IPN Progress Report 42-167 November 15, 2006

Servo Performance Parameters of the Deep Space Network Antennas

W. Gawronski[1]

The performance of an antenna control system is evaluated using performance parameters such as settling time, bandwidth, steady-state error in rate offsets, and antenna root-mean-square servo error while tracking in wind gusts. The performance parameters are measured in the field or obtained through analysis and simulations. Limited access time to antennas, incomplete test equipment, limited test/analysis time, and partial models do not allow for determination of all the parameters. However, field practice and analytical results indicate correlation between them; hence, even the incomplete knowledge of the performance parameters would allow for estimation of the missing ones.

The article investigates the relationships of the antenna performance parameters as a function of controller gains. It also establishes the inter-relationship between the parameters. It does this for an idealized (or rigid) antenna and extends the relationships to the NASA Deep Space Network antennas (flexible structures with dish sizes of 34 or 70 meters). The obtained results should simplify antenna testing and allow for better performance evaluation from limited data.

I. Introduction

The antenna servo error while tracking in wind gusts is the primary measure of the antenna control system performance. However, the error is not easily measured, and antenna performance is frequently poorly estimated. The difficulty of evaluating the servo error in wind gusts led to the search for alternative (or indirect) measures of the antenna pointing performance in wind.

We analyze the control systems (or servos) of the 34-meter beam-waveguide (BWG) antennas, 34-meter high-efficiency (HEF) antennas, and 70-meter antennas of the NASA Deep Space Network (DSN). It was observed that the servo performance parameters of the antennas, such as settling time and bandwidth, are related to the servo error. Quantitatively, the shorter the settling time or the wider the bandwidth, the smaller is the servo error in wind gusts. In this article, the quantitative knowledge is transformed into a qualitative one. We establish the relationships between controller gains and performance parameters, as well as between the parameters themselves. We obtained these relationships for the 34-meter and 70-meter antennas. They allow one to estimate the antenna servo error in wind (which is not easy to measure) using the settling time (which is simple to measure). Since the results of the analysis are similar

---

[1] Communications Ground Systems Section.

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

for the 34-meter and 70-meter antennas, it is assumed that they are valid for many other antennas and radio telescopes.[2]

II. Antenna Servo Performance Parameters

The antenna servo performance is characterized by the following parameters:

(1) Settling time, s
(2) Bandwidth, Hz
(3) Root-mean-square (rms) servo error in wind gusts, mdeg

The mean servo error in rate offsets is the additional performance parameter. Since it always is required to be zero, we do not include it in the analysis.

The settling time in the position offsets is the time needed to achieve the commanded value within the threshold of ±3 percent of the final value (see Fig. 1). The settling time is measured from the antenna small position offsets, typically 20 mdeg. The position offset is the most straightforward measurement available at the DSN antennas.

The bandwidth is the frequency for which the magnitude of the closed-loop transfer function crosses the 0.7 (or -3 dB) level (see Fig. 2). The bandwidth is available from the closed-loop frequency tests or from the open-loop system identification with the additional calculations of the closed-loop properties.

The ultimate measure of antenna servo performance is the rms servo error (called further servo error, for simplicity) in wind gusts during spacecraft tracking. The servo error is the difference between the commanded and actual position of the antenna. It consists of the constant (mean) component and the variable component. The constant component is required to be zero. The variable component is characterized by its standard deviation (or rms error).

Servo error measurement is straightforward, but requires long logging time to obtain reliable statistical estimates. It depends on the wind speed, wind direction with respect to antenna position (angle of attack), and antenna elevation position. The important factor, not to be ignored, is the availability of wind gusts during measurement. For this reason, measurements of the servo error in wind gusts require time, patience, and significant data processing, which explains why they are rather scarce. However, the current requirement for the DSN antenna control systems is given as the azimuth and elevation servo errors in 32 km/h wind gusts; thus, we must have tools to obtain their estimates.

During the last 10 years, occasional servo performance measurements and analysis results indicated a connection between the servo error and other antenna parameters, such as settling time or bandwidth, and also a connection between the servo error and antenna servo proportional and integral gains. The importance of these facts lies in the fact that measurement of the settling time or bandwidth is much simpler and less time consuming than measurement of the error in wind gusts, while the servo gains do not need to be measured—they are given.

The purpose of this article is to establish the relationships between the servo error and antenna servo gains, between the settling time and the gains, and between bandwidth and the gains. Additionally, the relationships between the settling time and the servo error, and between bandwidth and the servo error, are derived.

