70-Meter Antenna Tracking and Mode Switching Near the Master Equatorial Keyhole

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The 70-m antenna servo system consists of the antenna itself and the master equatorial (ME). The two subsystems track in different coordinates: the antenna moves in the azimuth/elevation (AZ/EL) coordinates while the ME moves in the hour angle/declination (HA/DEC) coordinates. Difficulties in tracking appear due to the existence of keyholes. Tracking near the keyhole requires rates that exceed the imposed rate limits, and the servo errors grow to unacceptable values. The 70-m antenna's keyhole is at EL = 90 deg, and the ME keyhole is at DEC = 90 deg, which corresponds to AZ = 0 deg and EL = 35.425 deg at Goldstone.

In this article, two control modes are analyzed near the ME keyhole: the autocollimator mode, in which the ME is commanded and the antenna follows it, and the ME encoder mode, in which the antenna is commanded and the ME follows the antenna. For the autocollimator mode, the analysis showed that near the keyhole the ME causes unacceptable delays (up to 120 s). In the ME encoder mode, the slow-moving ME destabilizes the antenna near the keyhole.

In order to avoid antenna lagging near the ME keyhole, the antenna controller should switch to the antenna encoder mode and the ME should be disconnected. In order to trigger the switch, the ME hour servo error is monitored. It was determined the switching should happen when the ME hour error exceeds the threshold value of 0.2 deg. The analysis showed that multiple switches occurred when transferring from one mode to another and that the switching causes jerks in the servo system. In the autocollimator mode, the command preprocessor (CPP) or low-pass filter smoothes the jerks; in the ME encoder mode, switching jerks are insignificant—the same as jerks in the autocollimator mode with the CPP.

I. Introduction

The 70-m antenna's servo system consists of the antenna itself and the master equatorial (ME). The antenna moves in the azimuth/elevation (AZ/EL) coordinates while the ME in the hour angle/declination (HA/DEC) coordinates. Each coordinate system has its own keyhole (or singular point). Tracking

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through (or near) the keyhole requires rates that exceed the imposed rate limits; therefore, either the antenna or the ME is slow near its own keyhole, and the servo errors grow to unacceptable values.

In order to avoid antenna lagging when tracking near the ME keyhole, the antenna controller should disconnect the ME and switch to the antenna encoder mode. The questions are when to switch, how many jerks are created by the switching, how large the jerks are, and how to reduce the impact of the jerks. Since the antenna control system works in two modes (the autocollimator mode and the ME encoder mode), the jerks during switching were analyzed in both modes.

In order to determine when to switch the ME, the hour servo error is monitored. The hour error rises dramatically near the keyhole and is easy to monitor. It was determined the switching should happen when the ME hour error exceeds the threshold value of 0.2 deg. The threshold value was chosen to be larger than errors caused by typical disturbances, but not so large as to cause large switching jerks.

II. Antenna Control Modes

The 70-m antenna control system consists of the antenna and the ME. They cooperate in three configurations, or modes (see [1]):

(1) Autocollimator (AC) mode

(2) ME encoder (MEE) mode

(3) Antenna encoder (AE) mode

The first configuration, called the AC mode (or Configuration A in [1]), is a modified current ME/antenna configuration. In this mode, the ME is commanded to follow the target; the antenna is optically coupled with the ME through the autocollimator and follows the ME. In the MEE mode (called Configuration B in [1]), the antenna is commanded to follow the target, and the ME follows the antenna. Since the ME is much faster than the antenna, it effectively serves as a position sensor. In the antenna encoder (AE) mode, the antenna utilizes its own encoders to close the loop and to follow the target, while the ME is not active.

The antenna and ME move in two different coordinate systems. The ME moves in the HA/DEC coordinates, while the antenna in the AZ/EL coordinates. Each coordinate system has its own keyhole (or singular point). Tracking through (or near) the keyhole requires rates that exceed the rate limits; therefore, the ME or antenna is slow, and the servo error near the keyhole grows to unacceptable values. The 70-m antennas have two keyholes: the ME keyhole (at $dec = 90$ deg, which corresponds to $az = 0$ deg and $el = 35.425$ deg), and the antenna keyhole (at $el = 90$ deg).

Since the ME keyhole is singular, it is expected that servo error near the keyhole will also be singular; thus, the antenna and ME tracking errors are analyzed near the ME keyhole. Also, the switching from the AC to the AE mode and from the MEE to the AE mode is investigated, and implementation of the command preprocessor (CPP) and low-pass filter for jerk reduction is evaluated.

III. ME and Antenna Velocity and Distance from the Keyhole

The ME keyhole is located at $dec = 90$ deg, which (at Goldstone) corresponds to:

$$az = 0.000 \text{ deg}$$

$$el = 35.425 \text{ deg}$$

Denote azimuth angle as az, elevation angle as el, hour angle as ha, declination angle as dec, and station latitude angle ($lat = 35.435$ deg) at Goldstone as lat. The relationship between the ha, dec and az, el angles is as follows:

$$az = \operatorname{atan}\left(\frac{-\cos(dec)\sin(ha)}{-\cos(dec)\cos(ha)\sin(lat) + \sin(dec)\cos(lat)}\right) \tag{1}$$

$$el = \operatorname{asin}\big(\sin(dec)\sin(lat) + \cos(dec)\cos(ha)\cos(lat)\big) \tag{2}$$

This relationship can be inverted simply by replacing ha with az and dec with el.

The ME declination angle is used as a measure of distance from the keyhole. The DEC distance can also be measured equivalently by the azimuth and elevation angles. Figures 1(a) and 1(b) illustrate the above equations near the keyhole. These figures show that a constant value in declination maps into a circle of constant radius, d, in the AZ/EL coordinates.

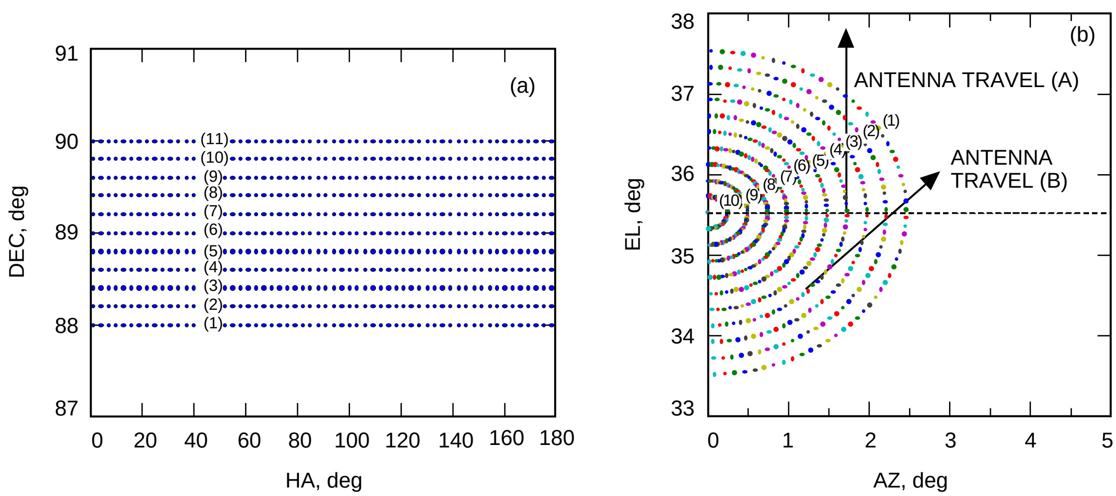

Fig. 1. Coordinates near the keyhole: (a) HA/DEC and (b) AZ/EL.

