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New Mode Switching Algorithm for the JPL 70-Meter Antenna Servo Controller

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This article describes the design of new control mode switching algorithms and logic for JPL's 70-m antenna servo controller. The old control mode switching logic was reviewed and perturbation problems were identified. Design approaches for mode switching are presented and the final design is described. Simulations used to compare old and new mode switching algorithms and logic show that the new mode switching techniques will significantly reduce perturbation problems.

I. Introduction

The servo controller for the NASA/JPL 70-m-diameter antenna contains three control algorithms by which antenna position is controlled. The control algorithms provide control for antenna slewing, computer tracking, and precision tracking.

Switching between control algorithms plays a key role in tracks which require frequent slewing between target positions. Mission support and particularly Very Long Baseline Interferometry (VLBI) tracks require frequent slewing, for which antenna repositioning time is critical. Thus, not only must the control algorithms be designed to minimize antenna repositioning time, but switching between the control algorithms must be optimized to minimize perturbations.

The transition between control algorithms must be smooth to prevent acceleration/rate perturbations which can excite structural resonances, thereby increasing repositioning time and adding to mechanical wear. Reducing perturbations is particularly important for the 70-m antenna because of its low structural resonances and existing mechanical gear wear. This article describes new mode switching logic and algorithms which will minimize acceleration/rate perturbations in previous servo controllers.

II. Background

The antenna servo control system consists of a position loop closed around a rate loop. The rate loop is an analog type I controller. A rate command (voltage) from the position loop controller is compared to filtered tachometer feedback rate (voltage) to create a rate error. The rate loop adjusts the actuator command signal to null the rate error which results in moving the antenna at the commanded rate.

The position loop is closed by a digital computer, the Antenna Servo Controller (ASC). The ASC positions the antenna based on predicts (position commands). Three control algorithms reside in the ASC: (1) a slew mode called the Large Error mode; (2) a computer tracking mode called the Small Error mode; and (3) a precision tracking mode called the Precision mode. The Large Error mode is used to slew the antenna over large angular displacements. The Small Error mode is used to track predicts with encoder feedback. The Precision track mode is used to track a precision positioner, the master equatorial (ME), using an optical link (an autocollimator) as a position feedback device.

In the old Large Error mode, a digital rate servo was used to slew the antenna. The input to the rate servo was calculated from predicts and accounted for target motion. The rate servo was a state controller where the state variables were estimated by a constant gain state estimator. Encoder feedback was used to update the state estimator.

The old Small Error mode was a type II position controller. The Small Error mode also positioned the antenna based on predicts. A state controller with an added integral error state was used for the type II position controller. The state variables were estimated by a constant gain state estimator. On-axis encoder feedback was used to update the state estimator and ultimately position the antenna.

The old Precision mode used a type II position controller similar to the Small Error mode. Position feedback was provided by an autocollimator instead of on-axis encoders. The autocollimator measures optical misalignment between the antenna and the master equatorial and produces a voltage proportional to the position error. The autocollimator signal, once sampled, was digitally filtered and a secant correction was applied to the azimuth position error for high elevation angles. The autocollimator error signal was used to calculate the integral error and the position error states in the state estimator. The rest of the estimated states were calculated from the antenna's on-axis encoder feedback. Using encoder feedback for estimating the other state variables improved damping.

Each of the above control algorithms calculated a rate command needed to drive the rate loop. The rate command was limited before being converted to an analog voltage. Both rate and acceleration limiters were used to limit the rate to ±0.25 degree/sec and the acceleration to ±0.20 degree/sec^2.

Switching between the three control modes was based on the magnitude of rate commands, position errors, and autocollimator acquisition. Figure 1 presents the old switching logic state diagram. The initial state was the Small Error algorithm. A transition to the Large Error algorithm occurred when the absolute value of the new rate command was greater than a predetermined upper limit (|NEW_RATE| > U_LIMIT). The transition from the large to the Small Error algorithm occurred when the position error was less than the error limit (|POS_ERROR| < LARGE_ERROR).

Switching between the Small Error and Precision modes was more complicated. Three conditions were needed prior to switching to the Precision mode from the Small Error mode: (1) the Precision mode was commanded (i.e., PRECISION_MODE = 'TRUE'); (2) the autocollimator was within signal acquisition range (i.e., ACQUISITION = 'TRUE'); and (3) the digitally filtered autocollimator signal was small (i.e., |F_ERROR| < FILTER_LIMIT). All three conditions had to be met to switch to the Precision mode from the Small Error mode.