---

[2] A full report on the servo performance parameters of the BWG, HEF, and 70-meter antennas can be found on the JPL Deep Space Communications and Navigation Systems (DESCANSO) internal Web site, Jet Propulsion Laboratory, Pasadena, California, October 2006.

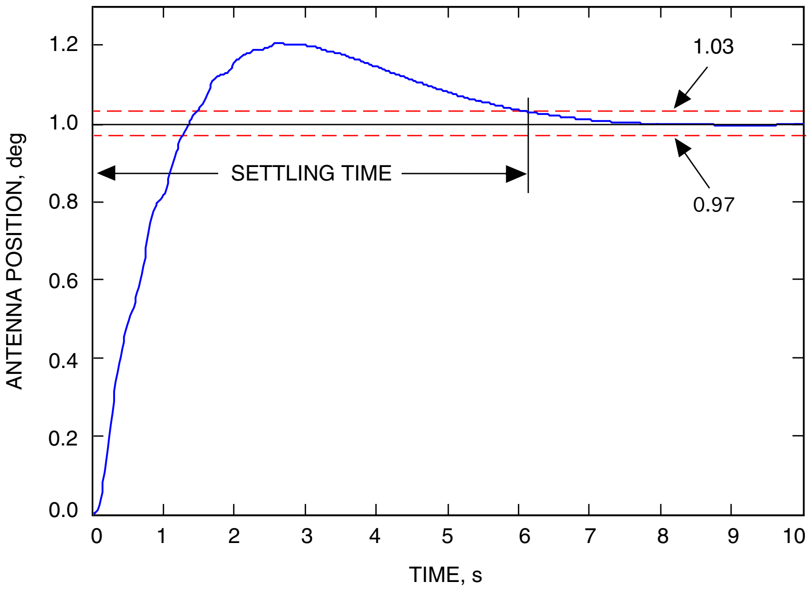

Fig. 1. Determining settling time (6.2 s) in a step response.

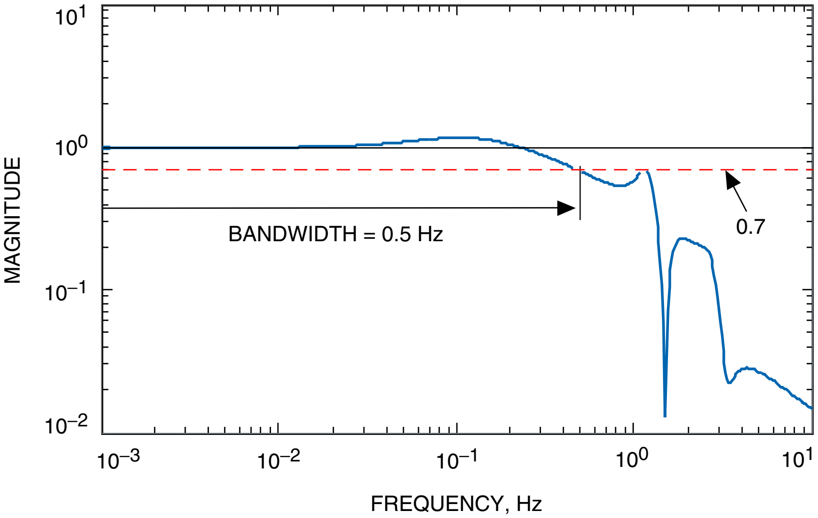

Fig. 2. Determining bandwidth from the magnitude of the closed-loop transfer function.

III. Performance of the Rigid Antenna and Proportional and Integral Controller

Our analysis starts with a rigid antenna. The rigid antenna is considered a perfect antenna, with no flexible deformations, for which the controller needs to overcome inertia forces only. The proportional and integral (PI) controller is a suitable choice to control the position of this idealized plant. The closed-loop system of the rigid antenna with the PI controller is shown in Fig. 3.

For the perfectly rigid antenna, the open-loop transfer function, G_r, is an integrator

