Feed-Forward Control Upgrade of the Deep Space Network Antennas

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In order to improve the accuracy of high-rate tracking of NASA's DSN antennas, the position-loop controller has been upgraded with a feed-forward loop. Conditions for perfect and approximate tracking with the feed-forward loop are presented. The feed-forward loop improves tracking performance and preserves wind disturbance rejection properties of the previous closed-loop system.

Pointing accuracy of a proportional and integral (PI) control system for the DSN antennas [1] is satisfactory for slow-tracking antennas but significantly deteriorates when tracking fast-moving objects. In order to improve the tracking accuracy in the latter case, a PI control system has been augmented with a feed-forward loop, as shown with the block diagram in Fig. 1. In this diagram, G_p, G_c, G_f, and G_w denote transfer functions of the antenna's rate loop, PI controller, feed-forward gain, and wind disturbance, respectively; and r is a command, y is output (elevation and azimuth angles), e is tracking error in azimuth and elevation, u is plant input, and w is wind disturbance. The plant transfer function $G_p(\omega)$ is a 2×2 matrix, with elevation and azimuth rates as inputs and elevation and azimuth angles as outputs.

In order to analyze the impact of the feed-forward gain on the closed-loop system performance, the transfer function from the command r and wind disturbance w to the tracking error e was derived. From Fig. 1, one obtains

$$e = r - y \tag{1a}$$

$$y = G_p u + G_w w \tag{1b}$$

$$u = G_f r + G_c e \tag{1c}$$

Assuming $I + G_p G_c$ to be nonsingular and denoting that $G_o = (I + G_p G_c)^{-1}$, from Eqs. (1a), (1b), and (1c), one obtains

$$e = G_o(I - G_p G_f)r - G_o G_w w \tag{2}$$

From the above equation one obtains perfect tracking (i.e., $e = 0$) in the absence of wind disturbances for the feed-forward gain G_f such that

$$G_p(\omega) G_f(\omega) = I \tag{3}$$

In the case of the DSN antennas, the condition (3) can be satisfied in a certain frequency range only. Simply by inspection of the magnitudes of the plant transfer function in Fig. 2(a–d), one can see that for frequencies $0 \leq \omega \leq 2\pi$

rad/sec ($0 \leq f \leq 1$ Hz), the plant transfer function G_p can be approximated with an integrator

$$G_p \cong G_{po} = (j\omega)^{-1} I_2 \quad \text{for } 0 \leq \omega \leq 2\pi \text{ rad/sec} \tag{4}$$

Thus, the feed-forward differentiator

$$G_f = j\omega I_2 \tag{5}$$

will satisfy Eq. (3) in the frequency range $0 \leq \omega \leq 2\pi$ rad/sec. In Fig. 2(a), the diagonal terms of the differentiator transfer function of Eq. (5) are shown with dotted lines. Their inverses (dashed lines) are equal to the plant transfer function, as in Fig. 2 for frequencies up to 1 Hz. The off-diagonal terms of Eq. (5) (transfer functions from elevation command to azimuth position, and from azimuth command to elevation position) should be zero; actually, they are small for frequencies up to 1 Hz, as in Fig. 2(b) and Fig. 2(d).

The closed-loop transfer functions for a system with and without the feed-forward gain are compared in Fig. 3. Figures 3(a) and 3(c) show that for frequencies up to 1 Hz, the system with the feed-forward gain has superior tracking properties when compared with the system without feed-forward gain. This is confirmed by tracking simulations with a trajectory like that in Figs. 4(a) and 4(b). The DSS-13 antenna, with the proportional gain $k_p = 0.5$, and the integral gain $k_i = 1.8$ in azimuth and elevation, was investigated. The tracking errors in elevation and cross-elevation are compared for the antenna with the feed-forward loop (Fig. 5) and without the feed-forward loop (Fig. 6). A significant improvement in tracking accuracy for the system with the feed-forward loop was observed, namely, from 73.1 to 1.4 mdeg in elevation, and from 60.1 to 0.2 mdeg in cross-elevation. However, the high-frequency components of the command are strongly amplified for the system with feed-forward gain when compared with the system without feed-forward gain. This effect can be observed from the transfer function plots in Fig. 3, where the resonance peaks of the system with feed-forward gain are much higher than the ones of the system without feed-forward gain. Also the intensive oscillatory motion in the pointing error plots (see Fig. 5) is observed. As a result, any sharp change in the command may cause excessive vibrations of the antenna.

