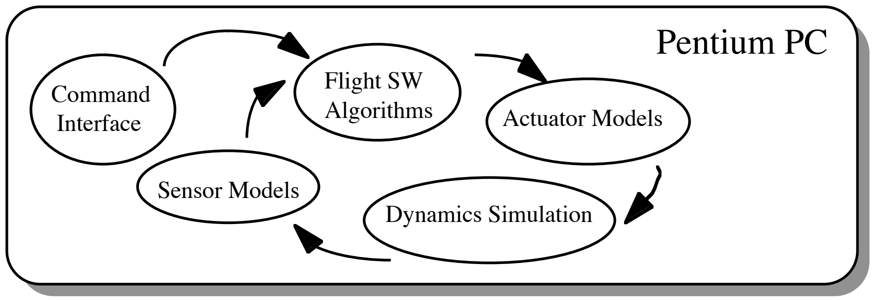


**Figure 2 INDOSIM Structure**

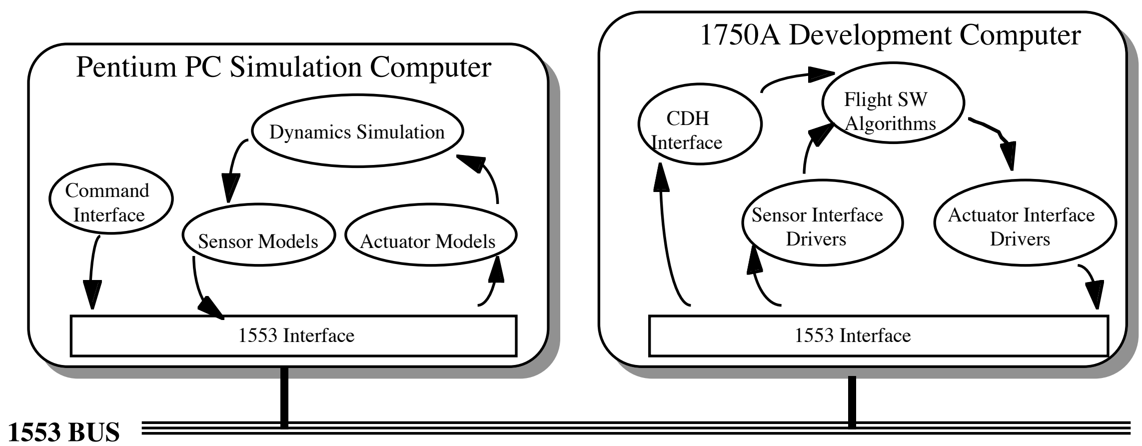


**Figure 3 CLSIM Structure**

INDOSIM includes Sensor and Actuator models, a Dynamics Simulation and a Command Interface in addition to the Flight Software (SW) Algorithms. This simulator runs on a Pentium PC. CLSIM provides a Closed Loop SIMulation of the Indostar ADACS software. CLSIM differs from INDOSIM by moving the Flight SW Algorithms onto a 1750A Development Computer and connecting the Pentium PC Simulation Computer to the 1750A Development Computer via a 1553 Bus connection. The Sensor and Actuator Models now interface to Sensor and Actuator Drivers on the 1750A via the 1553 Bus connection. Throughout the development stage, the code for the Flight SW Algorithms in both simulators were maintained to be identical. Prior to launch these simulators were used to validate the ADACS design and to test the flight software.

The operation of both INDOSIM and CLSIM was based on setting up a group of related files that together define the run to be made. These files include the command, output definition, input data, and “fail” files. The command file contains the “scripts” which are a set of time ordered commands to be executed and the execution time for each command. The specified output parameters to be observed reside in an output definition file. Initialization parameters including the simulation run time reside in an input data file and any failure parameters to be introduced reside in a separate “fail” file. The actual simulation output data corresponding to the specified output parameters are stored in an output file. To analyze the output data files, MATLAB scripts are used to plot the output parameters. Results from the two simulators will be presented later in the paper.

## TRANSFER ORBIT OPERATIONS

Following the launch and transfer orbit operations to place Indostar into geosynchronous orbit, Indostar-1 was transitioned from a spin stabilized satellite to a 3-axis stabilized, pitch momentum bias satellite. The launch vehicle injected the spacecraft into transfer orbit spinning at 5 RPM. The first ADACS event was the Spin Precession Maneuvers (SPM) to the Apogee Motor Firing (AMF) attitude. During the SPM, nutation in excess of 5 degrees was noted which was much greater than expected. However, it damped out after the maneuver was completed and well in advance of the data collection period for attitude determination and any subsequent trim SPMs to correct the pointing for the AMF. Following the SPM the ADACS was used to spin up the satellite to 60 RPM which is the spin rate at which the AMF would be done.