$$G_r = \frac{1}{s} \tag{1}$$

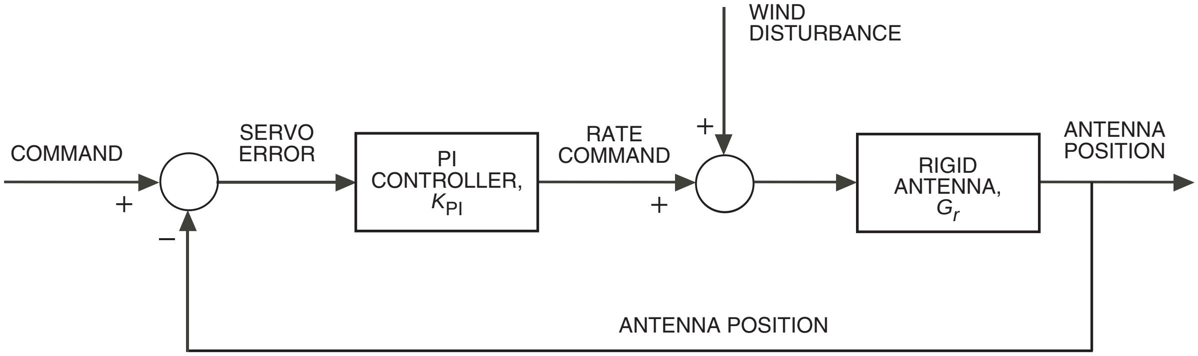

Fig. 3. Rigid antenna with a PI controller.

while the transfer function of the PI controller is as follows:

$$K_{\mathrm{PI}} = k_p + \frac{k_i}{s} \tag{2}$$

where k_p is the proportional gain and k_i is the integral gain.

Using the above equations, the closed-loop transfer function, from the command, r, to the antenna position, y, is

$$T_{ry} = \frac{k_p s + k_i}{s^2 + k_p s + k_i} \tag{3}$$

and from the wind disturbance, w, to the antenna position, y, it is

$$T_{wy} = \frac{s}{s^2 + k_p s + k_i} \tag{4}$$

Using Eqs. (3) and (4), we simulated the step responses, frequency responses, and wind errors for the proportional gains, k_p, from the range $k_i = [0.5 - 3.0]$, and the integral gains, k_i, from the range $k_i = [0.2k_p - 0.9k_p]$, to obtain settling time, bandwidth, and servo error in wind gusts (for the wind gust modeling, see [1]). The results are plotted in Figs. 4(a) through 4(c).

The plots show that

(1) The settling time significantly decreases with the increase of the proportional gain, and it also decreases with the increase of the integral gain.

(2) The bandwidth increases linearly with the proportional and integral gains.

(3) The servo error in wind decreases with the increase of the proportional gain and with the increase of the integral gain.

Figures 4(a) through 4(c) can be recombined to show how the bandwidth and the servo error in wind gusts depend on the settling time; see Figs. 5(a) and 5(b). The bandwidth decreases and the servo error increases with the increase of the settling time.

