Command Preprocessor for the Beam-Waveguide Antennas

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The high-gain linear quadratic Gaussian (LQG) controllers, designed for 32-GHz (Ka-band) monopulse tracking, have small tracking errors and are resistant to wind disturbances. However, during antenna slewing, they induce limit cycling caused by the violation of the antenna rate and acceleration limits. This problem can be avoided by the introduction of a command that does not exceed the limits. The command preprocessor presented in this article generates a command that is equal to the original command if the latter does not exceed the limits and varies with the maximal (or minimal) allowable rate and acceleration if the limits are met or exceeded. It is comparatively simple since it requires only knowledge of the command at the current and the previous time instants, while other known preprocessors require knowledge of the terminal state and the acquisition time. Thus, the presented preprocessor is more suitable for implementation into the antenna control software. In this article, analysis of the preprocessor is presented. Also, the performances of the preprocessor itself and of the antenna with the preprocessor are illustrated with typical antenna commands.

I. Introduction

Recently designed high-gain linear quadratic Gaussian (LQG) controllers improved Deep Space Network (DSN) antenna pointing precision. However, their implementation is limited due to antenna limit cycling during slewing operations, as reported in [1]. The limit cycling is due to the nonlinear dynamics caused by imposed antenna rate and acceleration limits. In order to avoid the cycling, one can either apply gain scheduling (different controller gains for tracking and for slewing) or use a command preprocessor (CPP). The preprocessor is computer software that generates a modified command, identical to the original one, if the rate and accelerations are within the limits and a command of maximal (or minimal) rate and acceleration when the limits are met or violated.

A preprocessor algorithm was developed by Tyler [2]. In order to generate a modified trajectory, this algorithm requires advance knowledge of the final state (i.e., position and rate) of the antenna and the time required to reach the final state. In many cases, the final state is not known (for example, in the case of acquiring a moving target), and the time of acquisition cannot be precisely determined. Thus, two requirements—knowledge of the acquisition state and time—make this algorithm useful in selected applications only. The algorithm proposed below does not require knowledge of the above parameters. It

[1] Communications Ground Systems Section.

determines the preprocessed command based on the current and previous values of the original command. The basic idea of this preprocessor was previously described in [3].

II. CPP Description

The block diagram of the CPP is shown in Fig. 1. Its main line consists of a derivative, an integrator, and rate and acceleration limiters. The proportional feedback loop has variable gain k_i; the gain depends on the preprocessor error, e_i. The sampling time is denoted T (where $T = 0.02$ s); the command at the ith time instant, $t = iT$, is denoted r_i; the command rate is v_i; the preprocessed command is denoted r_{pi}; the input to the integrator is u_i; and the preprocessor error is $e_i = r_i - r_{pi}$.

Consider a case wherein the command r_i does not exceed the rate and acceleration limits. In this case, the system is linear, and the rate and acceleration limiters in Fig. 1 are replaced with a unit gain. For the linear case, the equations are

$$r_{pi} = r_{pi-1} + Tu_i \tag{1a}$$

for the integrator,

$$v_i = \frac{r_i - r_{i-1}}{T} \tag{1b}$$

for the derivative,

$$e_i = r_i - r_{pi} \tag{1c}$$

for the error, and

$$u_i = k_i e_{i-1} + v_i \tag{1d}$$

for the integrator input. Combining the above equations, one obtains

$$r_{pi} - r_{pi-1} + Tk_i r_{pi-1} = r_i - r_{i-1} + Tk_i r_{i-1} \tag{2}$$

The above equation shows that $r_i = r_{pi}$ for zero initial conditions. In consequence, if the preprocessed command reaches the original command, it follows exactly the latter one.

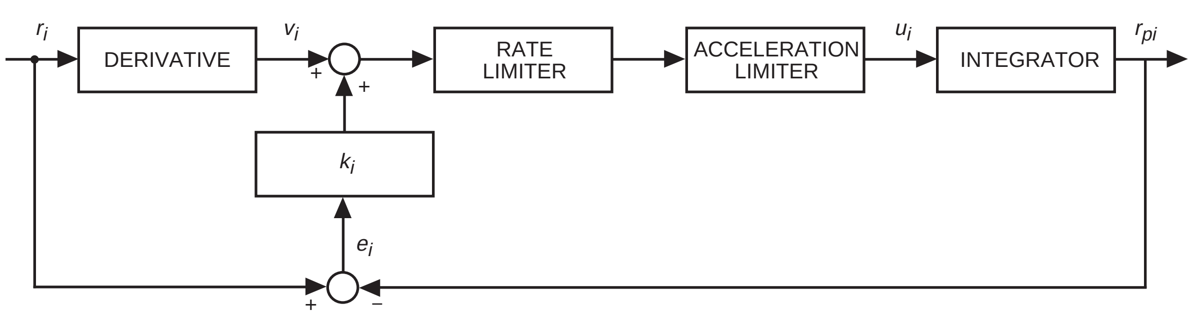

Fig. 1. The command preprocessor.