Following the AMF, the satellite had to be spun down for the SPM to orbit normal attitude in preparation for the Dual Spin Turn (DST). As a result of the nutation observed during the initial SPM at 5 RPM a decision was made to spin down to 10 RPM for the SPM to orbit normal. Another argument for this decision was that at 10 RPM any residual nutation would damp out faster than at 5 RPM. Following the spin down and the SPM to orbit normal, the spin rate of the satellite was adjusted to the proper rate for the DST. The MWA speed command was then transmitted to the satellite followed by the DST mode command and the transition from a spin stabilized satellite to a three axis momentum bias state had commenced. The transition went as predicted by the simulators and the satellite had re-oriented itself with the +Y axis along the orbit normal south direction and significant nutation had damped out within a half hour.

When the nutation was reduced to less than 1 degree the pitch acquisition sequence commenced. Thrusters were used to reduce the pitch rate in preparation for pitch capture. After watching the earth sensor roll and pitch errors for a few rotations it was apparent that at the existing pitch rate the pitch acquisition loop would capture. The pitch acquisition itself was almost anti-climactic and it captured the Earth immediately. The roll error was so small that Indostar-1 was commanded directly to NormalModeMWA/MTA and the magnetic torquers removed the residual nutation.

## STATIONKEEPING ANOMALY

At this point Indostar-1 was drifting to its operating longitude over Indonesia. After verifying that all thrusters were operational and that the NormalModeMWA/MTA was operating properly, preparations were made for the first stationkeeping maneuver. The purpose of this maneuver was to slow down the drift rate as Indostar-1 approached its target longitude. The yaw gyro was turned on and allowed to warm up for the allotted time prior to calibration and recompensation of the measured drift rate. However, as soon as the ADACS mode was changed from the NormalModeMWA/MTA to Stationkeeping an instability was noted in both the roll and pitch loops prior to activating the maneuver thrusters. The maneuver was immediately terminated by switching back to the NormalModeMWA/MTA and allowing the magnetic torquers to remove the nutation induced by the thruster firings.

Figure 4 shows the observed spacecraft response in roll and pitch when Stationkeeping mode was entered for the first time on November 19, 1997. Prior to entering Stationkeeping, the pitch error was very small while the roll error was approximately 0.33 degrees. Stationkeeping mode was entered at 6:53:50 GMT and one see the greater authority of the thrusters in quickly reducing the roll error. The mode was aborted at 7:1:30 GMT at which time NormalModeMWA/MTA was entered.

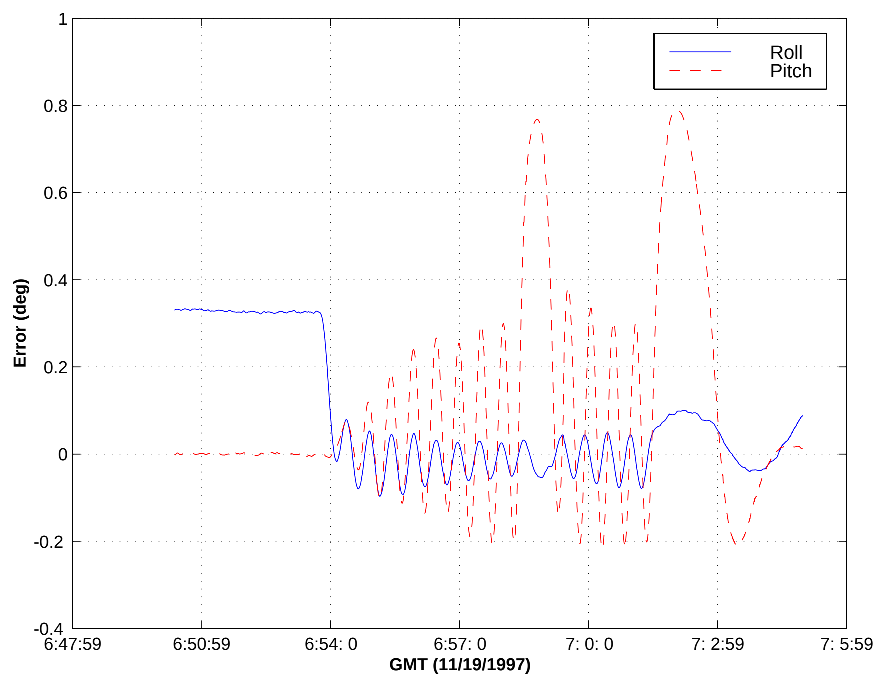


**Figure 4 Roll and Pitch Responses During the First Stationkeeping Maneuver**

INDOSIM and CLSIM were then brought into play to determine why the roll and pitch stationkeeping loops were unstable. Before the problem could be solved, it was necessary to replicate the observed instability on the simulators. Since the spacecraft response about yaw did not exhibit the large oscillations seen about the other two axes, it was hypothesized that the time delay in the processing of the earth sensor data as modeled in the simulators may be in error. To test this hypothesis, a continuous time linear analysis was performed using MATLAB and it was discovered that a delay of approximately 2 seconds would destabilize the system.