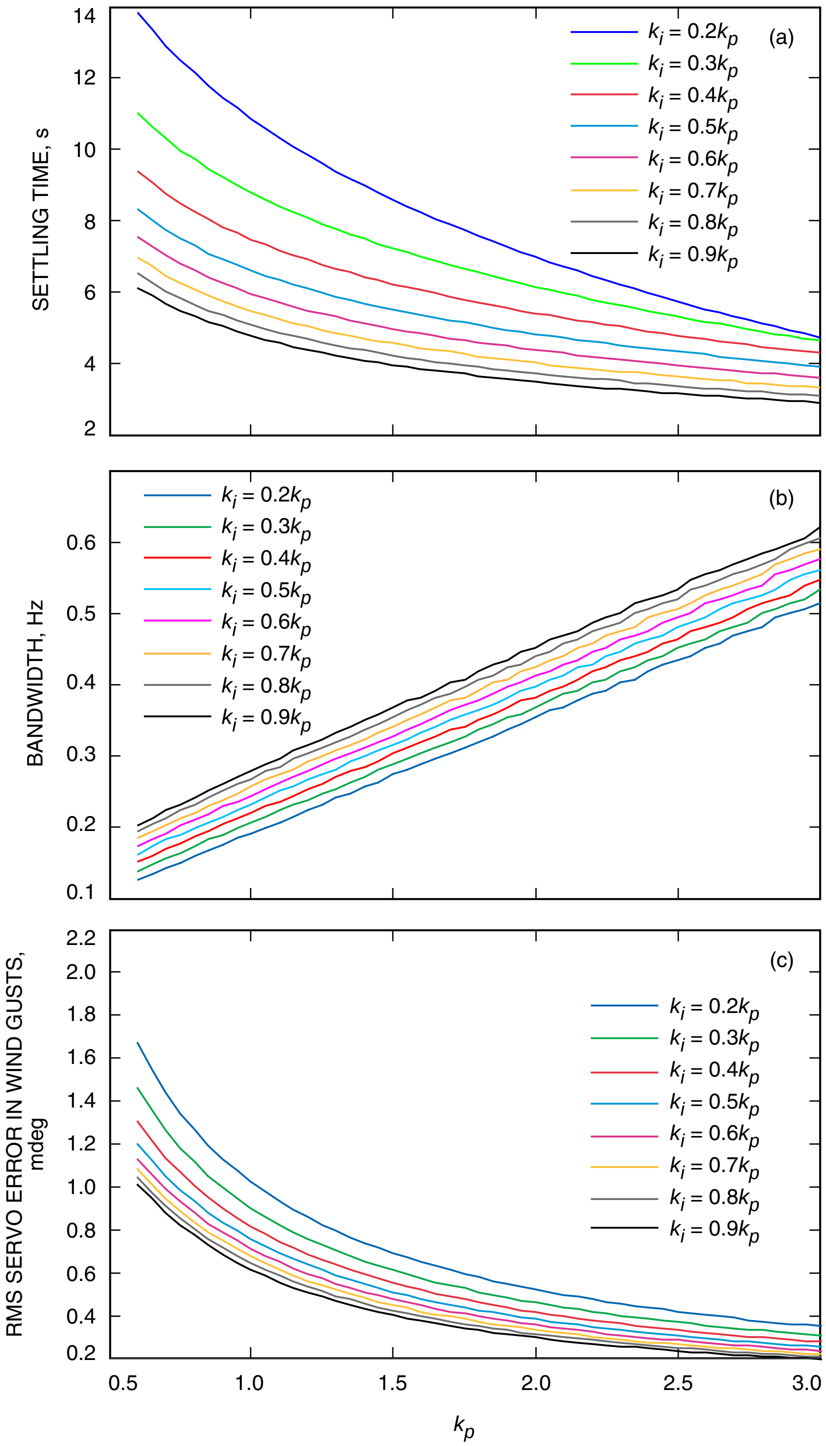

Fig. 4. The performance parameters of the rigid antenna with PI controller as a function of the controller gains: (a) settling time, (b) bandwidth, and (c) rms servo error in 32 km/h wind gusts.

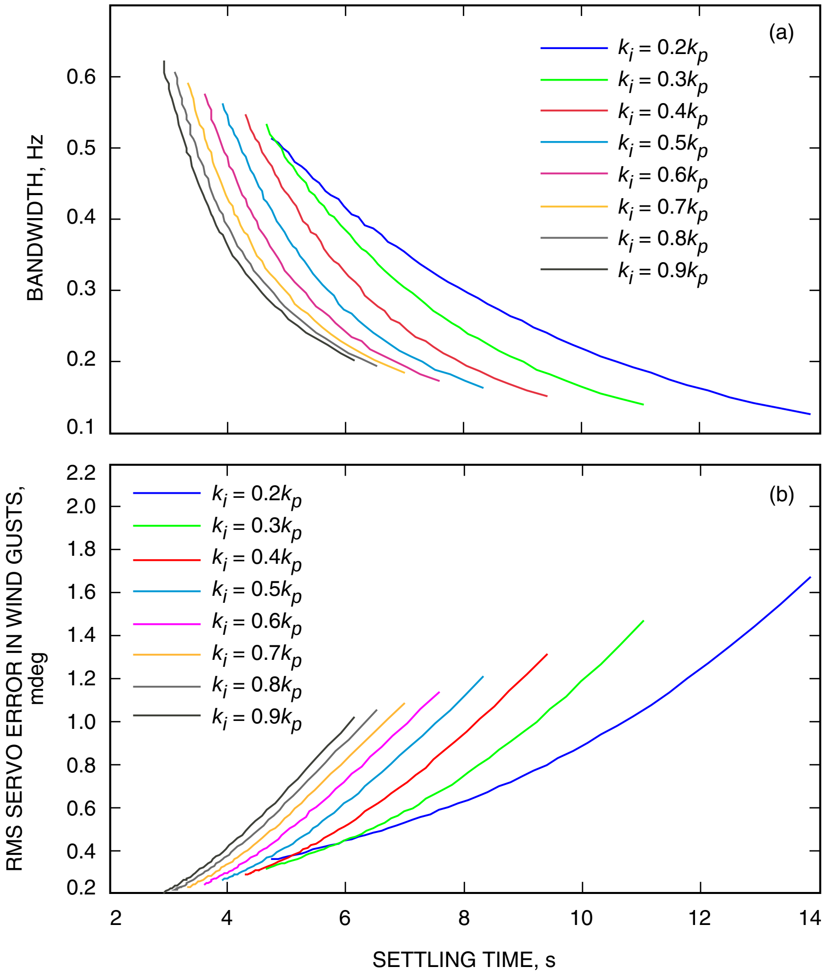

Fig. 5. The performance parameters of the rigid antenna with PI controller as a function of the settling time: (a) bandwidth and (b) rms servo error in 32 km/h wind gusts.