Consider a circle tangential to the spacecraft trajectory and with a center at the keyhole, as in Fig. 2(a). The distance of the antenna to the keyhole is equal to the radius of the circle. If az and el are the antenna azimuth and elevation positions, and lat is the station latitude, the distance is therefore

$$d = \sqrt{az^2 + (el - lat)^2} \tag{3}$$

In order to characterize a trajectory near the keyhole, one has to know (besides the distance) the antenna velocity, v (mdeg/s), at the smallest distance from the keyhole. The antenna velocity is tangential to the trajectory, as shown in Fig. 2(a). The velocity is the rms sum of the antenna azimuth and elevation rates, i.e.,

$$v = \sqrt{v_{az}^2 + v_{el}^2} \tag{4}$$

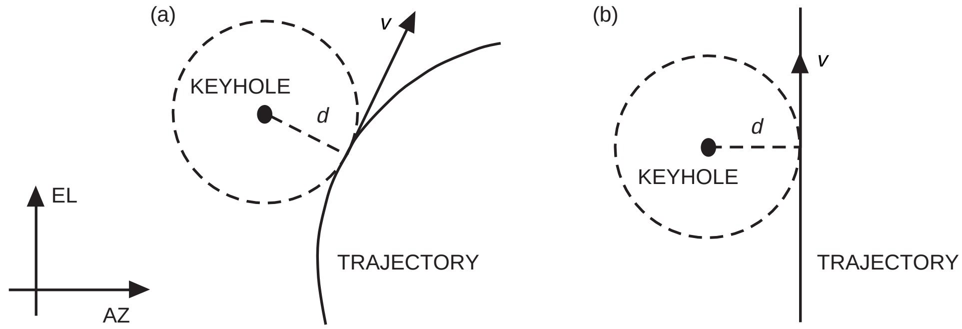

Fig. 2. Trajectory (a) distance and (b) velocity near the ME keyhole.

IV. Simulation Set-up Near the Keyhole

While traveling near the keyhole, the ME (in the HA/DEC coordinates) hits the rate and acceleration limits (in hour angle), causing significant hour servo error. The following questions need to be answered:

(1) Is the antenna, while following the ME, stable?

(2) How long does it take for the ME to catch up with the command?

(3) How close can the ME approach the keyhole without causing significant servo error?

(4) Does the servo error depend on the velocity in the neighborhood of the keyhole?

We will show that in both modes the servo error (in AZ/EL coordinates) depends not only on the ME distance from the keyhole but also on the azimuth rate near the keyhole.

In order to test an antenna near the keyhole, we created a trajectory such that the analysis or measurements are simple, i.e., such that the distance and rate could be easily measured. For example, a trajectory that simplifies the analysis is one that has constant elevation velocity and zero azimuth velocity: it is constantly rising in elevation [see Fig. 2(b)]. From Eq. (4) it follows that in this case the antenna total velocity is equal to the elevation velocity, $v = v_{el}$. Also in this case, when the antenna is at the position $el = lat = 35.425$ deg, the antenna's smallest distance from the keyhole is $d = az$ [insert $el = lat = 35.425$ deg into Eq. (3)]. Thus, when one moves the antenna upward in elevation and measures both its elevation velocity and azimuth position at $el = lat = 35.425$ deg, one determines the antenna's smallest distance and rate near the keyhole as follows:

$$d = az$$

and

$$v = v_{el}$$

at $el = lat = 35.425$ deg. This situation is illustrated in Fig. 1(b), with the arrow marked "antenna travel (a)." It is equivalent to any other situation at the same distance, such as the one marked "antenna travel (b)"; however, the first one is simpler to simulate.

The line $el = lat = 35.425$ deg [the horizontal line in Fig. 1(b)] relates dec with az. It is done by introducing $el = lat$ into Eq. (2), obtaining

$$dec = \operatorname{asin}\left(\sin^2(lat) + \cos^2(lat)\cos(az)\right)$$

The plot of the above relationship is shown in Fig. 3. Therefore, one can determine d in azimuth coordinates and easily translate them into declination coordinates.

Since the ME "indisposition" around the keyhole depends on the distance from the keyhole and on the antenna rate as well, we are going to determine the relationship between the distance and rate for which the unacceptable errors appear. In order to do this, we move the antenna with a constant rate in elevation and at a fixed azimuth position (see "antenna travel (a)" in Fig. 1). The azimuth angle at $el = 35.425$ deg is a distance d from the keyhole, and the elevation rate (tangential to the circle) is the rate v. This scenario is equivalent to any other antenna travel of the same declination distance and the same rate, e.g., "antenna travel (b)" in Fig. 1.

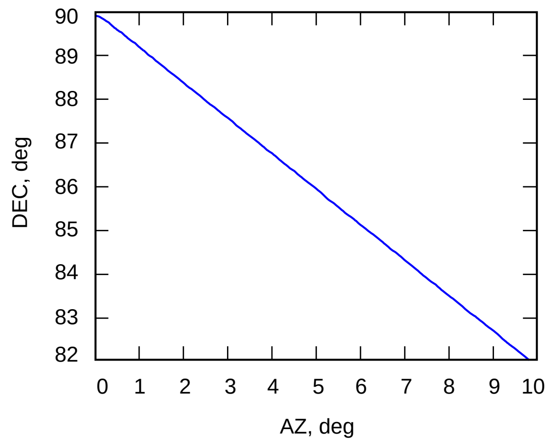

Fig. 3. The AZ-DEC relationship at *el* = 35.425 deg.

The simulation algorithm is as follows:

(1) Move the antenna with constant elevation rate v with fixed azimuth position d.

(2) Record e_{ha} and e_{dec}: the hour and declination servo errors at $el = 35.425$ deg.

(3) Find the rms error, $e = \sqrt{e_{ha}^2 + e_{dec}^2}$.

(4) If $\max(e) \geq 100$ mdeg, drop the elevation rate, keeping the same azimuth position until $\max(e) < 100$ mdeg. Note the corresponding elevation rate, v, and azimuth position, d.

(5) For the determined azimuth position, find the matching declination position (from Fig. 3).

V. Simulation Results Near the Keyhole

Simulink models for the autocollimator mode are shown in Figs. 4 and 5. The models consist of the command preprocessor, ME, and antenna. The ME model [Fig.4 (b)] includes the coordinate conversion blocks from AZ/EL to HA/DEC and from HA/DEC to AZ/EL [Fig. 4(c)] and the blocks to set the initial conditions in azimuth and elevation. In Fig. 4(c), the nonlinear block "azel2ha" represents Eq. (1), while the block "azel2dec" represents Eq. (2). The ME model consists of the ME itself and its controller [Fig. 4(d)], while the ME controller is shown in Fig. 4(e). The antenna model was described in [1].

The Simulink model of the ME encoder mode is shown in Fig. 5, where all the sub-blocks are the same as in Figs. 4(b) through 4(e). Note that the models consist of combined models in azimuth and elevation (rather than single azimuth and elevation models) since they are coupled through the ME and its HA/DEC coordinates.