Conversely, when one of the following three conditions was satisfied, a switch was made from the Precision mode to the Small Error mode: (1) the Small Error mode was commanded (PRECISION_MODE = 'FALSE'); (2) autocollimator acquisition was lost (ACQUISITION = 'FALSE'); or (3) the absolute value of the calculated rate command was greater than an upper limit (i.e., |NEW_RATE| > U_LIMIT). Switching from the Large Error mode to the Precision mode and vice versa was an illegal state transition.

III. Undesirable Perturbations

The old switching logic caused rate perturbations when switching between control algorithms. Figure 2 is a strip chart record of the rate command for the old switching sequence from Small to Large and from Large to Small Error modes. The data represent the rate command measured at the output of the D/A (digital to analog) converter. Initially, the Small Error algorithm was holding position. A one degree position command created the condition (NEW_RATE > U_LIMIT) causing a switch into the Large Error mode. The rate command increased linearly to the maximum rate because of acceleration limiter saturation. As the antenna slewed, the position error was reduced. When the position error became small enough a switch was made to the Small Error mode. A transient rate command occurred because of gain differences between Small and Large Error modes.

The old switching sequence from Small to Large and from Large to Small Error modes caused undesirable perturbations. The rate perturbations are excessive and can excite structural resonances and increase gear wear.

The old switching sequence from Small to Precision and from Precision to Small Error modes was simulated. Figure 3 presents the results of the transition based on a 30 millidegree misalignment between the antenna and the ME. The rate command measured at the D/A converter was plotted versus time. Initially, the Small Error mode held position. A switch was made into Precision mode. After five seconds, a second switch was made back to Small Error mode. Simulations showed that instability existed due to misalignment errors and differences in the gain vectors between Small and Precision modes. Misalignments greater than 20 millidegrees cause instability and antenna oscillations. Misalignments less than 50 millidegrees would oscillate but eventually become stable.

The old switching sequence from Small to Precision and from Precision to Small modes caused undesirable perturbations. The transitions exhibit unstable response for large misalignment errors and perturbations which can excite structural resonances and increase gear wear.

The design goal was to develop new switching algorithms and logic which minimize slew time and rate perturbations and provide stable transitions. Therefore, the settling time required to move the antenna between targets through large angle differences will be minimized for VLBI tracking. Also, perturbations will be minimized to reduce structural resonance excitation and drive gear wear.

IV. New Design Approach

The design approach was to redesign the transition algorithms and logic. Switching between Small and Large Error modes and that between Small and Precision Error modes were treated separately. Note that the basic tracking control strategies, acceleration limiting, and rate limiting were not changed.

A. Switching Between Small and Large Error Modes

Analysis of switching logic between Small and Large Error modes showed that transition perturbations could best be improved by developing a new Large Error mode. Several control strategies for replacement of the Large Error mode were investigated, i.e., rate servos, proportional controllers, gain scheduling, and nonlinear gains. The control strategies were analyzed for smooth mode transitions, response time, stability, and simplicity. Design iterations suggested that a two-part Large Error algorithm provided the "best" switching strategy in terms of stability. First, a new Large Error mode will accelerate the antenna from the Small Error mode to the maximum slew rate. A new Modified Small Error algorithm, which will be part of the Small Error mode, will decelerate the antenna from the maximum slew rate to Small Error algorithm tracking.

Accelerating from the Small Error mode to maximum slew rate will be accomplished by using a predetermined acceleration profile. This profile will minimize rate perturbations, provide known acceleration time, and smooth transitions.

Decelerating from maximum slew rate to Small Error mode tracking will be accomplished by a modified Small Error algorithm which eliminates the integral error state. The Modified Small Error algorithm would then be a type I controller. Transition to the type II Small Error algorithm is accomplished by adding the integral error state. The transition to the Small Error mode from the modified algorithm will be smooth and stable with minimal settling time.

B. Switching Between the Small Error and Precision Modes

Both gain matching between Small and Precision modes and new switching algorithms were investigated to minimize rate perturbations during mode switching. Matching small and precision mode state feedback gain vectors improved transition performance but did not improve transition stability. Thus, a switching algorithm was needed. Potential transition algorithms included gain scheduling, a rate servo, and filtering the position error. Investigations showed that filtering position error significantly improved stability and provided smooth mode switching.