Despite the increased sensitivity to the command inputs, the disturbance rejection of the antenna with feed-forward gain remains the same as that for the antenna without feed-forward gain. This follows from Eq. (2), where it is shown that the tracking error e due to wind disturbance w is independent of the feed-forward gain G_f. Thus the pointing errors due to wind gust disturbances are comparable with the results obtained for the DSS-13 antenna with the PI controller (see [2]).

References

[1] W. Gawronski and J. A. Mellstrom, "Modeling and Simulations of the DSS 13 Antenna Control System," *TDA Progress Report 42-106*, vol. April–June, Jet Propulsion Laboratory, Pasadena, California, pp. 204–248, August 15, 1991.

[2] W. Gawronski, B. Bienkiewicz, and R. E. Hill, "Pointing-Error Simulations of the DSS-13 Antenna Due to Wind Disturbances," *TDA Progress Report 42-108*, vol. October–December, Jet Propulsion Laboratory, Pasadena, California, pp. 109–134, February 15, 1992.

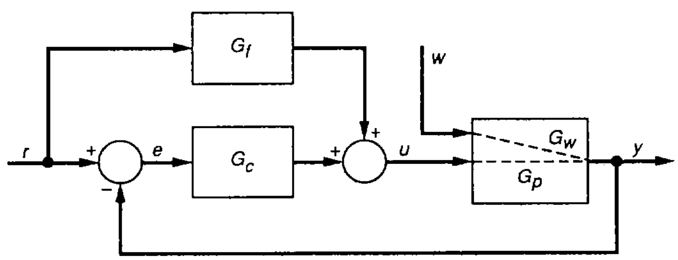


Fig. 1. Antenna control system with the feed-forward loop.