The transient motion of the CPP has to be investigated. In order to do this, Eq. (2) can be rewritten as

$$e_i = \alpha_i e_{i-1} \tag{3a}$$

where

$$\alpha_i = 1 - T k_i \tag{3b}$$

This is an equation of the transient dynamics of the CPP error. From Eq. (3a), it follows that the system is stable if $|\alpha_i| < 1$. For $0 < \alpha_i < 1$, there is no overshoot, and for $-1 < \alpha_i < 0$, the transient is oscillatory, $i = 1, 2, \cdots$. Consider further only positive α_i, the case with no overshoot of the preprocessed command over the original command. Note in this case that the smaller the gain α_i is, the quicker the error dies down. The gain k_i controls the value of α_i [see Eq. (3b)]; therefore, for large-gain k_i, the transient between the original and the preprocessed command is strongly damped.

However, too large of a gain may cause the violation of the rate and/or acceleration limits, which, in turn, causes nonlinear behavior and increases the error. In order to avoid this situation, the variable gain is introduced. It depends on the error e_i. The gain is large for small error, and smaller for large error. It is assumed in the form

$$k_i = k_o + k_v e^{-\beta|e_i|} \tag{4}$$

where k_o is the constant part of the gain, k_v is the variable part of the error, and β is the error exponential. The plot of $k_i(e_i)$ for $k_o = 1$, $k_v = 5$, and $\beta = 10, 20, 40$, and 100 is shown in Fig. 2. From this figure, one can see that, for a small error, the gain reaches its maximal value, and for the large error, the gain is minimal.

Step inputs are used as a mean of determining the variable-gain parameters. For the antenna sampling time $T = 0.02$ s and the rate limit $v_{max} = 0.8$ deg/s, the maximal step that does not violate the rate

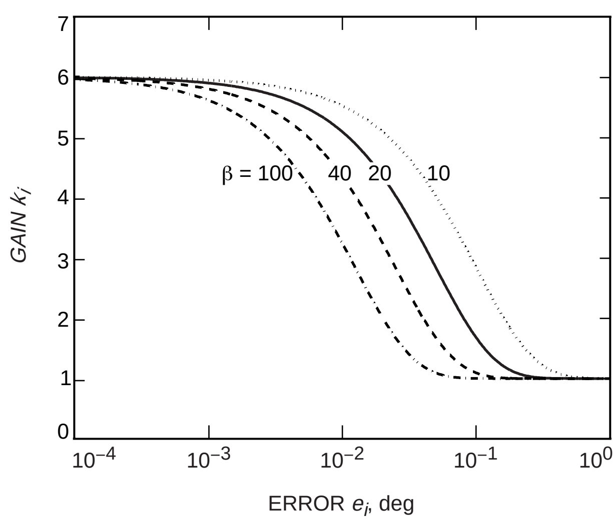

Fig. 2. The CPP gain versus the CPP error with β = 10, 20, 40, and 100.

limit is $v_{max}T = 0.016$ deg. On the other hand, our measurements show that the step responses above 0.15 deg already show nonlinear behavior. The gain k_o, the lower value of k_i, was assumed to be 1 in order to perform properly for small steps of 0.016 deg or smaller. The upper value of the variable gain, $k_o + k_v$, is assumed to be 6 for acceptable performance at large steps of 0.15 deg or larger. This process is illustrated later. For the error within the interval [0.016, 0.150] deg, the gain varies from its maximal to its minimal value. The exponential constant β defines this gain variation. We have chosen $\beta = 20$ since, for this value, the gain changes from its maximal to minimal value within the segment of [0.016, 0.150] deg.

The nonlinear behavior of the CPP mimics the antenna nonlinear dynamics. Namely, in the CPP shown in Fig. 1, the integrator is a model of an ideal (or rigid) antenna; the derivative represents the antenna feed-forward gain (that perfectly inverses the rigid antenna model); the gain k_i represents the antenna controller; and the rate and acceleration limiters are located at places corresponding to the antenna locations. In this way, the nonlinear dynamics of the CPP are close to the desirable dynamics of an antenna.