V. Detailed Design of Mode Switching Algorithms

The new mode switching algorithms and logic were designed to switch between Small and Large Error modes and between Small Error and Precision modes. The switching logic determines when to switch to a different control algorithm while the mode switching algorithms control the transition between control algorithms.

The new 70-m antenna control algorithm switching logic is presented in Fig. 4. The Small Error mode is the initial state in the state diagram. Switching to the Large Error mode from the Small Error mode occurs when a new position command requires the antenna to move over a large angle. New position commands are received and evaluated once per second to determine if a slew is required. Transitions from the Large to the Modified Small Error algorithm occur when the maximum slew rate is attained. All transitions between the Small Error and Precision modes remain the same as the old transition logic.

Three new mode switching algorithms were developed: a Large Error algorithm, a Modified Small Error algorithm, and a digital filter between Small Error and Precision mode transitions. The new Large Error algorithm has two parts: (1) to accelerate the antenna to the maximum slew rate (this is called the new Large Error mode); and (2) to decelerate the antenna from maximum slew rate and transition into the Small Error algorithm (this is part of the new Small Error mode).

The purpose of designing a new Large Error mode is to smoothly accelerate the antenna to the maximum slew rate. When a slew is required, a predetermined acceleration profile is used to accelerate the antenna from the tracking rate to the maximum slew rate in the appropriate direction.

The acceleration profile is generated in real time by using a digital filter. Initializing the filter with the last rate command and commanding the maximum rate produce a step response referenced to filter initialization. A third order Bessel digital filter was used as the Large Error algorithm rate command filter. The advantages are twofold: a small overshoot due to a step in rate and a smooth acceleration profile. The bandwidth of the filter is selected such that the ratio of maximum rate to maximum acceleration is less than or equal to the ratio of the rate limit to the acceleration limit. The 70-m antenna has a rate limit of ±0.25 degree/sec and an acceleration limit of ±0.20 degree/sec^2. Thus, the maximum acceleration to rate ratio must be less than or equal to 0.8.

Figures 5 and 6 show the rate step response and its derivative, respectively, for a Bessel filter with a 1 rad/sec bandwidth. The step response shows how the rate command (filter output) accelerates to the maximum rate and has a 4 percent overshoot. The derivative of the step response (in Fig. 6) shows the acceleration profile by which the antenna is accelerated. The acceleration to rate ratio is 0.8.

Once the maximum rate is achieved in the Large Error mode, a transition is made to a type I controller. For simplicity, the tracking Small Error algorithm is used for the type I controller with the integral error limited to zero which effectively "turns off" the integrator. As a result, the tracking controller acts as a type I controller and smoothly decelerates the antenna. When the position error is small (a 30 millidegree threshold is used), the integral error is "turned on" and tracking with a type II controller begins. Setting the integral error limit to a finite value prevents oscillations from occurring when tracking rates vary.

The transitions between Small Error and Precision modes were also improved by digital filtering. The same Bessel filter described above was used to filter the position and autocollimator errors during transitions. Figure 7 describes the Small-to-Precision and Precision-to-Small-Error mode state switching diagram. When a Small Error to Precision transition is made, the mode switching filter is initialized with the last position error. The new position error (or equivalently the autocollimator error) is calculated. The new position error is filtered by the transition filter. This filtered error is used by the precision control algorithm to position the antenna. When the filtered error is greater than the position error, the filter is "turned off." The same procedure is used when switching from the Precision mode to the Small Error mode.

VI. Simulation Results

The new transition algorithms and logic were coded in the 70-m antenna simulation software and simulated using a Monte Carlo simulation. Mode switching simulations between Small and Large Error modes and between Small and Precision modes were made.

A mode switching simulation was made between the new Small and Large Error modes to demonstrate switching logic and algorithms. Figure 8 presents the simulated rate command measured at the output of the D/A converter. Initially, the Small Error algorithm was holding position. A one degree position command caused a switch into the Large Error algorithm (the new Large Error mode). The rate command smoothly accelerated to the maximum rate. At the maximum rate, the transition was made to the Modified Small Error algorithm (part of the new Small Error mode). No rate perturbations occurred at the transition because the rate command produced by the Modified Small Error algorithm is greater than the maximum slew rate and is thus limited to the maximum slew rate. The rate limiter effectively eliminates transition perturbations.