IV. The Linear-Quadratic-Gaussian Controller Structure and Properties

It is known that for larger, flexible antennas (the ones with resonance frequencies within the antenna bandwidth) the PI controllers become unstable when their proportional gain (and the integral gain to a lesser extent) is too large. The excessive gains excite antenna vibrations. However, the linear-quadratic-Gaussian (LQG) controller allows for a significant increase in the gains without excitation of vibrations.

The application of the LQG controllers to antennas and radio telescopes is described in [2] and [3]. The LQG controller structure is shown in Fig. 6. By appropriate selection of the coordinate system, the LQG controller is divided into the PI part and the flexible mode part. Theoretically, the performance of the LQG controller does not depend on the selection of the coordinate system. From an implementation point of view, appropriate selection of the coordinates simplifies the controller design process and allows for use of the LQG controller as a PI controller, if necessary.

The coordinate system of the LQG controllers for the DSN antennas consists of

(1) Tracking coordinates, which include the antenna position and the integral of the position

(2) Flexible mode (modal) coordinates that represent the antenna structural dynamics

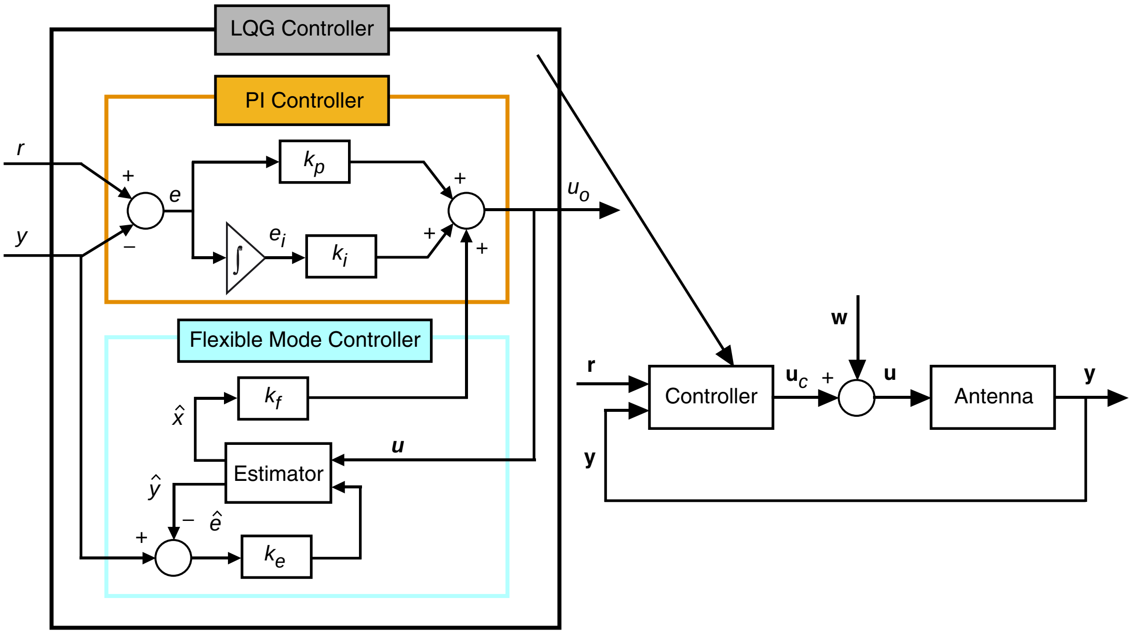

Fig. 6. Antenna with LQG controller.

This particular selection allows for separation of the antenna tracking motion from its vibrations. Consequently, the controller gains for the tracking coordinates (antenna position and its integral) control the antenna tracking motion and are simply the PI gains. The controller gains for the flexible mode coordinates impact the antenna vibrations. These gains are called the flexible mode gains.

For the DSN antenna, the flexible mode gains are of low authority; they are not excessive, i.e., they damp the antenna vibrations but do not impact its tracking properties. The PI gains also are moderate in that their reactions to disturbances do not exceed the imposed acceleration limit.

With these limitations, the distinctive relationships between antenna performance parameters (particularly between the settling time, bandwidth, and servo error) were observed. This allows us to replace the time-consuming and less reliable measurements of servo error in wind with the measurements of settling time and bandwidth, and to evaluate whether the servo satisfies the requirements.