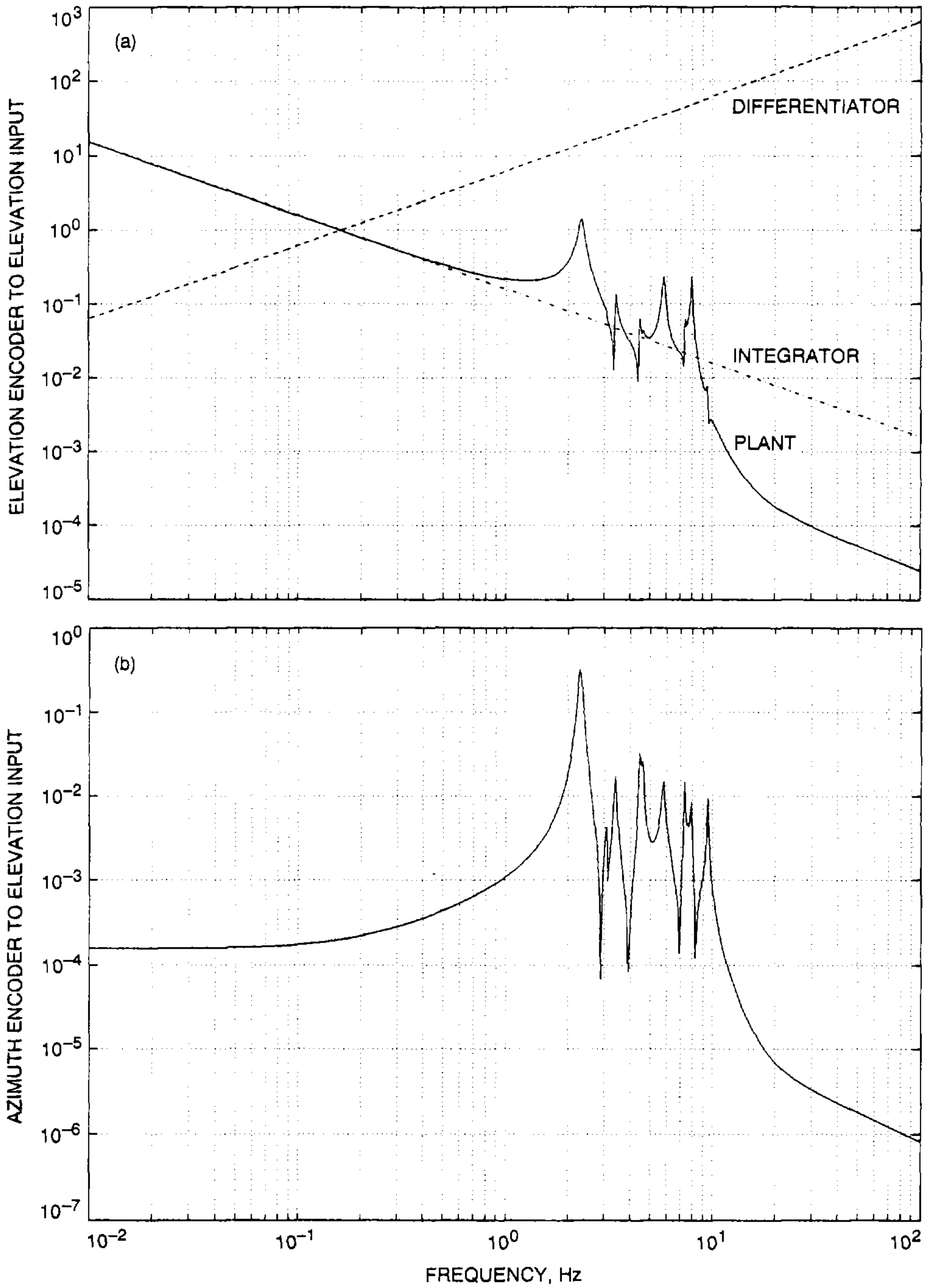


Fig. 2. Transfer functions of antenna rate loop model and of differentiator and integrator: (a) elevation encoder to elevation input; (b) azimuth encoder to elevation input; (c) azimuth encoder to azimuth input; and (d) elevation encoder to azimuth input.