III. CPP Dynamics

The CPP dynamics are checked for the three scenarios typical for DSN antennas:

(1) Step responses, both small and large. Small steps do not violate the limits; large steps do.

(2) Rate offsets.

(3) Acquisition and tracking of a typical trajectory.

We also will consider two types of CPP:

(1) One with constant gain that is k_i for all i.

(2) One with variable gain, as in Eq. (4), with $k_o = 1, k_v = 5$, and $\beta = 20$.

The rate and acceleration limits of the antenna are 0.8 deg/s and 0.4 deg/s^2, respectively, and the rate and acceleration limits of the CPP were 90 percent of the antenna limits.

For the large step of 10 deg, the preprocessed command, its rate, and its acceleration are shown in Figs. 3(a) through 3(c) (for the constant-gain CPP) and in Figs. 3(d) through 3(f) (for the variable-gain CPP). The figure shows little difference between the preprocessed command with the constant-gain CPP and with the variable-gain CPP. Both preprocessed commands begin with the maximal acceleration until they reach the maximum rate, then continue with the maximal (and constant) rate, and finally slow down with the minimal deceleration. After reaching the steady-state value of 10 deg, the error between the original and the preprocessed command is zero.

For a small step of 0.01 deg, the preprocessed command, its rate, and its acceleration are shown in Figs. 4(a) through 4(c) (for the constant-gain CPP) and in Figs. 4(d) through 4(f) (for the variable-gain CPP). The figure shows a significant difference between the preprocessed commands with constant and variable gain. Comparatively low constant gain ($k_o = 1$) results in the slow response of the CPP, namely a 6-s settling time. The variable-gain CPP generates a command with a 1-s settling time due to the high-gain value for the small error. The settling time is an important factor when the antenna dynamics are considered (see Section IV).

A rate offset was simulated and is shown in Fig. 5. The preprocessed commands (for the constant- and variable-gain CPPs) are almost the same. Small differences are in the rate and acceleration profiles.