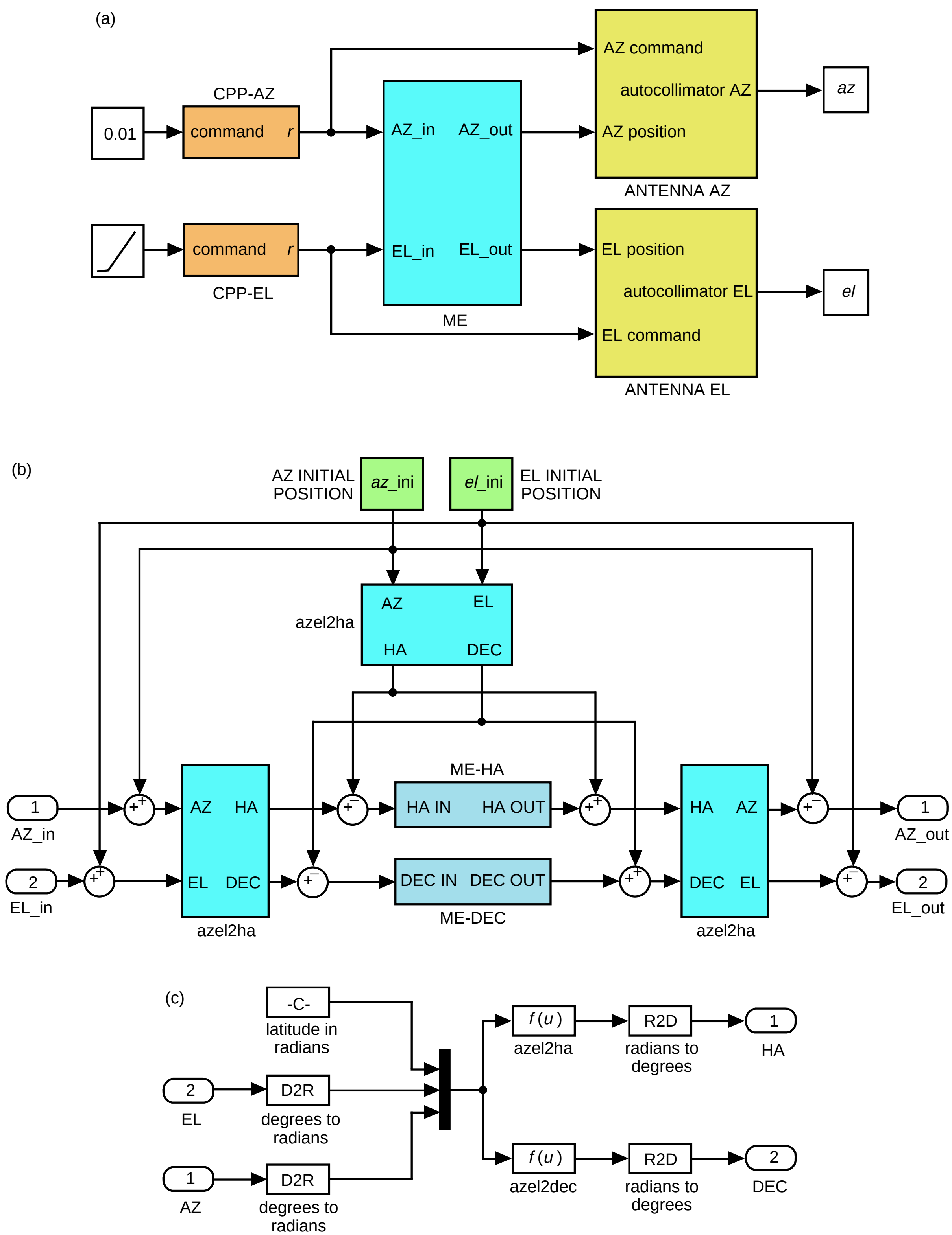

Fig. 4. Antenna and ME Simulink model, autocollimator mode: (a) overall system, (b) ME subsystem, (c) AZ/EL-to-HA/DEC transformation, (d) ME control system, and (e) ME controller.

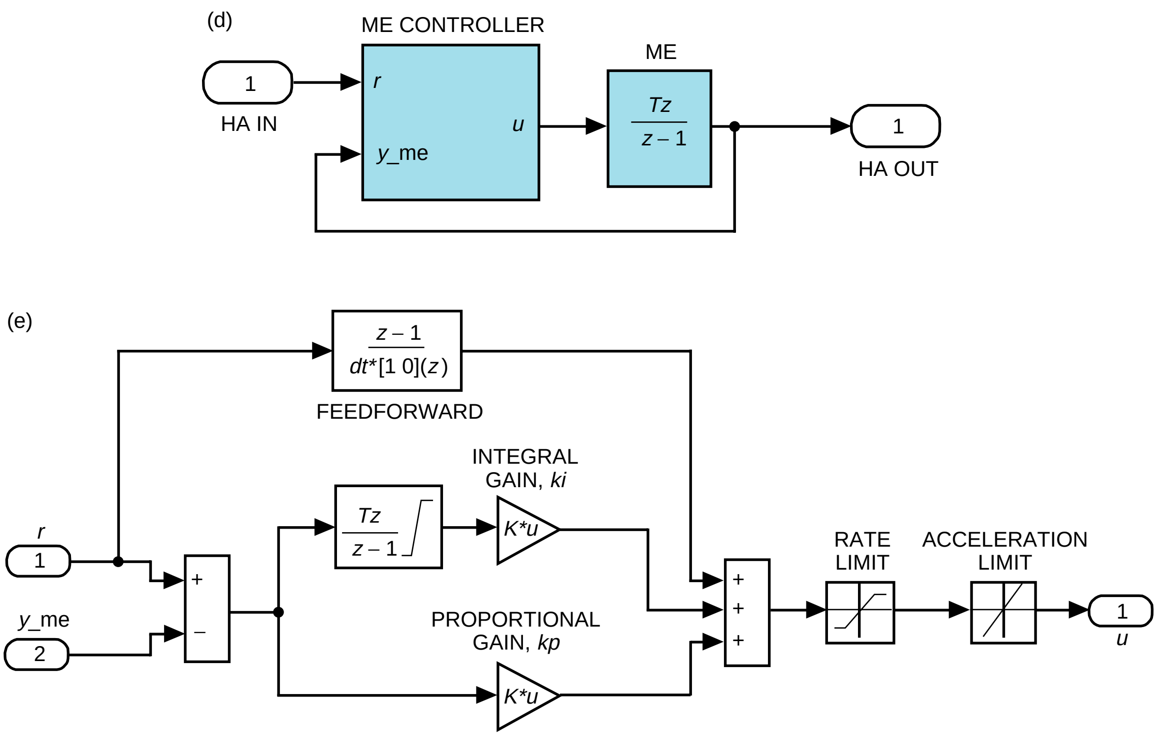

Fig. 4 (contd.).