This result was then verified by the simulators. The time delay in the INDOSIM Earth Sensor Model was incrementally increased to observe the effects on the stability of the roll and pitch stationkeeping loops. When a time delay of 1.5 seconds was used the instability noted on the satellite was observed in the INDOSIM results. This can be seen in Figure 5. The two lines in the roll and pitch plots correspond to the truth and the ESA measured angles. Stationkeeping was entered at 300 seconds.

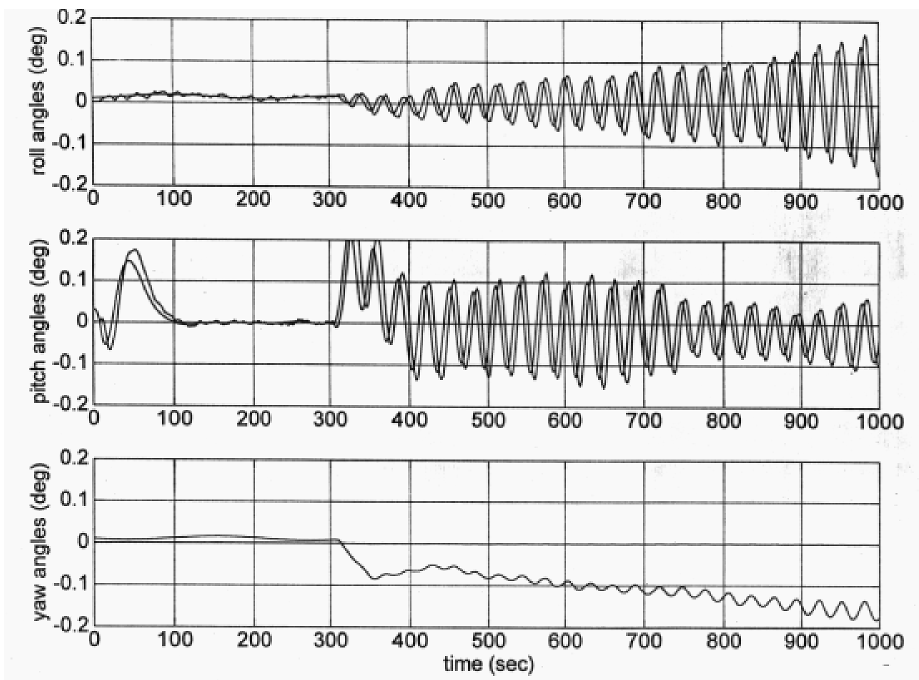


**Figure 5 INDOSIM Replication of Stationkeeping Anomaly**

Using this 1.5 second time delay in CLSIM, however, did not cause the roll and pitch stationkeeping errors to diverge. The time delay had to be increased to 2 seconds before the same instability was observed in CLSIM. This inconsistency between the two simulators still remains unresolved. Figure 6 shows the CLSIM spacecraft response with the 2 second delay. The mode switch into Stationkeeping occurred around 700 seconds. Notice that the response after this time more closely matches that of Indostar-1.