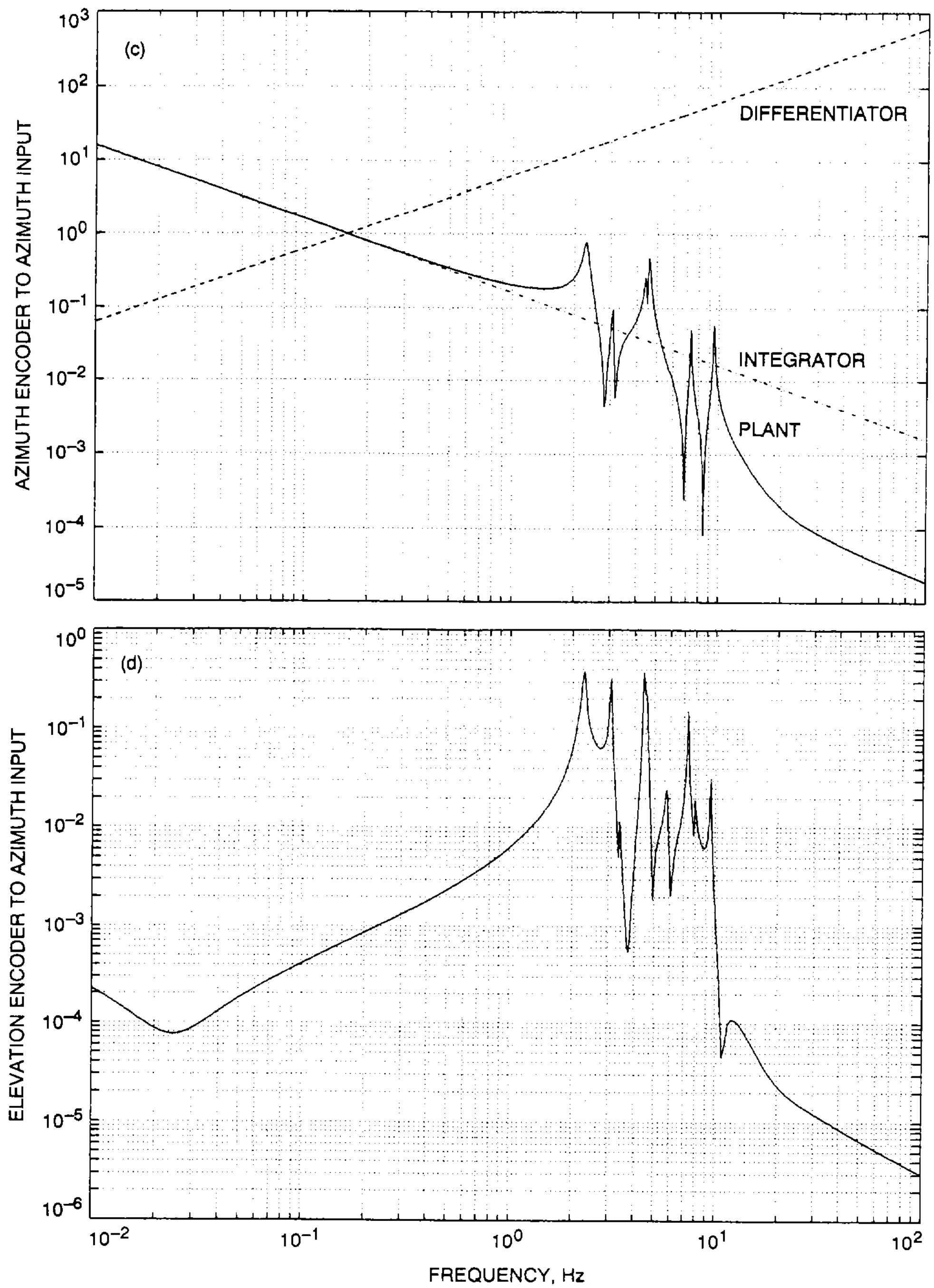

(c)
DIFFERENTIATOR
INTEGRATOR
PLANT
AZIMUTH ENCODER TO AZIMUTH INPUT
(d)
ELEVATION ENCODER TO AZIMUTH INPUT
FREQUENCY, Hz

Fig. 2 (contd).