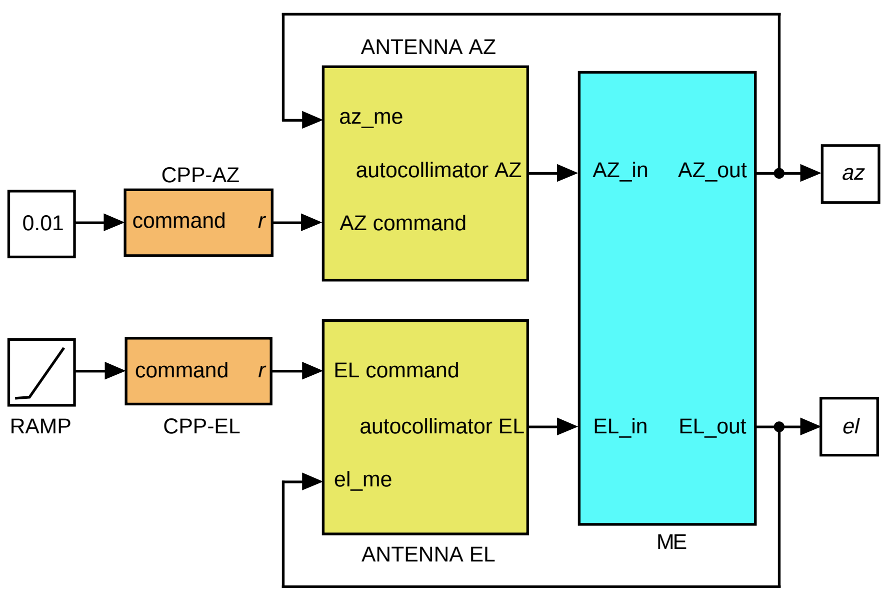

Fig. 5. Antenna and ME, Simulink model, ME encoder mode.

The analysis

(1) Determined the allowable antenna rates, v, and distances, d, near the keyhole for the autocollimator mode and the ME encoder mode.

(2) Modified the ME controller gains to optimize the ME performance near the keyhole. The new gains of the ME controller are the proportional gain, $k_p = 4.0$, and the integral gain, $k_i = 2.5$.

A. Autocollimator Mode

The previously presented test algorithm was simulated. We set the threshold for the ME servo error at ±200 mdeg. The ME servo errors exceeded the threshold when the ME hour rate hit the upper limit. The results of the rate and the corresponding azimuth positions and declination positions are plotted in Fig. 6. A similar relationship between the antenna distance from the keyhole, d, and antenna rate, v, is shown in Fig. 7. The figures show that, for the rate of 0.2 deg/s, the keyhole problem starts when the antenna is at a position smaller than ±7 deg in azimuth, or the declination distance from 84.3 to 95.7 deg. For the sidereal rate of 0.005 deg/s, the distance is 0.175 deg, or the declination position between 89.421 and 90.579 deg.

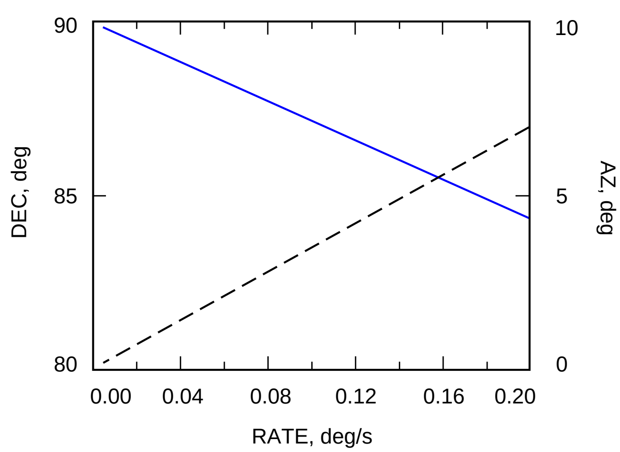

Fig. 6. The azimuth rate and AZ-DEC distance relationship for unacceptable behavior of the antenna near the ME keyhole.

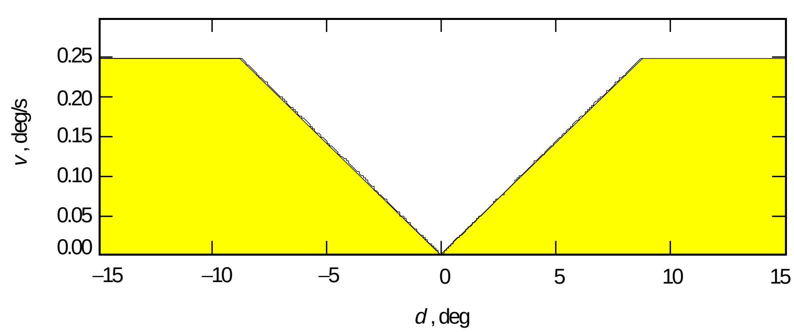

Fig. 7. Azimuth rate and declination position relationship for unacceptable behavior of the antenna near the ME keyhole.

An example of the antenna simulations for an elevation rate of 0.020 deg/s and $az = 0$ deg is shown in Fig. 8; an example for the same rate and $az = 0.69$ deg is shown in Fig. 9. The hour rate and acceleration for the latter case are shown in Fig. 10. This plot shows that the hour rate hits the upper limit of 2 deg/s.

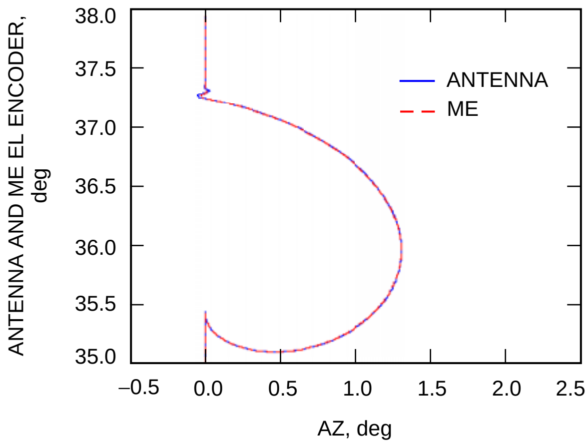

Fig. 8. AZ/EL antenna movement near the ME keyhole, autocollimator mode, for *d* = 0 deg and *v* = 0.02 deg/s.

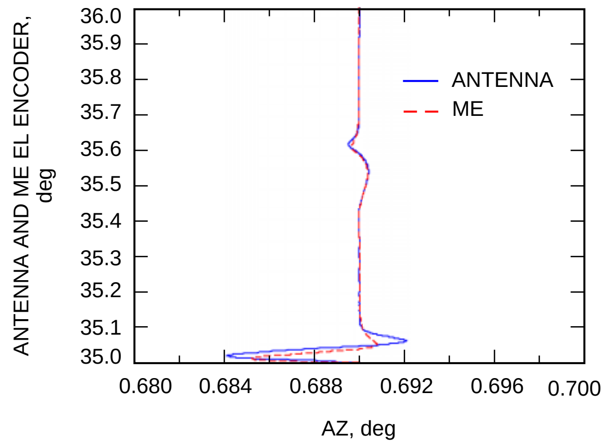

Fig. 9. AZ/EL antenna movement near the ME keyhole, autocollimator mode, for *d* = 0.69 deg and *v* = 0.02 deg/s.

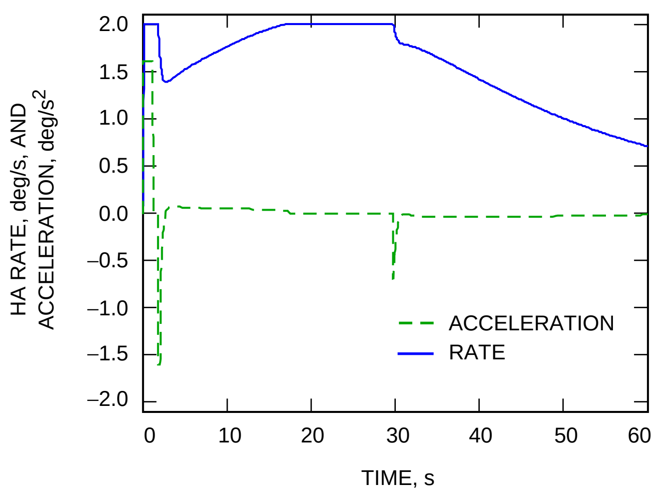

Fig. 10. HA rate and acceleration of the ME near the keyhole, *d* = 0.69 deg.