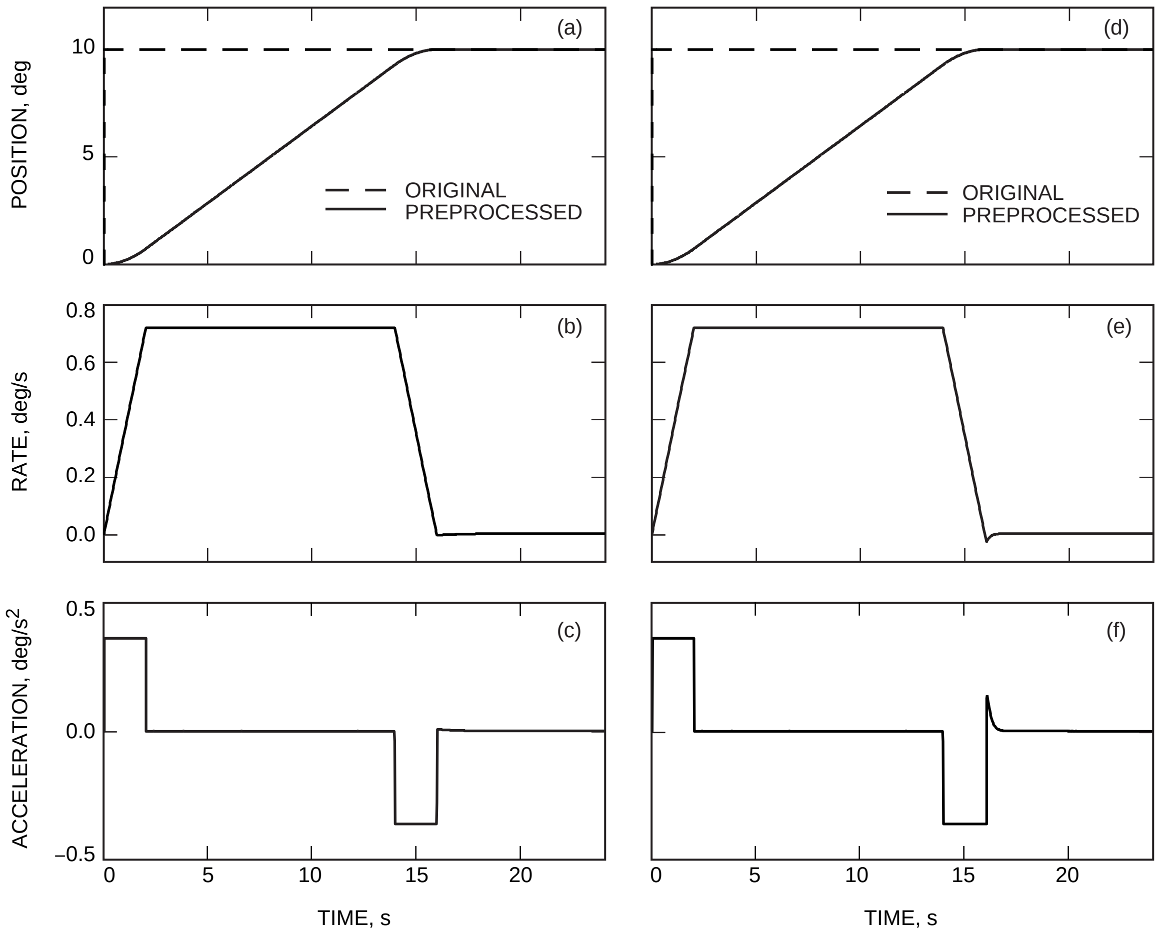

Fig. 3. The preprocessed large-step commands for the constant-gain CPP (a) command, (b) rate, and (c) acceleration, and for the variable-gain CPP (d) command, (e) rate, and (f) acceleration.

Finally, a typical azimuth trajectory acquisition and tracking by the CPP is shown in Fig. 6(a). The antenna position at the initial time is 14 deg, while the target position is at 24 deg. The target is acquired in 15 s with maximal speed [see Fig. 6(b)] and maximal acceleration [see Fig. 6(c)], and also with very small overshoot [cf. Fig. 6(a)]. The CPP error (the difference between the original and the preprocessed trajectory) after the acquisition is virtually zero.

IV. Dynamics of the Antenna With the CPP

In this section, the dynamics of the antenna with the constant and variable CPPs are presented. The antenna azimuth model is obtained from the field data collected at DSS 54 (Madrid). For this model, a high-gain LQG controller (of proportional gain 9.8 and integral gain 8.0) was designed. This controller was tested but not implemented due to limit cycling during antenna slewing. The following simulations show that the presented CPP prevents the cycling.

The response of the constant-gain CPP to the small-step input of 0.01 deg is shown in Fig. 7(a) (dashed line). It is a slow response of 6 s with no overshoot. In this case, the antenna follows closely the preprocessed command. The response of the variable-gain CPP to the small-step input is shown in Fig. 7(b). It is a rapid response of less than 1 s. The antenna follows the preprocessed command with the overshoot. This is similar to the response to the nonprocessed step of 0.01 deg.