V. Performance of the DSN Antennas with LQG Controllers

In this section, we analyze the elevation axis controller of the 34-meter DSN antennas. For the azimuth axis, the relationships are similar. The performance parameters have been determined as follows: For a selected proportional and integral gain, the LQG controller was designed, and the performance parameters for this controller were simulated. The process was repeated for another set of proportional and integral gain values.

Figures 7(a) through 7(c) show the dependency of the settling time, overshoot, bandwidth, and servo error in wind gusts on the proportional and integral gains of the LQG controller. Figures 8(a) and 8(b) show the dependency of the bandwidth and the servo error in wind gusts on the antenna settling time.

In Figs. 9(a) through 9(c), we compare the performance parameters of a rigid antenna, a 34-meter antenna, and a 70-meter antenna. The comparison is presented for the integral gain being half of the proportional gain, $k_i = 0.5k_p$, which is typical for the DSN antennas. The figures show that for the same gains

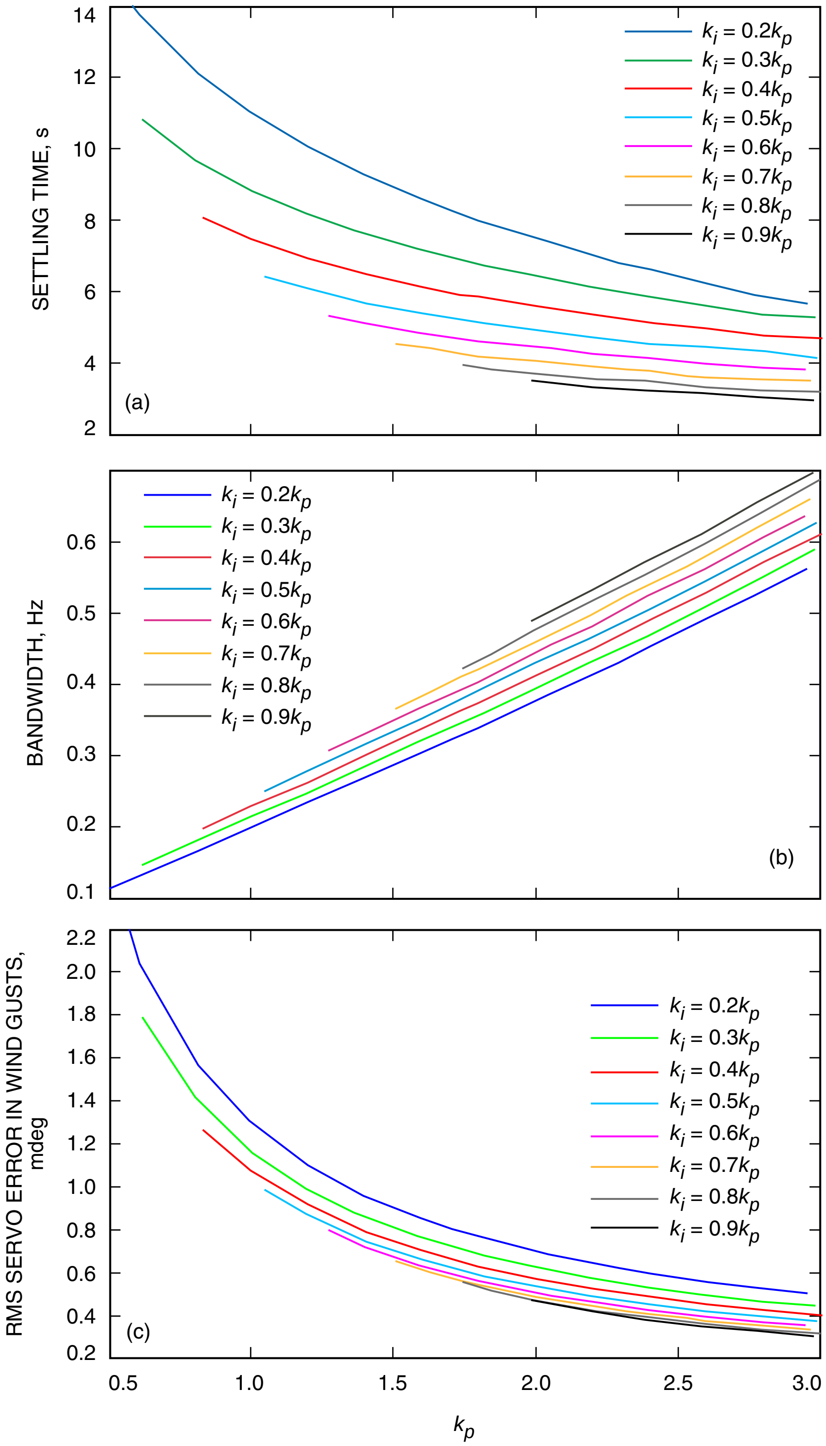

Fig. 7. The performance parameters of the 34-meter antenna (elevation axis) with LQG controller as a function of the controller gains: (a) settling time, (b) bandwidth, and (c) rms servo error in 32 km/h wind gusts.