As the position error decreased, the rate command dropped below the maximum slew rate. After the position error became small enough, a transition was made to the Small Error algorithm by "turning on" the integral error state.

Comparing Fig. 8 to the results of the old mode switching logic in Fig. 2 shows that a significant improvement was attained in the number of switching perturbations. The only discontinuity produced by the new mode switching occurs when initial deceleration from the maximum slew begins. At this point, the acceleration is discontinuous and has a jump which, at most, is equal to the acceleration limit. However, this discontinuity is acceptable.

The new mode switching algorithm between Small Error and Precision modes was also simulated. Figure 9 presents the simulated rate command measured at the output of the D/A converter. Initially, the Small Error algorithm was holding position. A transition was immediately made to the Precision mode. A second transition was later made from Precision to the Small Error mode. A 30 millidegree misalignment error between the antenna and the ME was assumed for both transitions. Simulations showed that transition instability due to misalignment errors was reduced. Misalignment errors of up to 50 millidegrees were simulated and were stable. With 50 millidegree misalignments the acceleration limiter started to become saturated but the control algorithm remained stable.

VII. Summary

New mode switching algorithms and logic were designed for switching between 70-m control algorithms. Transitions to the Large Error algorithm are made when the position command requires a large angular motion. A transition from the Large to Small Error mode is made when the position error is small. All transition logic between the Small Error and Precision modes remains the same as the old mode switching logic.

A new Large Error algorithm was designed. The Large Error algorithm was separated into two parts: the Large Error mode and the Modified Small Error algorithm. The Large Error mode accelerates the antenna from the Small Error mode to the maximum slew rate by using a digital Bessel filter. The Modified Small Error algorithm (which is also part of the new Small Error mode) is a type I controller. It decelerates the antenna from the maximum slew rate and transitions into the type II Small Error algorithm by "turning on" the integral error state in the state controller. Simulations showed the new mode switching between Small and Large Error modes provide smoother transitions with fewer acceleration/rate perturbations.

The mode switching between Small Error and Precision modes was improved by using the same Bessel filter as in the Large Error mode and by matching control gain. The misalignment error was filtered to provide smoother and more stable transitions. Simulations of the Small and Precision mode switching showed improved transition stability, robustness, and smoothness.

The new servo controller mode switching logic and algorithms for the 70-m antenna provide better overall performance than the old mode switching logic. The better performance will reduce potential structural resonance excitation and gear wear.