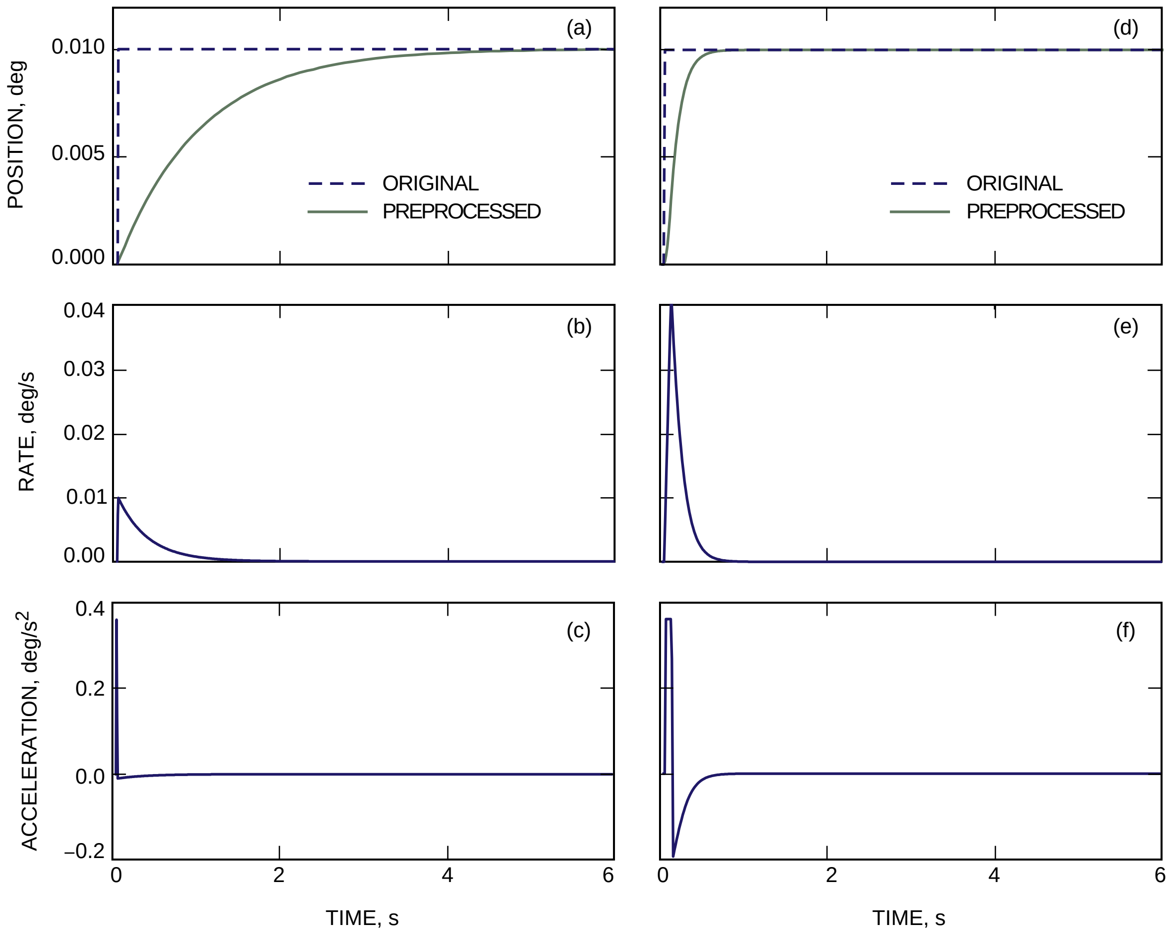

Fig. 4. The preprocessed small-step commands for the constant-gain CPP (a) command, (b) rate, and (c) acceleration, and for the variable-gain CPP (d) command, (e) rate, and (f) acceleration.

The responses of the constant-gain and variable-gain CPPs to a large-step input of 10 deg are shown in Fig. 8(a) (dashed line) along with the antenna responses (solid line). They are practically identical and have no overshoot. For comparison, the response of the same antenna to a nonprocessed step is shown in Fig. 8(b). Clearly, unstable limit cycling similar to the one previously observed during the antenna controller tests is visible.

The antenna responses to the preprocessed rate offset and to the preprocessed azimuth trajectory can be separated into two segments: a linear one (where the original command does not exceed the rate and/or acceleration limits) and a nonlinear one (where it does). Within the nonlinear segment, the antenna response is very close to the preprocessed command, and in the linear segment, the antenna response is identical to the response to the original command. This is illustrated in Fig. 9, where the antenna response to the preprocessed azimuth trajectory is as was shown in Fig. 6(a). In 15 s, the antenna acquires the original trajectory, since it follows very closely the preprocessed trajectory. In Figs. 9(a) and 9(b), the preprocessed trajectory is denoted with a dashed line and the antenna response with a solid line; both lines overlap.