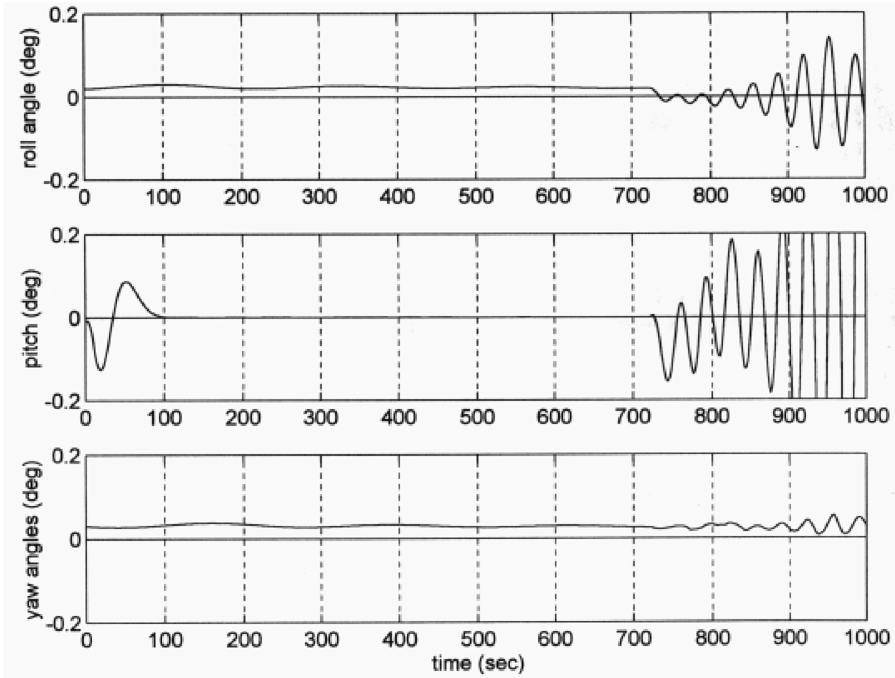


**Figure 6 CLSIM Replication of Stationkeeping Anomaly**

To rectify the instability, the bandwidth of the earth sensor noise filter for the roll and pitch outputs was increased from 0.5 radians/sec to 1.5 radians/sec, thus decreasing the total lag in the system. This change to the ESA filter bandwidth was made in both simulators and the roll and pitch stationkeeping control loop were now stable. Before trying this fix on the satellite the time delay in INDOSIM was increased to 2 seconds (the same value at which the instability was first observed in CLSIM) and the observed performance was still acceptable.*

Having shown that this fix worked successfully in both simulators, the filter bandwidths on the satellite were changed and a "test stationkeeping maneuver" was performed to determine stability of the stationkeeping loop and the effect of the increased earth sensor noise on the roll and pitch errors. Preparations were made to switch back to NormalModeMWA/MTA immediately should anything suspicious be observed. The fears were unfounded and the maneuver worked as expected. Both the loop stability and the effect of the earth sensor noise were within acceptable limits on the "test stationkeeping maneuver" and on all subsequent maneuvers performed. Figure 7 shows the improved response of the roll and pitch loops during a stationkeeping maneuver on May 1, 1998.

* Since the initial presentation of this paper, the authors have been informed by the ESA manufacturer that there is an effective two second delay in the output from the sensor used on Indostar-1.