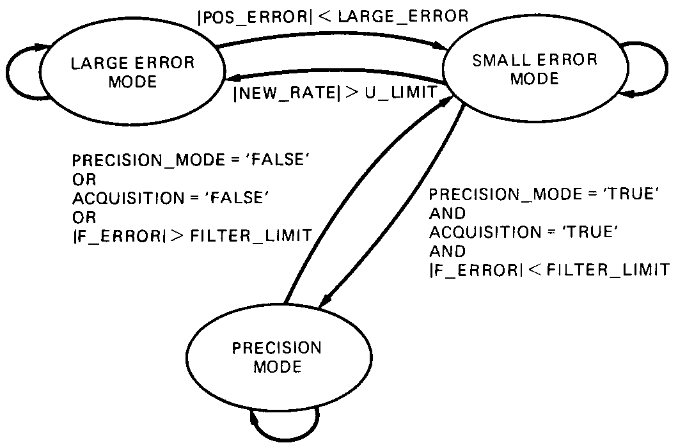

Fig. 1. Old control mode switching logic

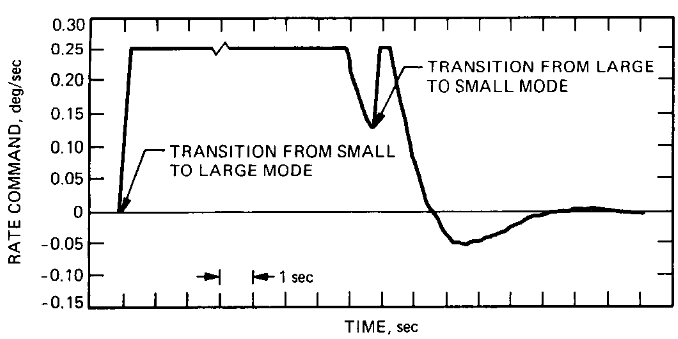

Fig. 2. Mode switching between Small and Large Error modes

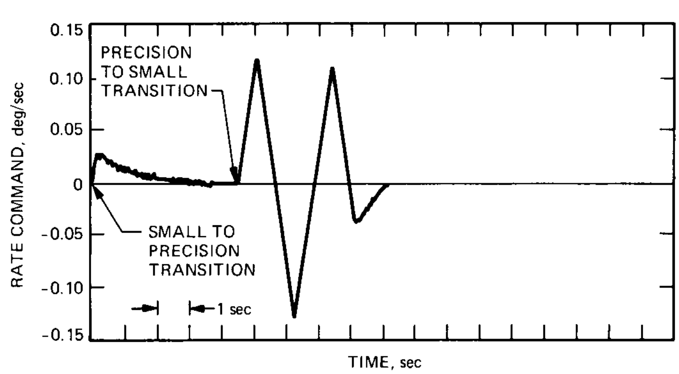

Fig. 3. Mode switching between Small Error and Precision modes (30-millidegree misalignment assumed)

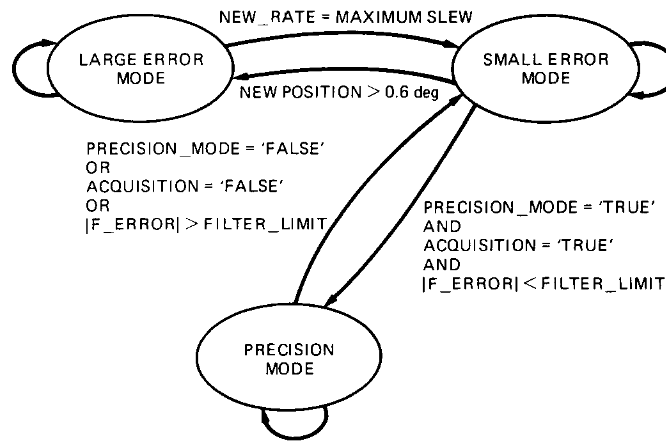

Fig. 4. New 70-m control mode switching logic

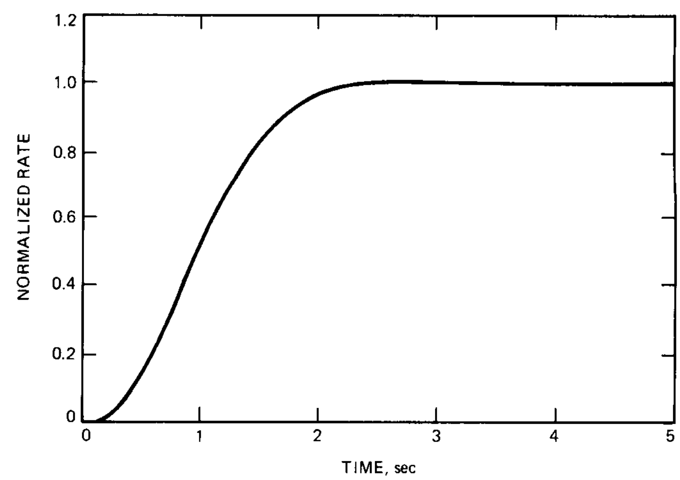

Fig. 5. Normalized Bessel filter step response (third-order Bessel filter; 1 rad/sec cutoff frequency)

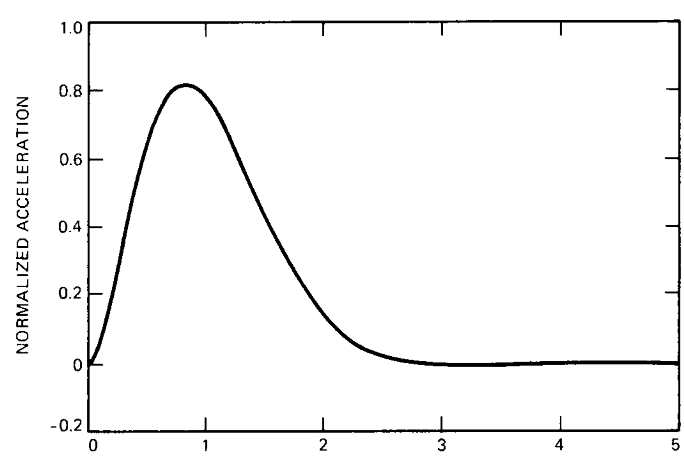

Fig. 6. Derivative of normalized Bessel filter step response (maximum acceleration is 80 percent maximum rate)