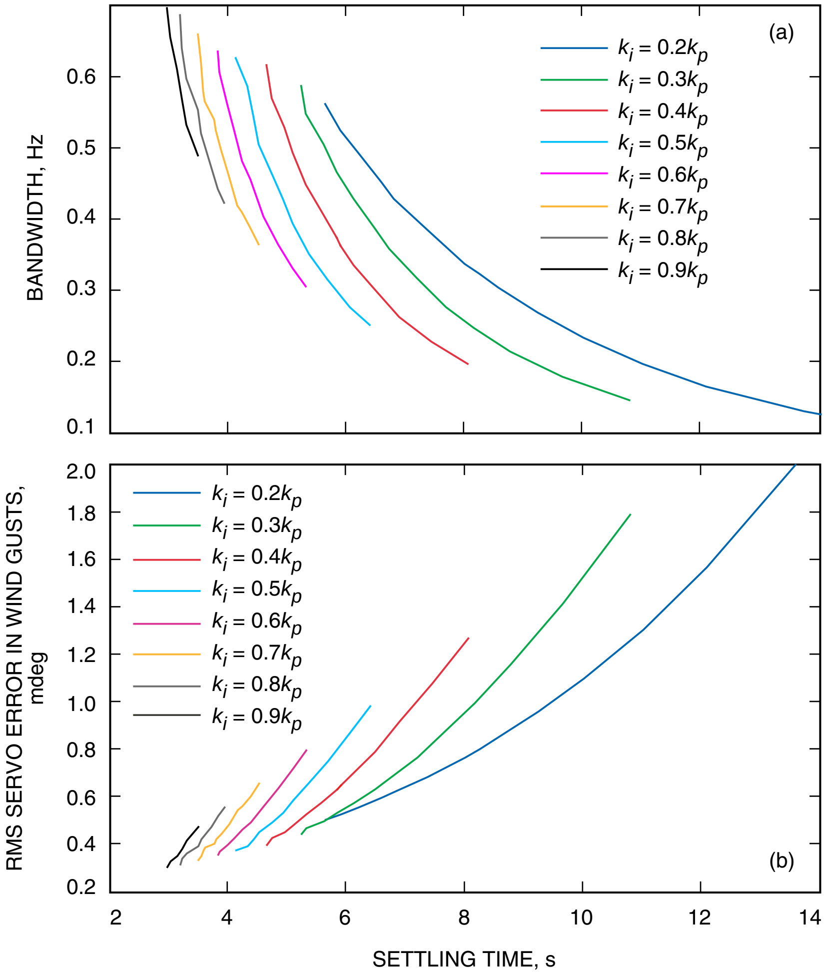

Fig. 8. The performance parameters of the 34-meter antenna (elevation axis) with LQG controller as a function of the settling time: (a) bandwidth and (b) rms servo error in 32 km/h wind gusts.

(1) The settling time is smallest for the rigid antennas. However, for other antennas, it is similar; the difference does not exceed 0.5 s.

(2) The 34-meter and 70-meter antenna bandwidths exceed the rigid antenna bandwidth.

(3) The servo error in wind gusts is definitely smallest for the rigid antenna. All the DSN antennas have very close servo error in wind gusts.

VI. Conclusions

This article presented the relationships between the controller gains and servo performance parameters (and also between the performance parameters) for the DSN antennas. They simplify the evaluation of the DSN antenna servo performance.