B. ME Encoder Mode

Similar analyses were conducted for the ME encoder mode, and similar results were obtained, i.e., Fig. 6 applies. However, the situation near the keyhole is different from in the autocollimator mode. In the neighborhood of the keyhole, when the distance and rate exceed the limits, the antenna becomes unstable. This occurs because near the keyhole the ME hits the rate limit and behaves as a faulty sensor that destabilizes the system.

VI. A Single Measure of Unacceptable Behavior of the ME

As we have shown before, the DEC distance from the keyhole combined with the antenna velocity determines the "unacceptable" ME behavior. However, there exists a single indicator that the ME is in trouble: its HA servo error. Indeed, when the ME is close to the ME keyhole, its HA rate must increase to pass near it, and eventually it hits the limit. With the limited speed, the HA error grows significantly; hence, it is a good indicator of ME troubles. Thus, if the error exceeds a selected threshold, it indicates ME problems.

Based on the simulation results, we have chosen an HA servo error threshold of 0.2 deg to indicate ME troubles. If the threshold is set lower, disturbances may activate the indicator. If the threshold is set higher, ME troubles are indicated too late.

VII. Mode Switching Near the Keyhole

The above analysis showed that near the keyhole the ME was slow, causing antenna lagging (in the autocollimator mode) or antenna instability (in the ME encoder mode). In order to prevent lagging or instability, it is recommended that near the keyhole one switch: eliminate the ME and include the antenna encoder. Since the HA servo error of the ME grows significantly near the ME keyhole, the moment of switching is determined by measuring this error, and the switch is triggered when the HA error exceeds the specified threshold.[2]

In the following sections, we analyze the antenna dynamics during and after switching, both in the autocollimator mode and in the ME encoder mode. Since an unwanted jitter may appear after switching, tools to smooth the jitter need to be proposed.

VIII. Switching at the Autocollimator Mode

In this mode, the ME is outside the antenna feedback loop; therefore, its delays near the keyhole do not destabilize the antenna. Also, adding filters to the ME does not destabilize the antenna; hence, we have the freedom to modify the ME to smooth the jerks during switching.

A. Smoothing Jerks with the CPP

The Simulink diagram of the control system with switching from the autocollimator to the antenna encoder mode is shown in Fig. 11. The control system consists of

(1) Command preprocessors in AZ and EL (CPP-AZ and CPP-EL).

(2) ME control system in HA-DEC coordinates. Although its inputs and outputs are in AZ-EL coordinates, the HA error is additional output of the ME that triggers the switches.

(3) AZ and EL switches.

(4) Command preprocessors (CPP-AZ1 and CPP-EL1) that preprocess jerky AZ and EL positions after switching.

(5) Antenna control systems in AZ and EL (labeled "antenna AZ" and "antenna EL").

This control system is similar to the one shown in Fig. 4, except for the switches and the CPPs right after the switches. Normally the control system works with the switches at the lower position. In this position, the ME is included in the system, and the ME position is compared with the antenna position (using the autocollimator). The resulting servo error (at the autocollimator) closes the feedback loop.

When the ME HA error exceeds the threshold value of 0.2 deg, the switches are moved to the upper position. With the switches at the upper position, the ME is bypassed, and the command is directly

[2] The exact threshold value should be determined during field tests, and currently the threshold of 0.2 deg is assumed.

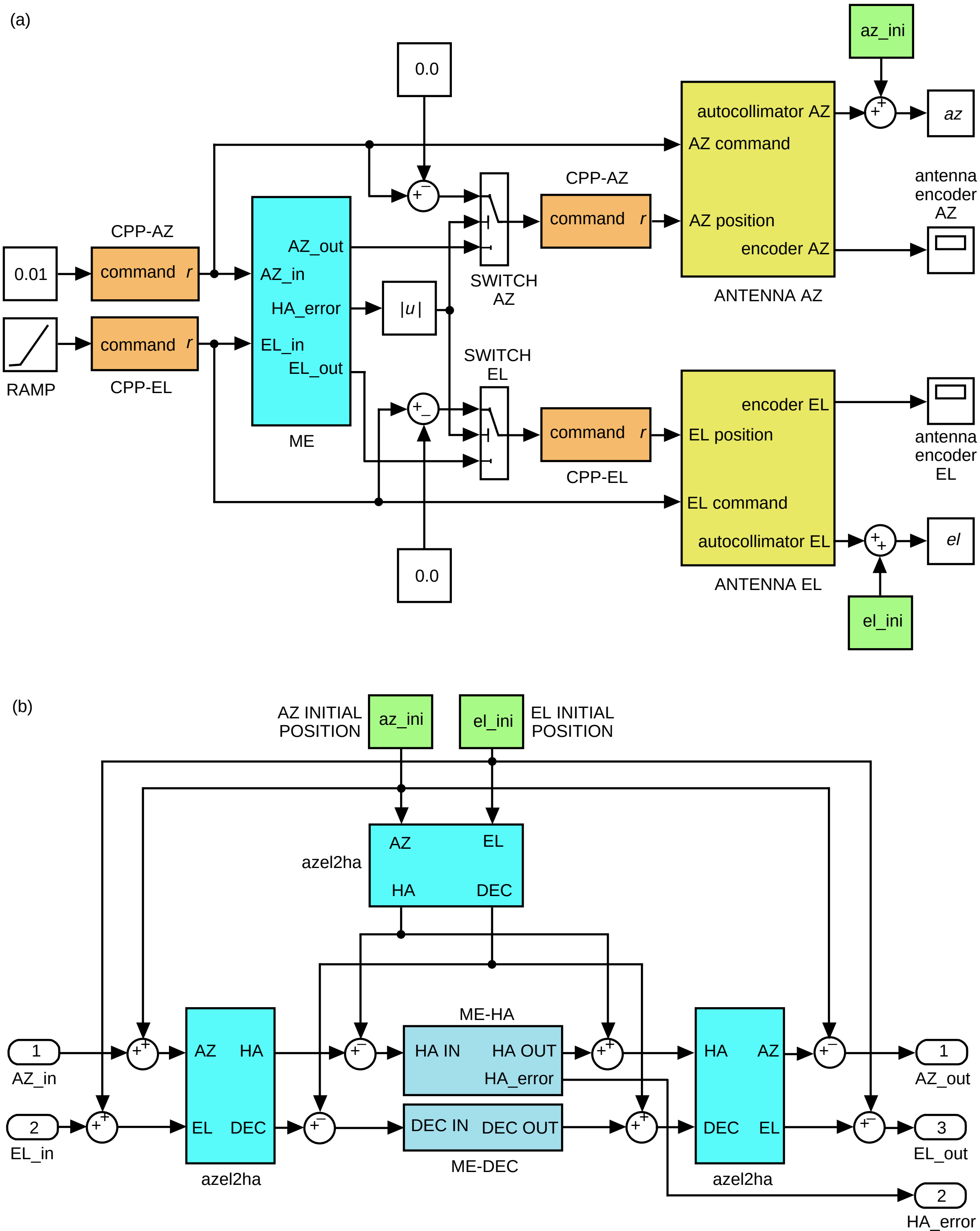

Fig. 11. The Simulink diagram of the control system with switching from the autocollimator to the antenna encoder mode: (a) overall system and (b) ME subsystem.

transmitted into the antenna and compared with the antenna encoder position to close the feedback loop. Consequently, the switch at the lower position engages the autocollimator to close the feedback loop, while the switch at the upper position engages the encoders to close the loop.