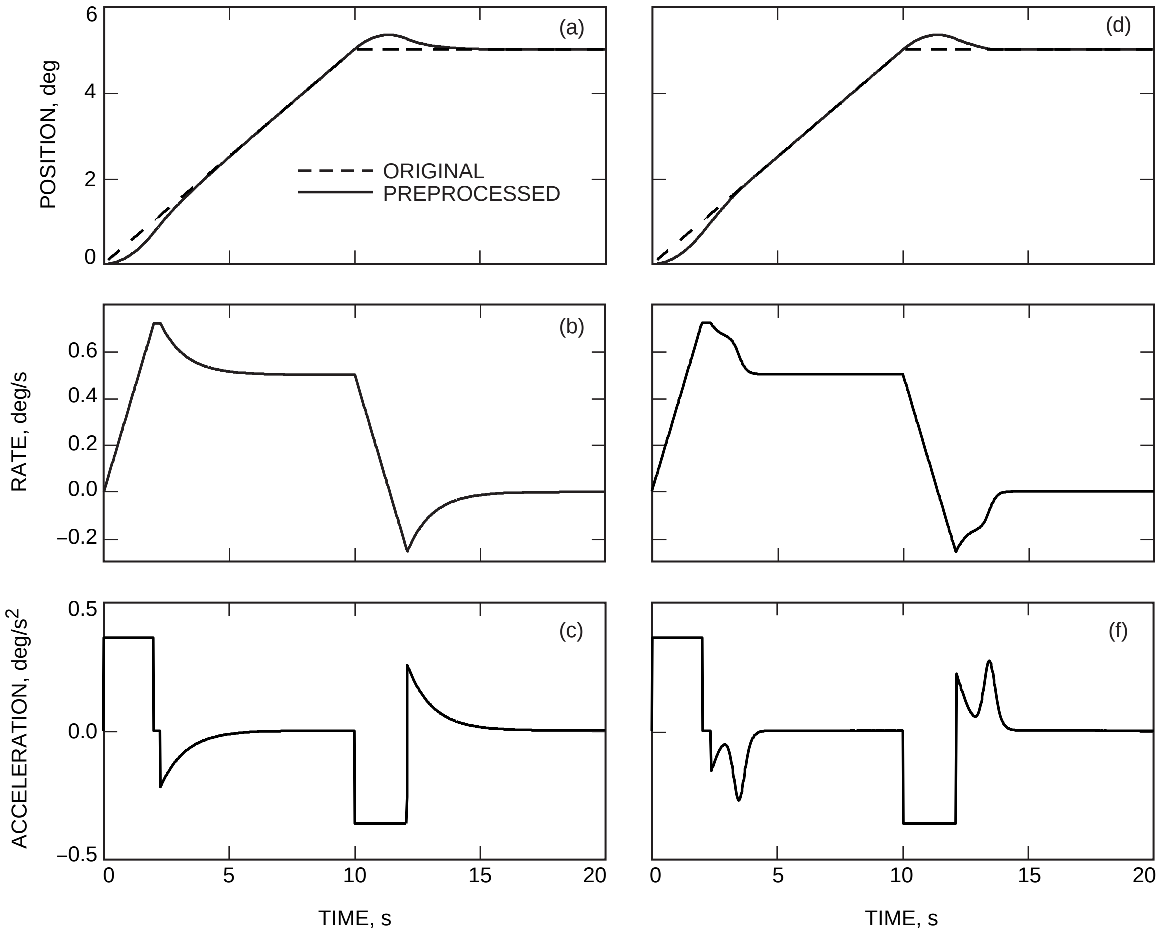

Fig. 5. The original and preprocessed rate offsets for the constant-gain CPP (a) command, (b) rate, and (c) acceleration, and for the variable-gain CPP (d) command, (e) rate, and (f) acceleration.

V. Conclusions

The proposed CPP is a computer algorithm that processes the antenna command. The processed command is identical to the original one if the latter does not exceed the antenna rate and acceleration limits. If the limits are exceeded, the preprocessed command variations are subject to the maximal or minimal rates and accelerations. The proposed preprocessor algorithm is simple since it does not require knowledge of future antenna positions. Rather, it uses the current and previous values of the original command. The simulation results show that the CPP commands make the high-gain LQG controllers stable in slewing and accurate in tracking.

References

[1] W. Gawronski, H. G. Ahlstrom, Jr., and A. B. Bernardo, "Design and Performance of the DSS-14 Antenna Controller," *The Telecommunications and Mission Operations Progress Report 42-135, July–September 1998*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–9, November 15, 1998. http://tmo.jpl.nasa.gov/tmo/progress_report/42-135/135E.pdf

[2] S. R. Tyler, "A Trajectory Preprocessor for Antenna Pointing," *The Telecommunications and Data Acquisition Progress Report 42-118, April–June 1994*, Jet Propulsion Laboratory, Pasadena, California, pp. 139–159, August 15, 1994. http://tmo.jpl.nasa.gov/tmo/progress_report/42-118/118E.pdf

[3] W. K. Gawronski, C. S. Racho, and J. A. Mellstrom, "Application of the LQG and Feedforward Controllers to the Deep Space Network Antennas," *IEEE Transactions on Control System Technology*, vol. 3, no. 4, pp. 417–421, December 1995.