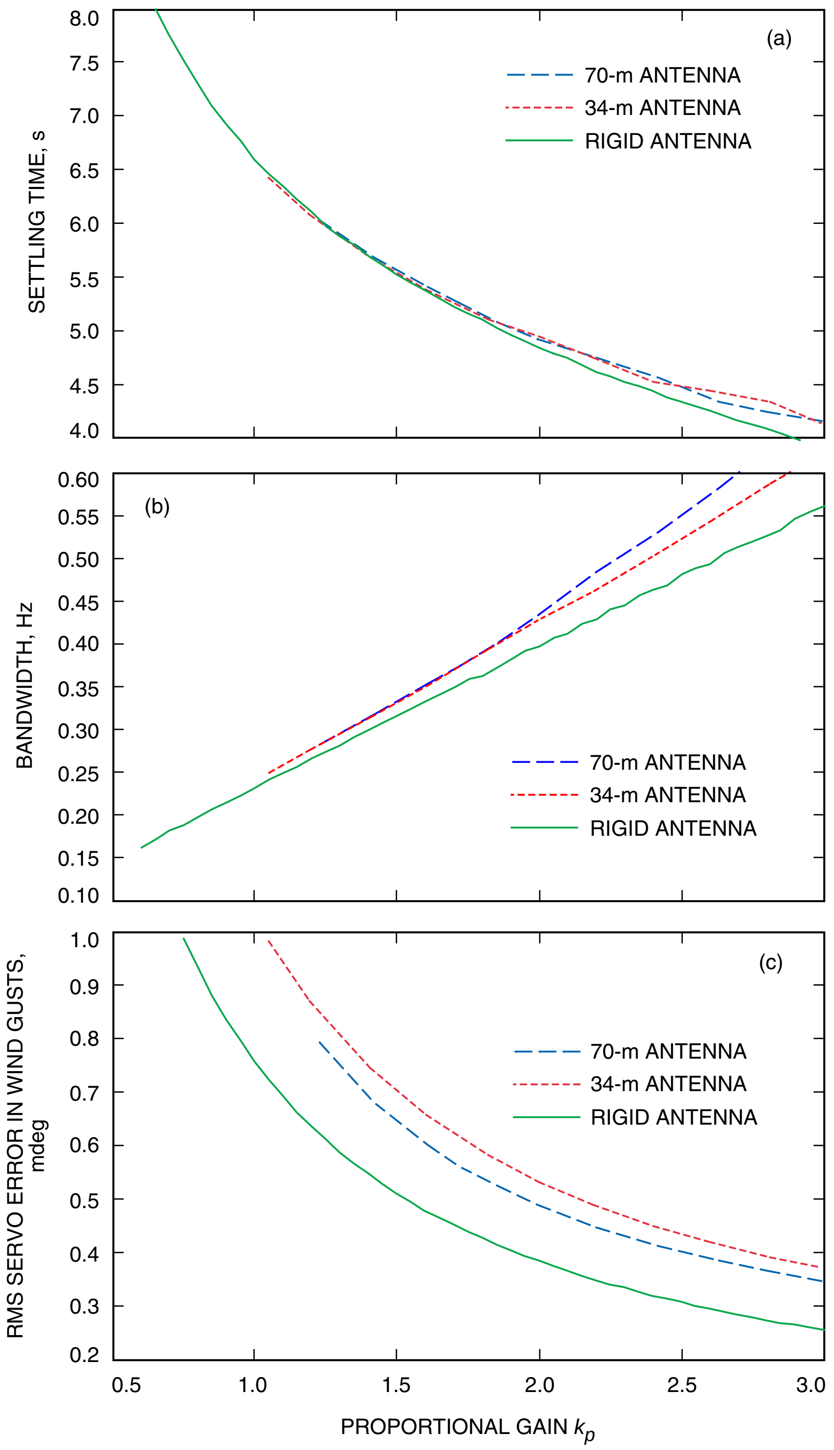

Fig. 9. Comparison of elevation axis performance of the rigid, 34-meter, and 70-meter antennas: (a) settling time, (b) bandwidth, and (c) rms servo error in 32 km/h wind gusts.

References

[1] W. Gawronski, “Modeling Wind Gusts Disturbances for the Analysis of Antenna Pointing Accuracy,” *IEEE Antennas and Propagation Magazine*, vol. 46, no. 1, pp. 50–58, 2004.

[2] W. Gawronski, C. Racho, and J. Mellstrom, “Application of the LQG and Feedforward Controllers for the DSN Antennas,” *IEEE Transactions on Control Systems Technology*, vol. 3, no. 4, pp. 417–421, 1995.

[3] W. Gawronski, “Antenna Linear-Quadratic-Gaussian (LQG) Controllers: Properties, Limits of Performance, and Tuning Procedure,” *The Interplanetary Network Progress Report*, vol. 42-158, Jet Propulsion Laboratory, Pasadena, California, pp. 1–18, August 15, 2004.
http://ipnpr.jpl.nasa.gov/progress_report/42-158/158H.pdf