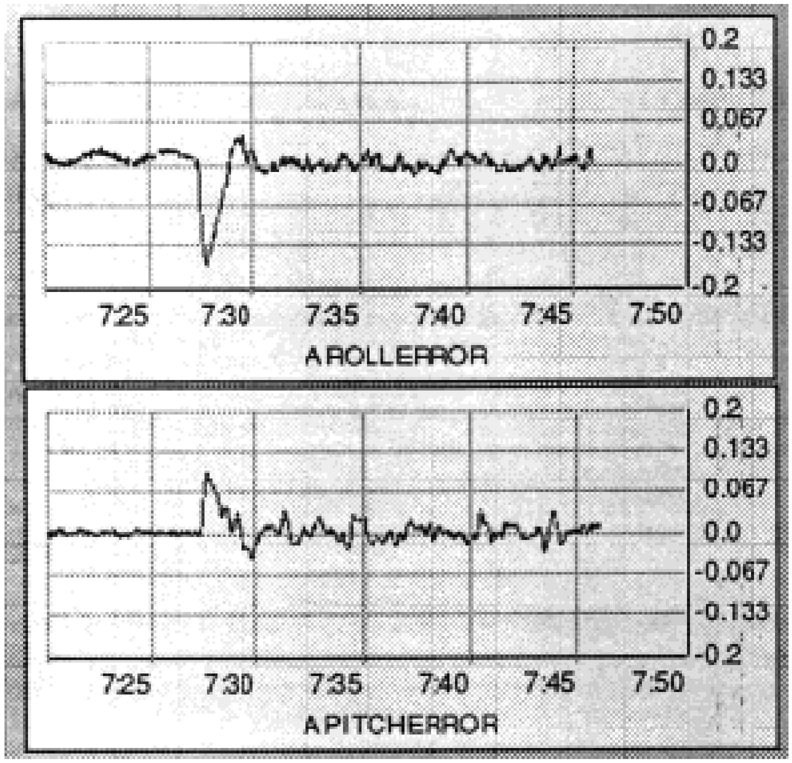


**Figure 7 Improved Indostar-1 Roll and Pitch Response During Stationkeeping Maneuver on May 1, 1998**

## MOMENTUM WHEEL UNLOADING

The second operation during which differences between the simulators and the actual spacecraft appeared was the unloading of the momentum wheel. This was done using the NormalModeREA/REA. This mode is used for required MWA unloads when they are not performed in conjunction with a stationkeeping maneuver. The first time this mode was used double sided pitch and roll firings were noted. During the second MWA unload, even though the roll error increased to approximately 0.3 degrees, there were no roll thruster firings and the double sided pitch firings were still present. The uncontrolled roll error can be seen in Figure 8. The next two unloads showed the same characteristic, i.e. no roll firings and double sided pitch firings. The lack of roll firings was attributed to the gain of the roll/yaw controller being too low. The commanded impulse was smaller than the minimum impulse bit of the thrusters so the roll thrusters were never activated. A redesign of the roll loop resulted in a set of larger gains that controlled too tightly and resulted in double sided roll thruster firings.

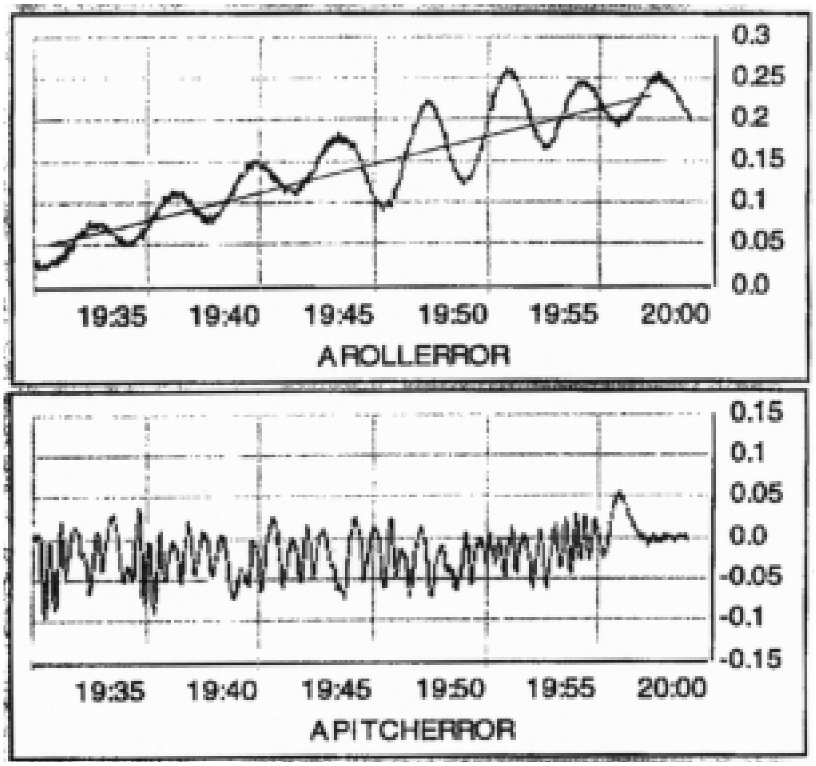


**Figure 8 Roll and Pitch Errors During MWA Unload on December 9, 1997**

Decreasing the gains of the roll and pitch loops by a factor of two solved the problem of the double sided firings; however, these double sided firings could not be replicated in the simulators. At this point a spread sheet was used to evaluate the MWA unload performance. Included in the spread sheet was a computation of the effective thrust of the REAs. The REAs are nominally 0.2 lbf thrusters, but the effective thrust being computed was on the order of 0.4 lbf, as can be seen in Figure 9.

The thruster dynamics could explain this apparent discrepancy. A typical model of a thruster pulse is shown in Figure 10. After being commanded on, the thruster valve opens and there is an exponential rise time before the maximum thrust is reached. The valve is left open the commanded length of time, after which there is an exponential decrease in thrust as the valve shuts off.

For long commanded pulsewidths, the contribution of these rise and fall times to the total impulse is small and the actual impulse closely matches that commanded. For short commanded pulsewidths, however, the rise and fall times can significantly affect the total impulse applied to the spacecraft. This is shown in Figure 11 where the fall time is assumed to be longer than the rise time.