In order to simulate and observe the switching near the keyhole, we keep the antenna at the constant AZ position of 0.6 deg and move it upward in EL at a rate of 0.1 deg/s, starting from the EL position of 34 deg. In this movement the ME will be positioned close to the keyhole, and the HA error will exceed the threshold value of 0.2 deg. Indeed, the plot of the HA error in Fig. 12 shows two moments of crossing the ±0.2-deg value. One appears between 21 and 25 s (where three crossings were observed, at 21.2 s, 21.8 s, and 24.8 s), and the second between 99 s and 102.2 s (where five crossings were observed, at 99.0 s, 99.3 s, 100.9 s, 101.4 s, and 102.2 s). As we see, multiple switches typically occur when transferring from the autocollimator to the antenna encoder mode.

1. Results of Switching at the AZ Axis. The plot of the AZ signal just after the "switch AZ" (see Fig. 11) is shown in Fig. 13(a). We can see the effect of multiple switching in the form of spikes that exceed the antenna rate and acceleration limits. The command preprocessor CPP_AZ1 serves as a filter to smooth the spikes. The result of smoothing is the plot of the signal just after the CPP_AZ1 [see Fig. 13(b)]. It is much smoother; in fact, it does not exceed the antenna rate and acceleration limits.

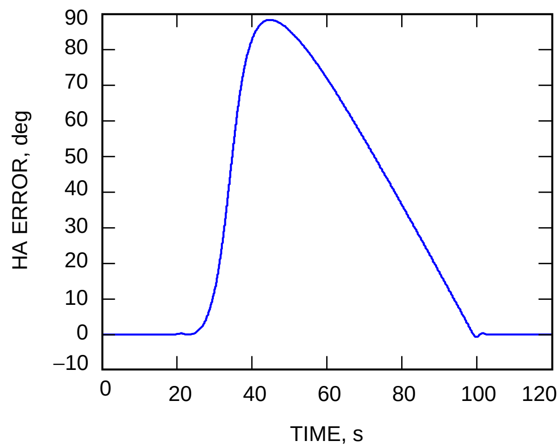

Fig. 12. ME servo error, HA component.

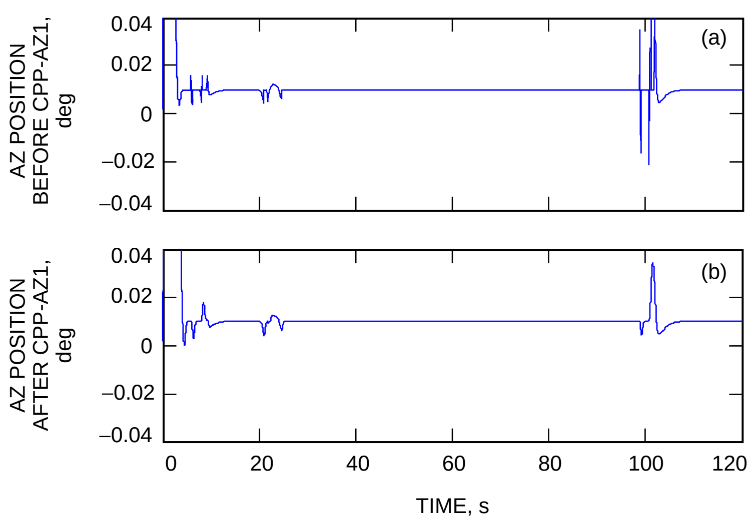

Fig. 13. AZ signal (a) after switch AZ in Fig. 11 and (b) after CPP_AZ1 in Fig. 11.

The antenna position due to this command is shown in Fig. 14. It shows that the antenna controller closely follows the smoothed command.

2. Results of Switching at the EL Axis. The plot of the EL signal just after the "switch EL" (c.f., Fig. 11) is shown in Fig. 15(a). At first sight, it does not show jitter due to the switch. This is because the variations are small. They can be visible after removing the trend, as in Fig. 15(b). This figure shows multiple switching (spikes), similar to the AZ axis case. Figures 16(a) and 16 (b) show the same signal after passing the CPP_EL1. The command preprocessor smoothes the switching spikes. Finally, the antenna EL servo error is shown in Fig. 17. The switching causes servo error less than 2 mdeg, and the time of the switching transient is about 5 s.

B. Smoothing Jerks with the Low-Pass Filter

The jerks created by switching can be smoothed by replacing the CPP with a low-pass filter. This approach is currently implemented, with the filter proposed by Nickerson [2]. The filter transfer function is as follows:

$$G(s) = \frac{15}{s^3 + 6s^2 + 15s + 15} \tag{5a}$$

(analog), and

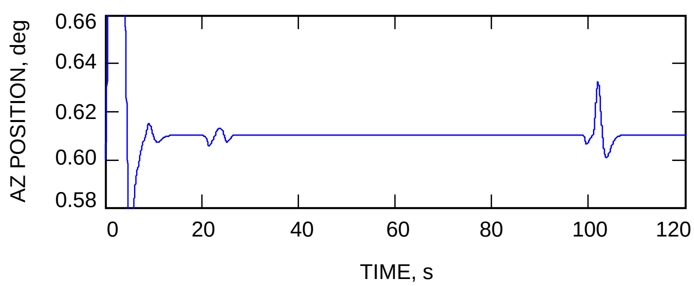

Fig. 14. Antenna position measured at the AZ encoder.

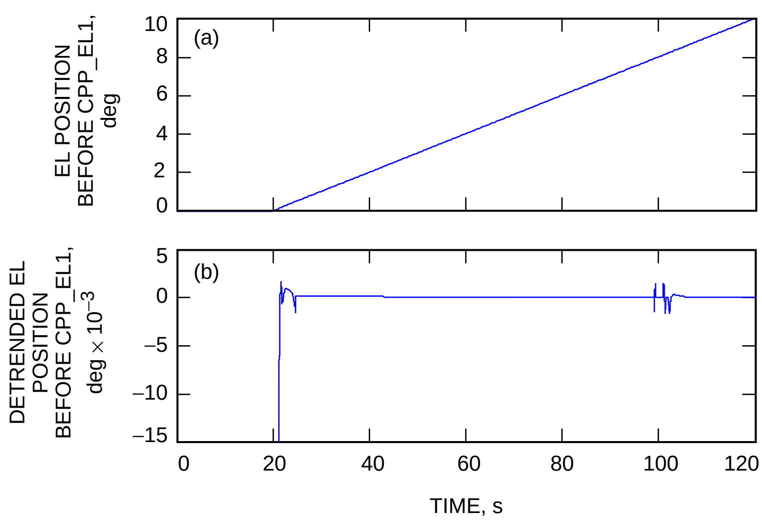

Fig. 15. EL signal after switch EL in Fig. 11: (a) original signal and (b) detrended signal.