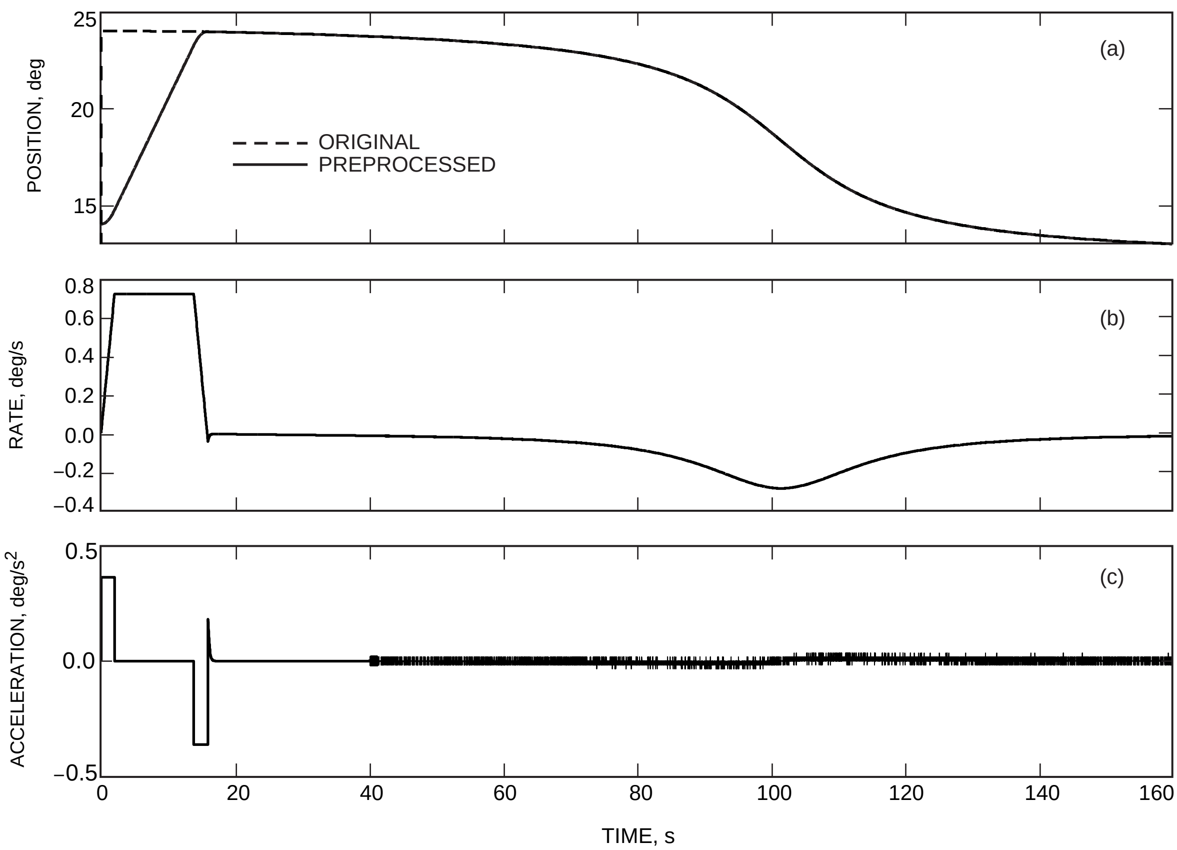

Fig. 6. The original and preprocessed azimuth trajectory: (a) command, (b) rate, and (c) acceleration.

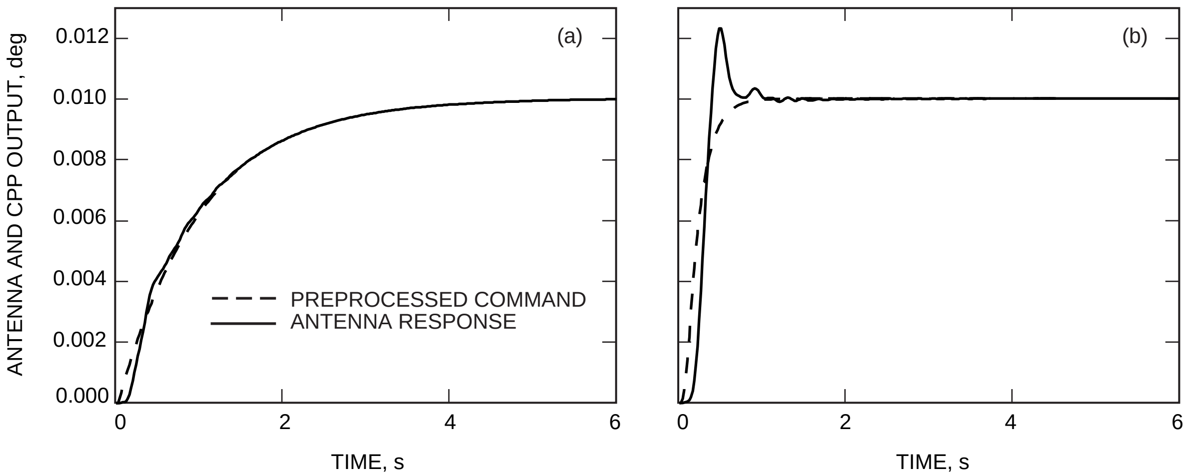

Fig. 7. The antenna response to the preprocessed small steps for the (a) constant-gain CPP and the (b) variable-gain CPP.