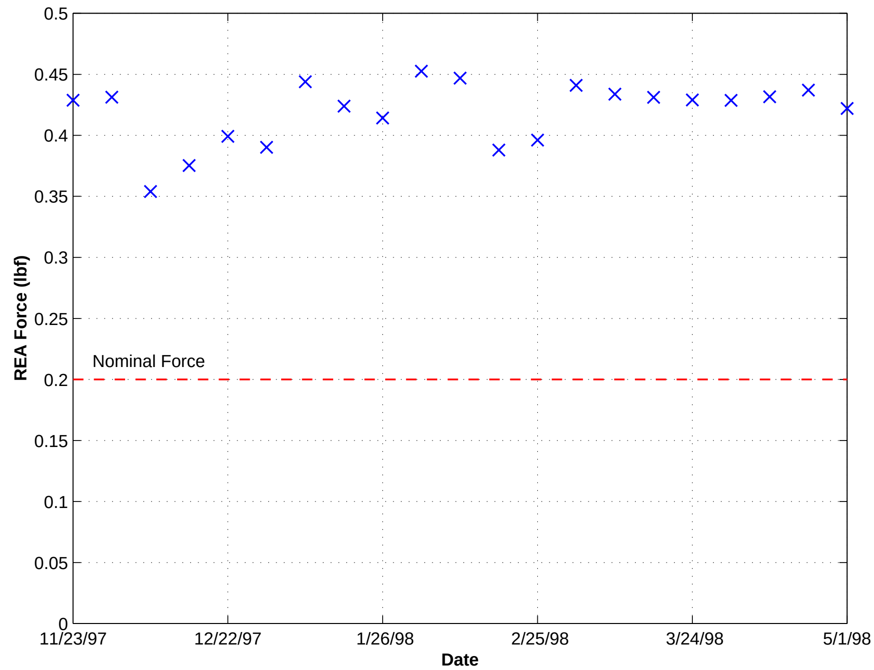


**Figure 9 Calculated REA Force During MWA Unloading**

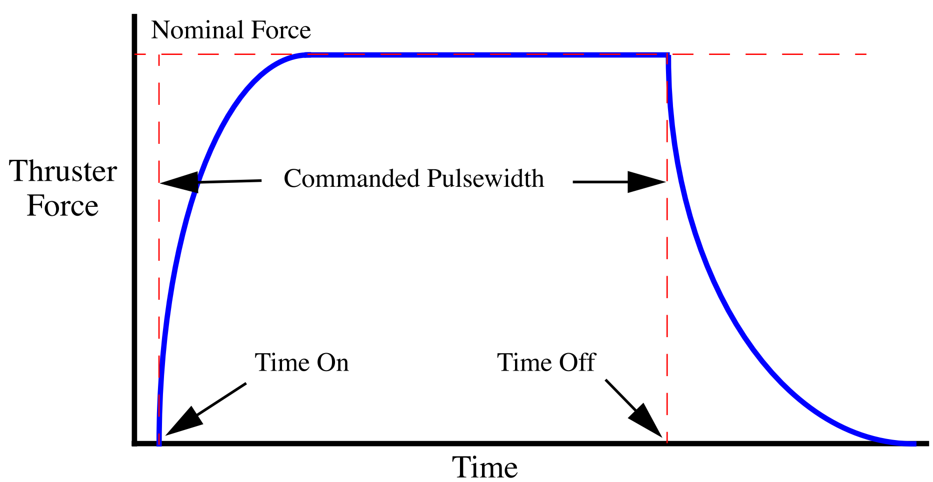


**Figure 10 Typical Thruster Force Model**

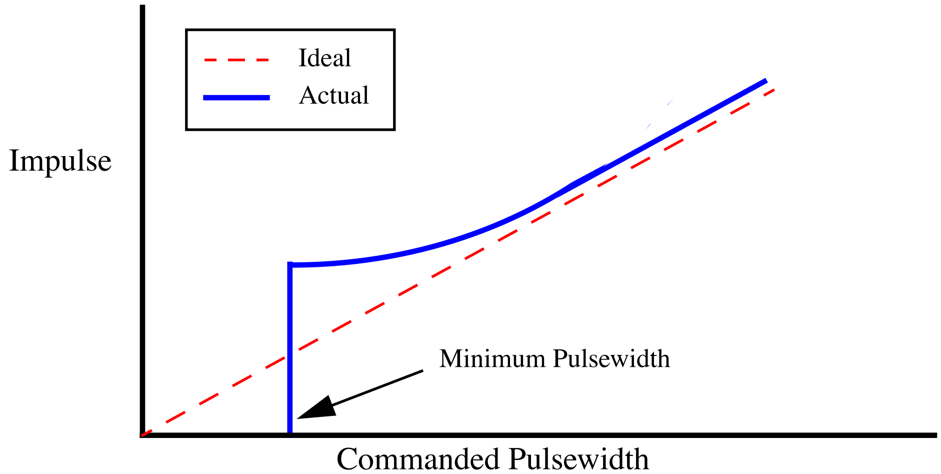


**Figure 11 Thruster Impulse vs. Commanded Pulsewidth**

Since the thrusters were being fired near their minimum pulsewidths during the MWA unloading, the thruster rise and fall times were contributing significantly to the total impulse being applied to the spacecraft. These time constants had not been used in the initial simulation runs. Both simulators were then modified to include thruster rise and fall time constants that would result in an effective 0.4 lbf based on the firing time requested by the control law.