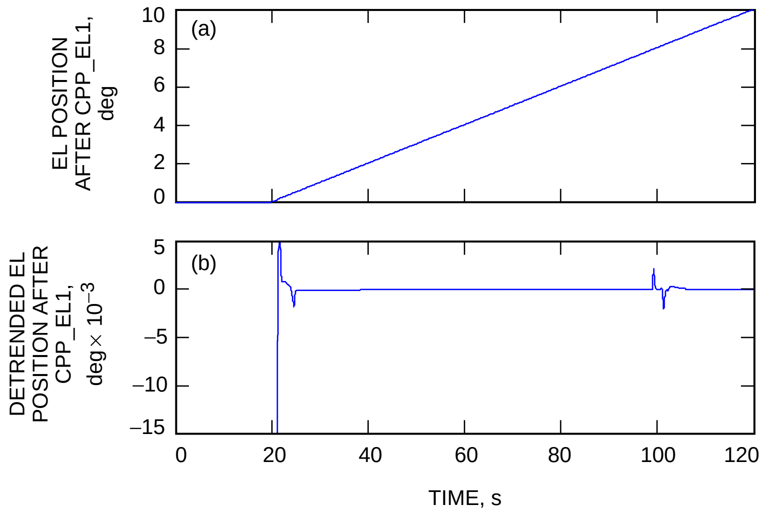

Fig. 16. EL signal after CPP_EL1: (a) original signal and (b) detrended signal.

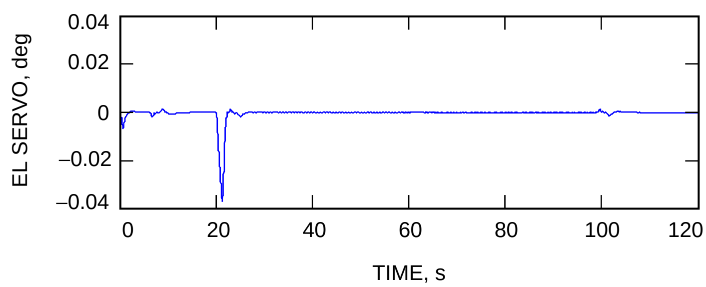

Fig. 17. Antenna position error measured at the EL encoder.

$$G(z) = 10^{-4} \frac{0.1941z^2 + 0.7534z + 0.1828}{z^3 - 2.8812z^2 + 2.7682z - 0.8869} \tag{5b}$$

(digital, with a sampling time of 0.02 s). The plot of this transfer function is shown in Fig. 18. From the plot, we can find that the filter bandwidth is 0.28 Hz.

1. Switching at the AZ axis. The plot of the AZ signal just after the "switch AZ" is shown in Fig. 19(a), with multiple switching in the form of spikes. The filter smoothes the spikes, as shown in Fig. 19(b). The antenna with filter response, shown in Fig. 20, is smoother than the antenna with CPP response (see Fig. 14).

2. Switching at the EL axis. The effect of switching is similar to that at the AZ axis and is not shown.

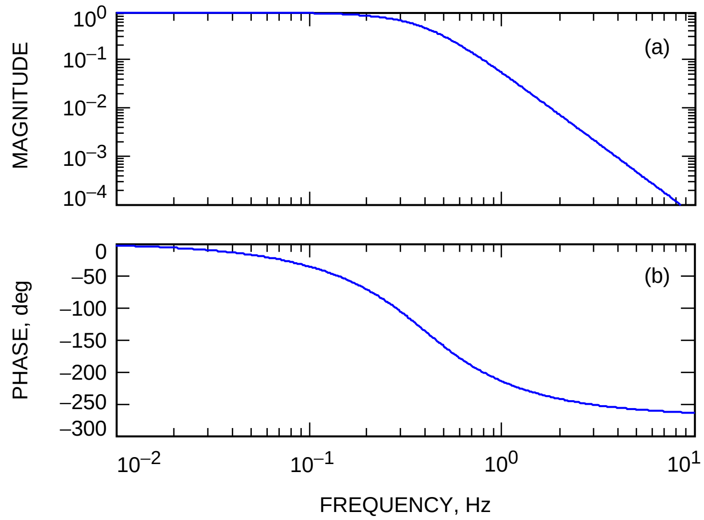

Fig. 18. Low-pass filter transfer function: (a) magnitude and (b) phase.

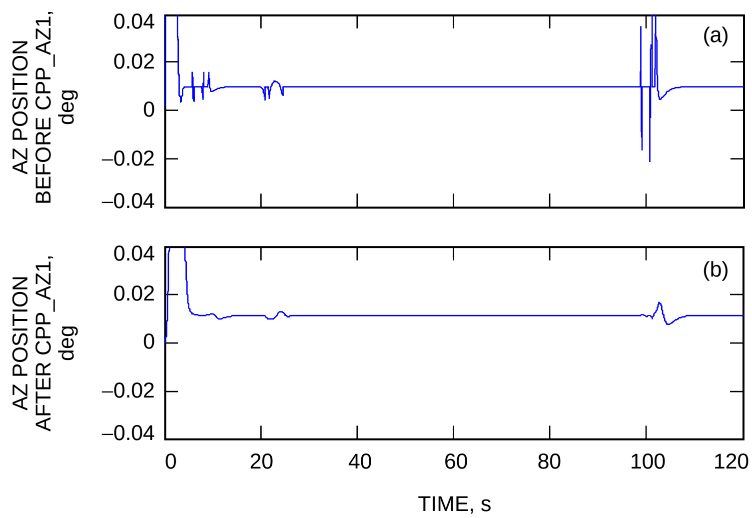

Fig. 19. AZ signal (a) after switch AZ in Fig. 11 and (b) after filter CPP_AZ1 was replaced with the filter in Fig. 11.

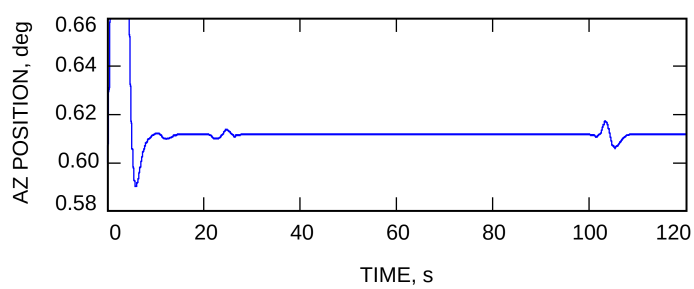

Fig. 20. Antenna position measured at the AZ encoder.

C. Comparison of the CPP and Filter During Switching

The CPP and the filter were implemented to smooth the effect of switching. The analysis produced the following conclusions:

(1) The filter produces smoother transition than the CPP during switching.

(2) The filter produces bias (i.e., steady-state error); thus it must be removed after switching. The CPP does not produce bias; hence it does not have to be removed after switching.

IX. Switching at the ME Encoder Mode

The ME encoder-mode Simulink diagram is shown in Fig. 21. In this mode, the ME follows the antenna, and as such it serves as a sensor to the antenna. In this mode, the ME is a part of the antenna feedback loop, and its modification impacts the antenna stability. Thus, action similar to that taken in the autocollimator mode—adding the additional CPP or filter after the switch—will not smooth the jitter. Instead, it will cause instability of the system. For this reason, we leave the ME encoder mode without the CPP or filter that smoothes the switching jerks.