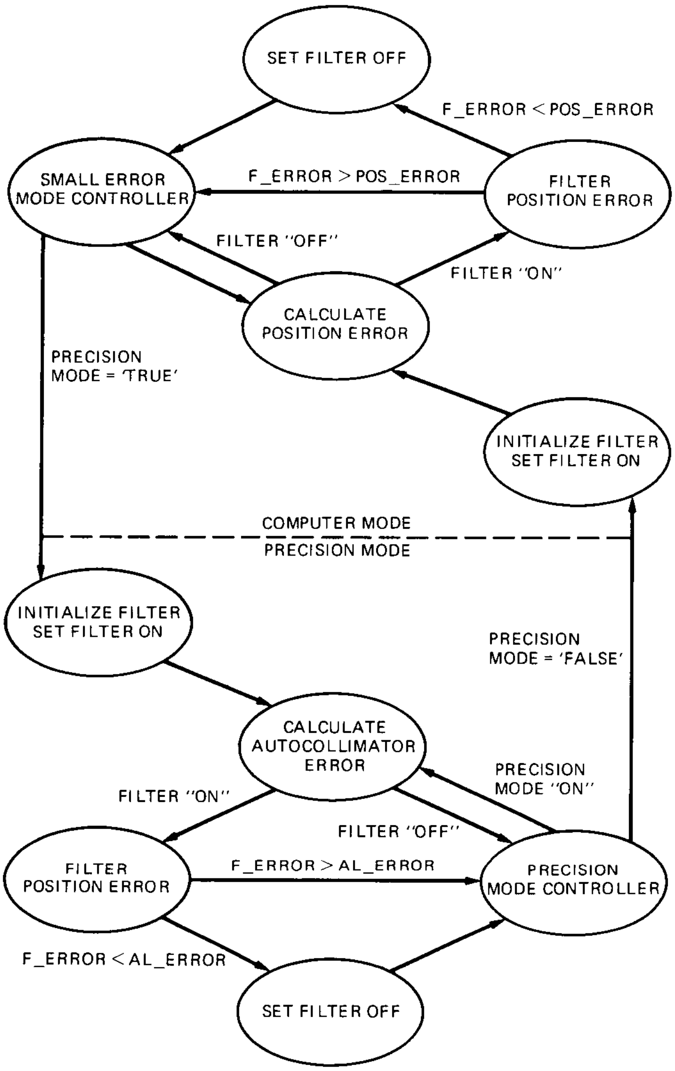

Fig. 7. New 70-m mode switching logic between Small Error and Precision modes

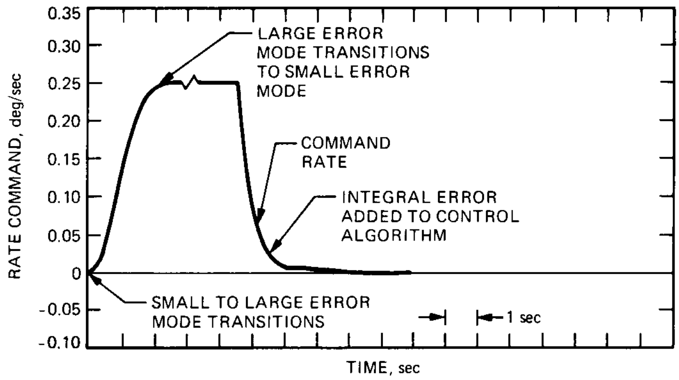

Fig. 8. New 70-m mode switching between Small and Large Error modes

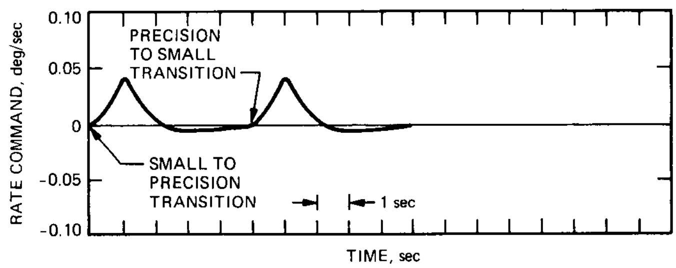

Fig. 9. New 70-m mode switching between Small Error and Precision modes (30-millidegree misalignment assumed)