The simulations were now in agreement with the observed spacecraft response and it was possible to optimize the gains to improve the efficiency of the unloads. Figure 12 shows the efficiencies of the first 21 MWA unloads. (The efficiency of an unload is measured by the ratio of unload thruster firing time to the total thruster on-time during an unload, which includes control firings.) Note that with the maneuvers commencing in March the variation in the efficiency of the maneuvers decreased substantially as we converged on a solution for optimizing the roll/yaw controller. Figure 13 shows the improved spacecraft response for the momentum unload performed on April 14, 1998.

A set of gains that gave acceptable performance was achieved, yet one operational problem existed. There was only one set of gains for the roll/yaw controller in the flight computer and the same gains were used for both the magnetic torquers and the thrusters. Pre-launch simulations indicated that the performance with both sets of actuators was acceptable. In practice, however, these gains were acceptable for roll/yaw and nutation control using the magnetic torquers in NormalModeMWA/MTA but not for roll/yaw control with the thrusters in NormalModeREA/REA. This meant that for every MWA unload and stationkeeping maneuver it was necessary to configure the gains for REAs before the maneuver and then reconfigure them again for MTA operation before going back to NormalModeMWA/MTA. Operationally this became a very tedious process and it was decided to see if some “compromise” set of gains could be found that would meet both requirements for the roll/yaw controller.