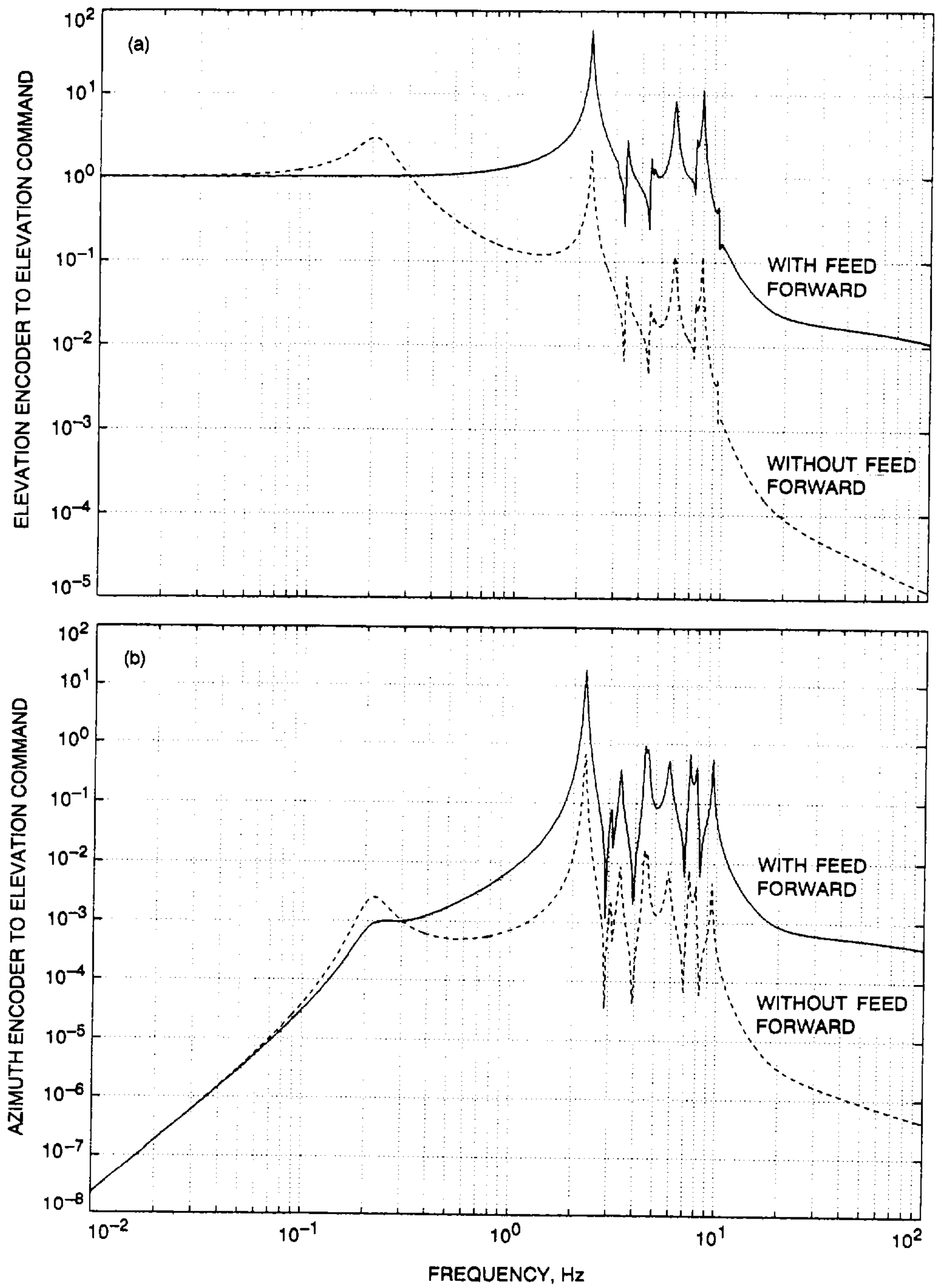
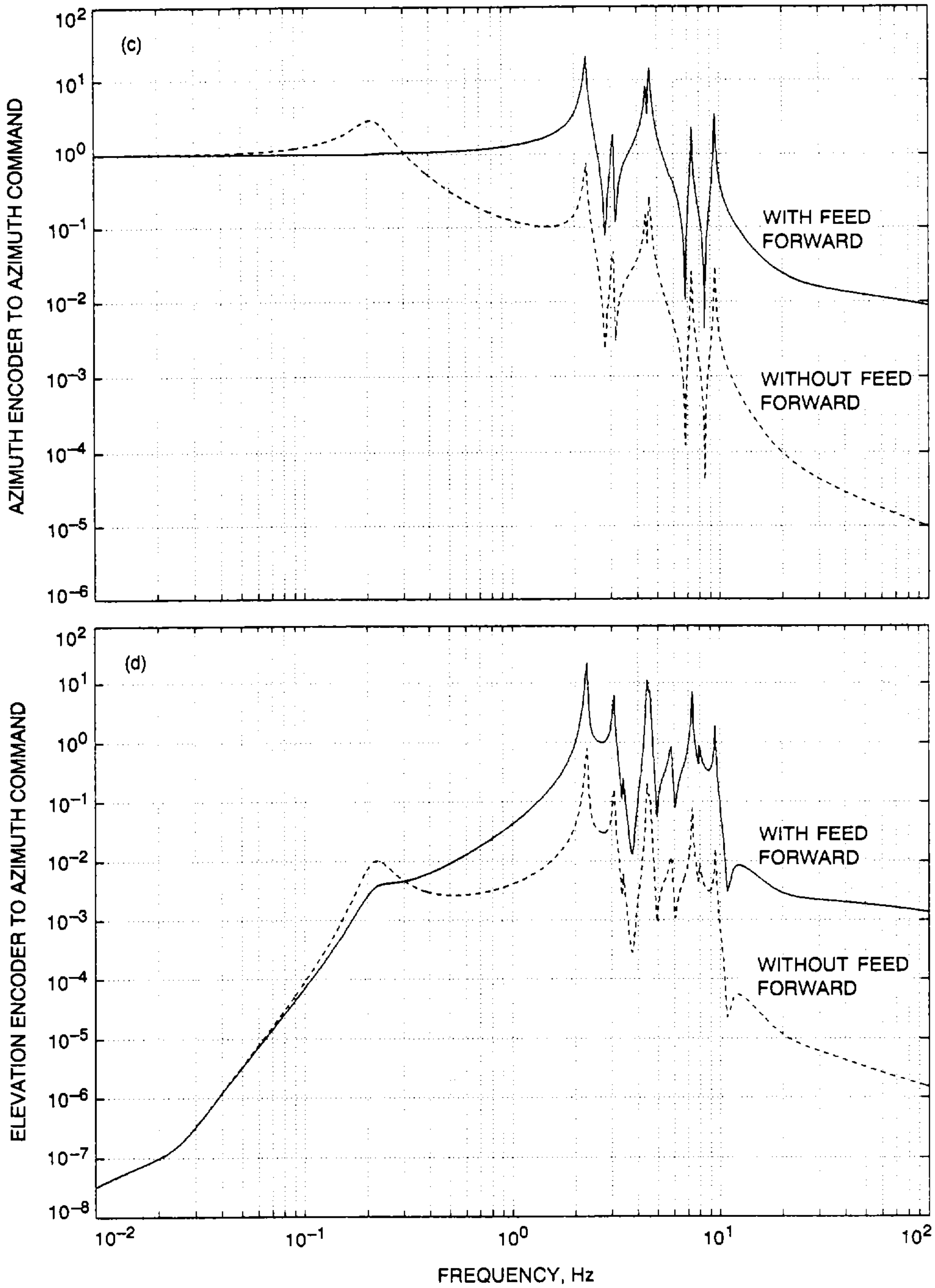