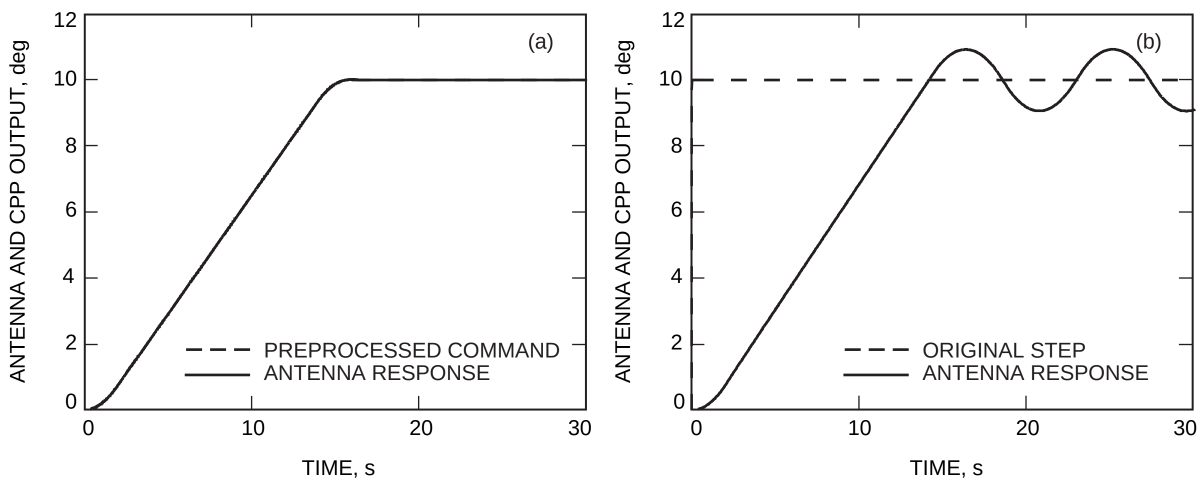

Fig. 8. The antenna response to the preprocessed large steps for the (a) preprocessed command and the antenna response and the (b) original step and the antenna response.

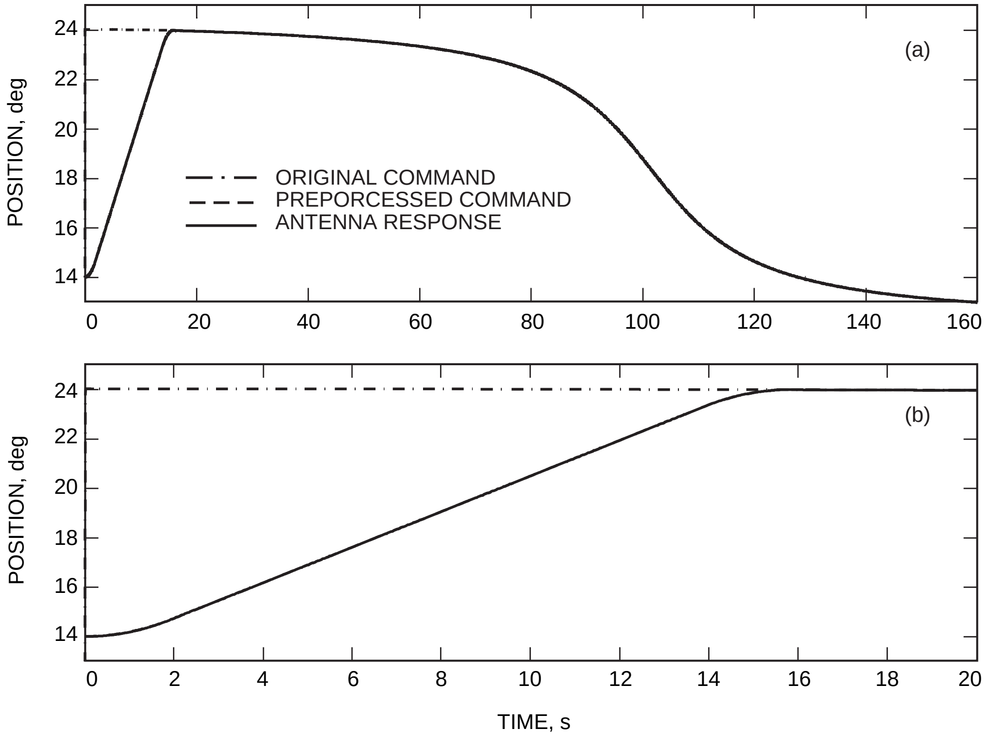

Fig. 9. Azimuth tracking of the original command, the preprocessed command, and the antenna response for the (a) total trajectory and (b) acquisition segment.