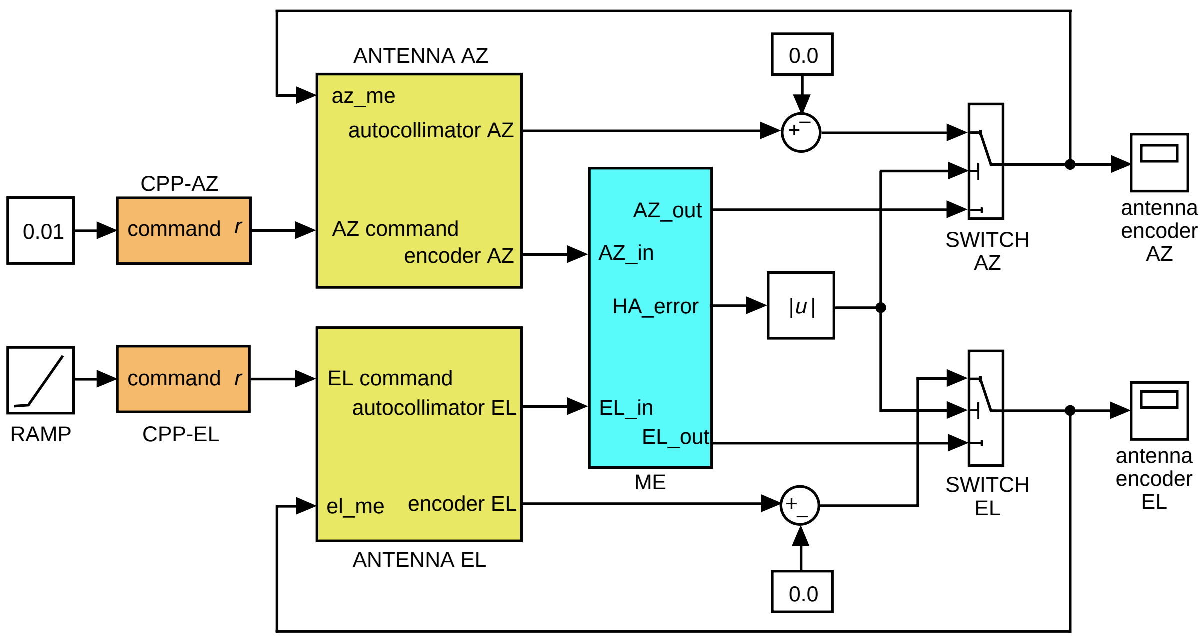

Fig. 21. Simulink diagram of the ME encoder mode.

Thus, the two configurations differ significantly. In the autocollimator mode, the antenna performance can be improved by adding an additional CPP or filter, while, in the ME encoder mode, the performance cannot be improved by adding filters or a CPP.

The performance of the ME encoder system with switching near the ME keyhole is illustrated in Figs. 22 through 24. Figure 22 shows the absolute value of the HA error that triggers the switches. The switch is triggered at 25.5 s and 101–105 s. Figure 23 shows the antenna AZ position. The error during the first switch is less than 2 mdeg and is smooth (no multiple switching appeared), and the error at the second switch (at time 101 s) is larger—up to 25 mdeg—and jerkier, due to multiple switches.

However, if one compares the autocollimator mode and the ME encoder mode, the switching errors are of the same amplitude—despite the lack of a filter in the latter mode. This phenomenon is due to the disturbance rejection properties of the closed-loop system: the switching jerks are within the loop and are suppressed in the ME encoder mode. They were outside the loop in the autocollimator mode, and they needed to be suppressed by adding a filter.

A similar situation is observed at the EL axis [see Figs. 24(a) and 24 (b)]. The servo error is small, despite the lack of a smoothing filter.

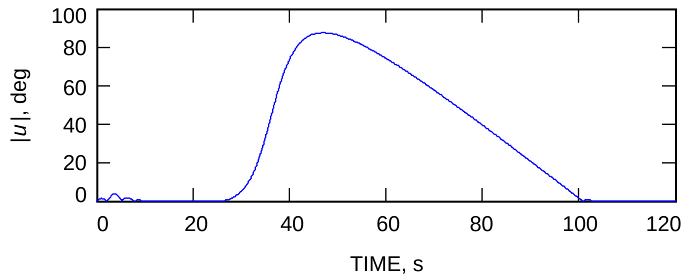

Fig. 22. Absolute value of the HA error.

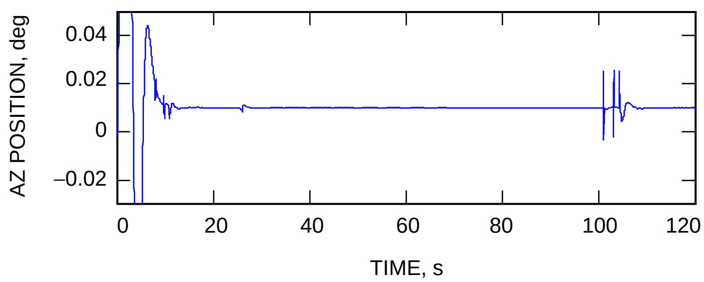

Fig. 23. Antenna AZ position.

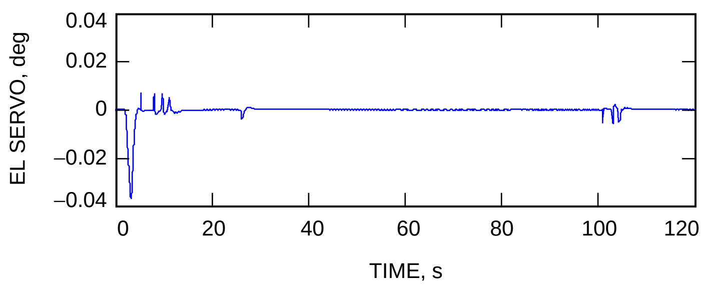

Fig. 24. Antenna EL servo error.

X. Conclusions

The autocollimator mode and ME encoder mode show that the behavior of the ME near its keyhole is unacceptable. This unacceptable behavior is expressed as large servo error for a prolonged period of time or as an unstable antenna. The distance from the keyhole where this behavior appears depends on the antenna rate and is summarized in Fig. 7. It follows from this figure that for the rate of 0.2 deg/s the distance is 7 deg, and for the sidereal rate of 0.005 deg/s the distance is 0.18 deg. The ME servo error rises dramatically near the keyhole, and it will serve as an indicator of unacceptable behavior of the antenna; when its value exceeds 0.2 deg, the antenna servo will switch to the antenna encoder mode.

The jerks during switching were analyzed in the autocollimator and ME encoder modes. In the AC mode, the switch is outside the position feedback loop; in the MEE mode, the switch is inside the loop.

The analysis showed that

(1) Multiple switches occurred when transferring from the modes.

(2) In the autocollimator mode, the CPP or low-pass filter smoothed the jerks.

(3) The filter has better smoothing properties but causes steady-state error. For this reason, if implemented, it shall be removed shortly after the switch.

(4) In the ME encoder mode, neither the filter nor the CPP can be implemented during the switch, since they destabilize the system. However, switching jerks are of the same value as jerks in the autocollimator mode with the CPP, since they were significantly reduced by the system feedback loop.

In this article, the ME and antenna tracking errors of both modes were analyzed near the ME keyhole. For the autocollimator mode, the analysis showed that the ME causes unacceptable errors that last up to 120 s. In the ME encoder mode, the slow ME destabilizes the antenna near the keyhole. This unacceptable behavior in both modes appears because the ME rate at the hour angle hits the limit of 2 deg/s.

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