Fig. 3. Closed-loop transfer functions—with feed-forward loop and without feed-forward loop: (a) elevation encoder to elevation command; (b) azimuth encoder to elevation command; (c) azimuth encoder to azimuth command; and (d) elevation encoder to azimuth command.



(c)
AZIMUTH ENCODER TO AZIMUTH COMMAND
WITH FEED FORWARD
WITHOUT FEED FORWARD
(d)
ELEVATION ENCODER TO AZIMUTH COMMAND
WITH FEED FORWARD
WITHOUT FEED FORWARD
FREQUENCY, Hz

Fig. 3 (contd).

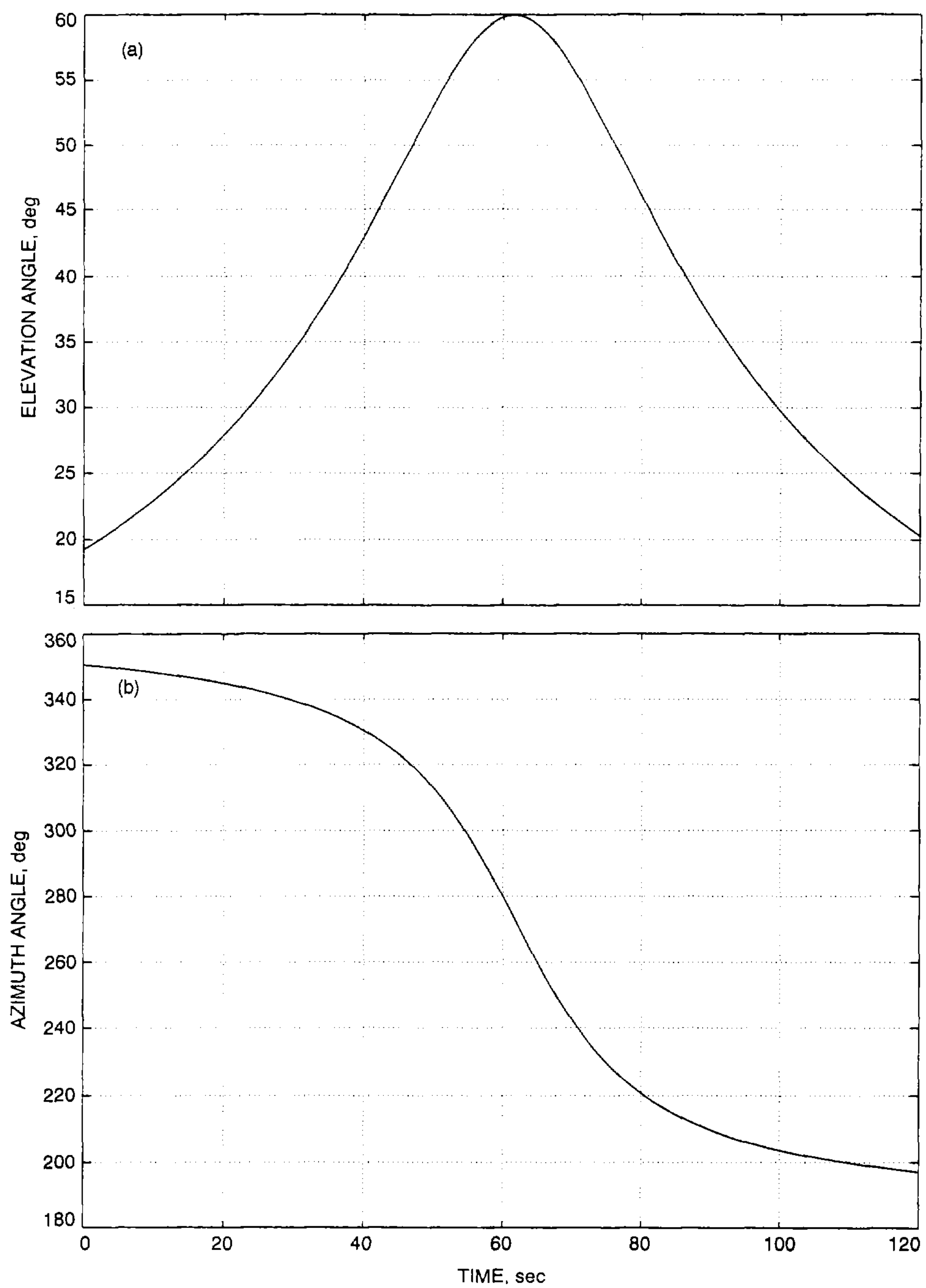


Fig. 4. Trajectory used for simulations: (a) in elevation and (b) azimuth.

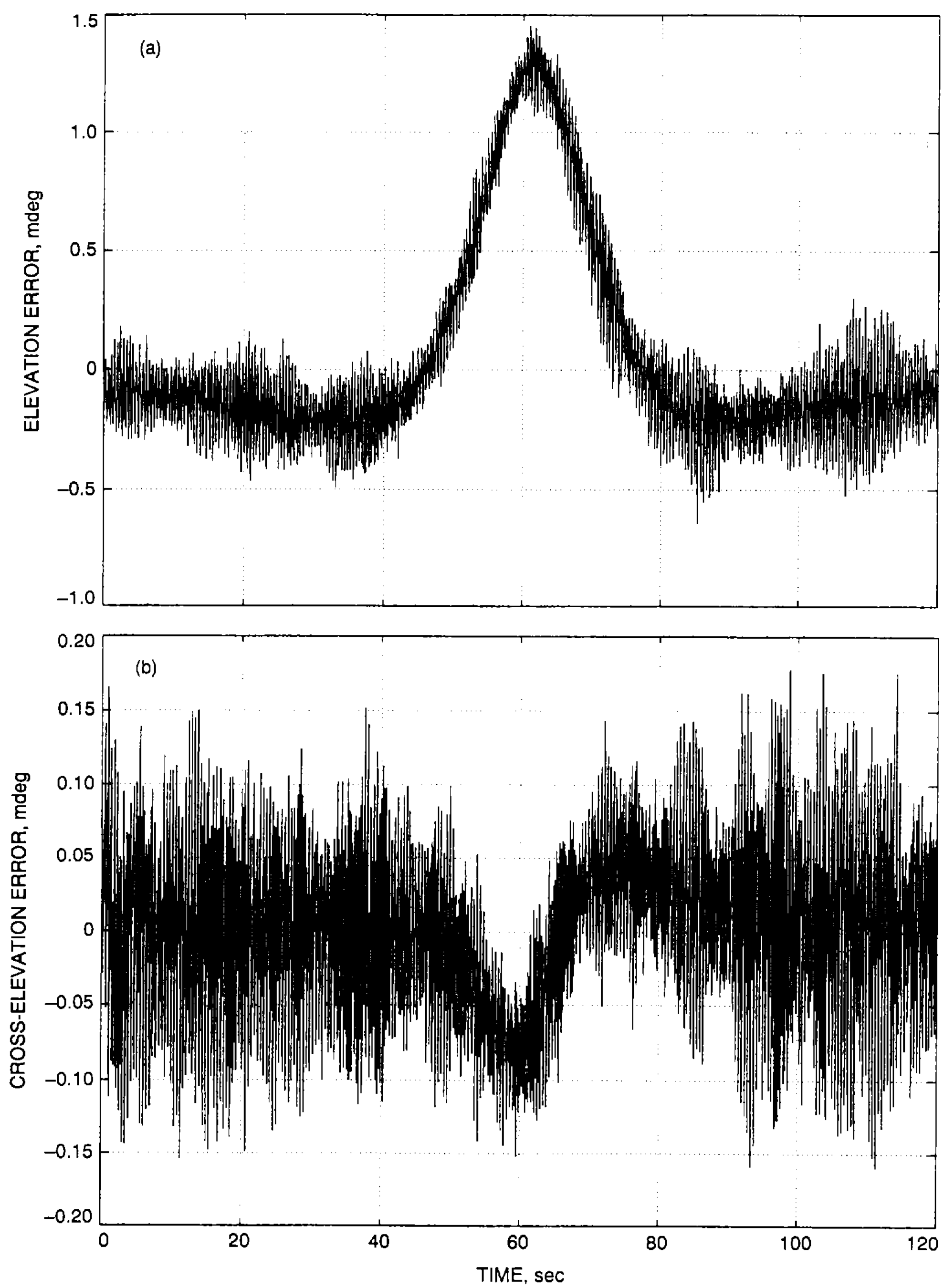


Fig. 5. Pointing errors for the control system with the feed-forward loop: (a) elevation error and (b) cross-elevation error.