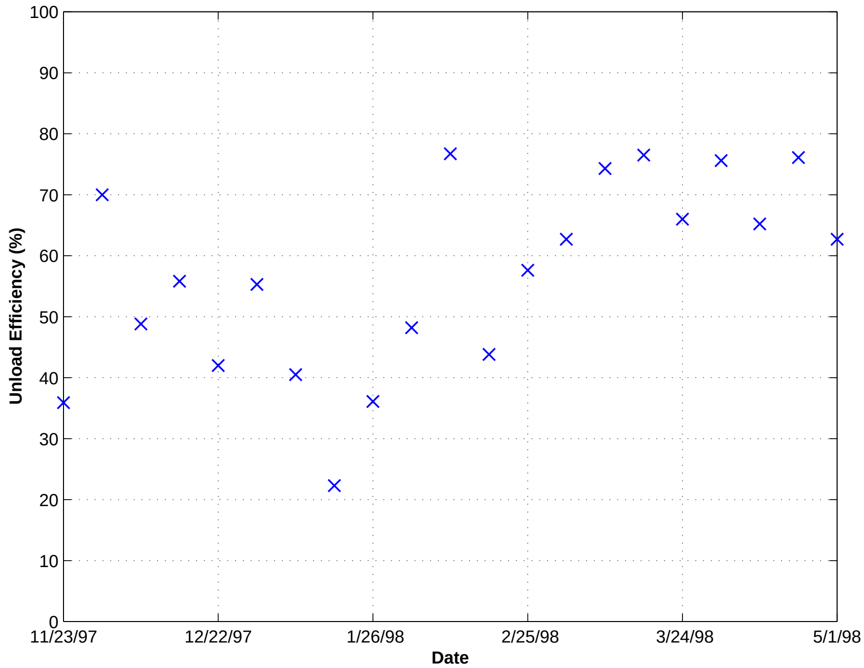


**Figure 12 Efficiency of MWA Unloads**

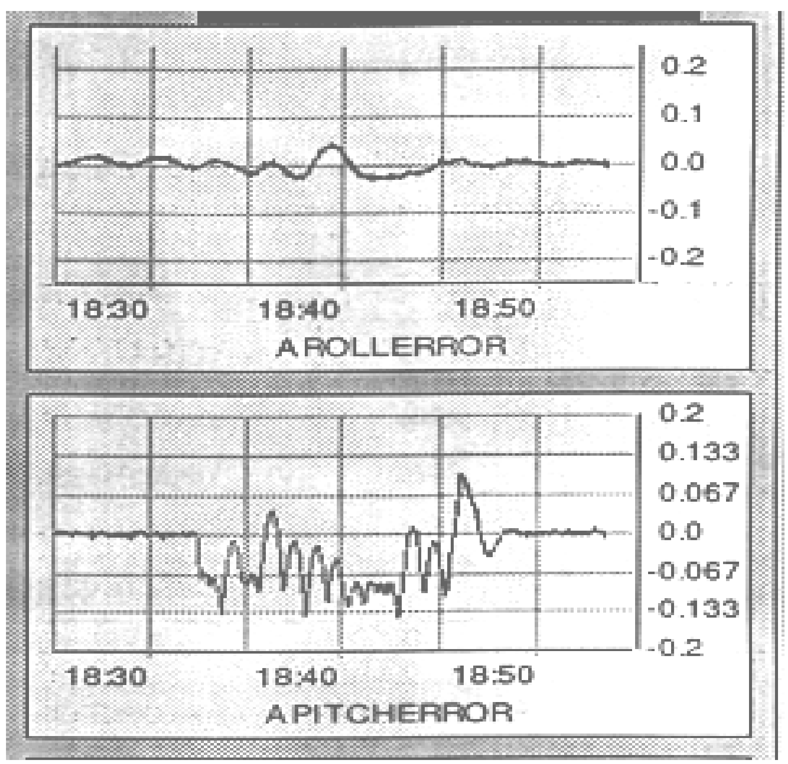


**Figure 13 Improved Roll and Pitch Errors During MWA Unload on April 14, 1998**

The goal during this redesign was to devise one set of gains that would ensure thruster firings in REA modes by commanding pulsewidths greater than the minimum and that would not saturate the MTAs when used in NormalModeMWA/MTA. Analysis quickly showed that this was not possible and it was decided to use the higher REA gains for all NormalModes with roll/yaw control. Although the torquers are saturated most of the time in NormalModeMWA/MTA and nutation is not removed as effectively as when dedicated MTA gains are used, the overall roll pointing error is better because of better low frequency disturbance rejection.

## LESSONS LEARNED

There are a number of lessons learned as a result of the early orbit operation of Indostar-1. These include the importance of accurately modeling spacecraft hardware and of taking these hardware dynamics into account when designing controllers, the utility of having multiple controllers onboard, not only for different modes, but also for different actuators, and the benefits of having easy-to-use and easy-to-modify spacecraft simulators for anomaly investigations.

The two anomalies seen in the ADACS during early operations of Indostar-1 were the result of unmodeled hardware dynamics. The unexpected delay in the earth sensors was able to be quickly discovered through analysis and then verified on the two simulators. It is important to have the ability to include and modify hardware delays in spacecraft simulators since not all delays might be known prior to launch.

As was seen during the MWA unloads, it is important to consider actuator dynamics when selecting controller gains. Both the minimum and maximum limits of the hardware should be considered. For Indostar-1, saturation of the magnetic torquers was not a problem since the pointing requirements were met and there were no integrators in the controller which could cause sluggish behavior. There was, however, the problem of having initial gains that were too low for the thrusters. The commanded impulse was less than the minimum impulse bit and consequently there was no roll control during MWA unloads.

The variation of thrust level as a function of pulse width was interesting to note and factor into the simulations but not that much of a surprise. This phenomena has been observed in the testing of the REAs when specific testing was been done to characterize control system firings using short duration pulses. This is a feature of REAs that should be taken into account when designing attitude control systems.

As a result of having to configure and then reconfigure gains for the roll/yaw controller it became evident that a better design would be to have the ability to store multiple sets of gains in the flight computer and by sending a command to point to the desired set of gains to be used. Changes have been made to PSS' SPACECRAFT CONTROL SYSTEM to allow multiple gain sets for each mode.

Finally, the use of modern software tools, such as MATLAB, and the two simulators INDOSIM and CLSIM, were invaluable in resolving the few anomalies encountered and in quickly verifying solutions.

## CONCLUSION

This paper presented the results of the early orbit operations of Indostar-1, Orbital Sciences Corporation's first geosynchronous satellite. After a flawless transfer orbit and Earth acquisition, anomalies were discovered during two maneuvers – stationkeeping and MWA unloading. It was determined that these anomalies were due to unmodeled hardware dynamics, including time delays, and corrective actions were taken. These activities revealed the benefits of being able to quickly analyze and simulate the spacecraft. After on-orbit check-out and verification, Indostar-1 went into commercial service in June, 1998.

## ACRONYM LIST

| | |
|---|---|
| ADACS | Attitude Determination and Control System |
| AMF | Apogee Motor Firing |
| DST | Dual Spin Turn |
| EHT | Electrically Heated Thruster |
| EOL | End of Life |
| ESA | Earth Sensor Assembly |
| GTO | Geostationary Transfer Orbit |
| MTA | Magnetic Torquer Actuator |
| MWA | Momentum Wheel Assembly |
| REA | Rocket Engine Assembly |
| SPM | Spin Precession Maneuver |
| SW | Software |

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