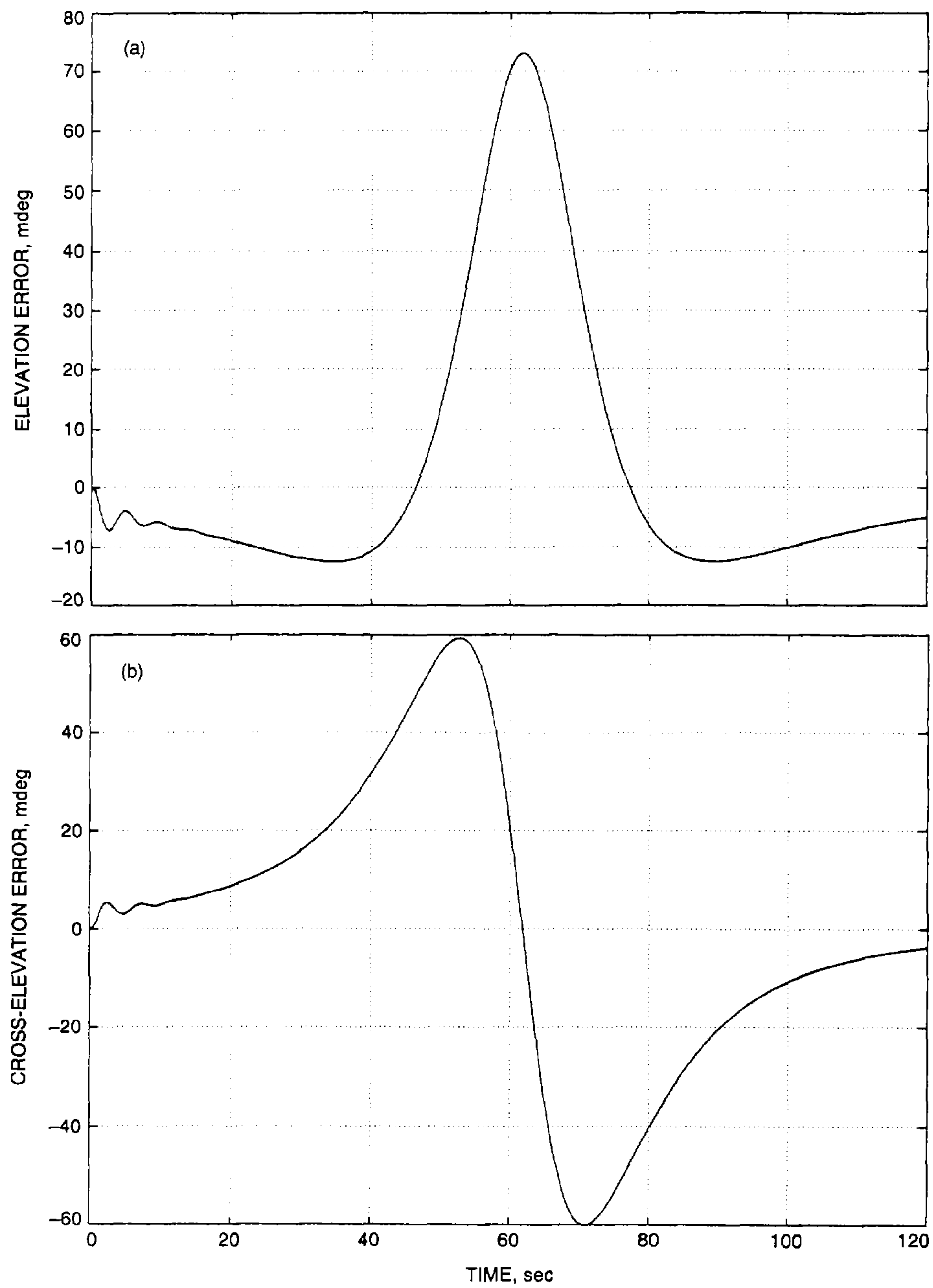


Fig. 6. Pointing errors for the control system without the feed-forward loop: (a) elevation error and (b) cross-elevation error.