Pointing-Error Measurements of the Master Equatorial Instrument

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The master equatorial is a precision instrument located on top of a concrete and steel tubular tower that is physically independent of the 70-m antenna structure and designed to direct the antenna in a precision of a few arcseconds by means of an optical link. After more than 30 years of service, the master equatorial may have deteriorated to a point at which the performance is affected. This article is intended to determine the accuracy of the instrument. The detailed setup of pointing-error measurements is presented. The results are shown graphically and discussed in depth with possible causes. The measurements show that the master equatorial has 4-mdeg random pointing error, which will not meet 32-GHz (Ka-band) pointing precision.

I. Introduction

The first DSN master equatorial (ME) instrument was installed on the DSS-14 (then 64-m) antenna back in 1964. The ME has operated nearly continuously since, having had only one (minor, as discussed below) mechanical refurbishment through transitions of computerization, a 64-m to 70-m upgrade, and two major earthquakes.

The ME resides on top of a steel tubular tower resting on a concrete foundation that is physically independent of the antenna structure and foundation. It is located such that its hour-angle (HA) and declination (DEC) axes' intersection is coincident with that of the antenna's azimuth (AZ) and elevation (EL) axes. Figure 1 shows the orientation of the master equatorial. This type of mount is often used in optical telescopes that provide singular motion in the hour angle, which (virtually) accounts for the Earth's rotational motions in the equatorial plane, amongst relatively stationary deep-space objects. Instead of the usual primary mirror, the ME has a 177.80-mm flat target mirror that is positioned perpendicularly to the pointing direction.

At the central back of the 70-m paraboloidal dish, one of two autocollimators servo the antenna's drive motors to maintain co-alignment so the main parabolic reflector follows in a direction perpendicular to the ME target mirror. Servo feedback is done by means of a light beam emitted from the

[1] Communications Ground Systems Section.

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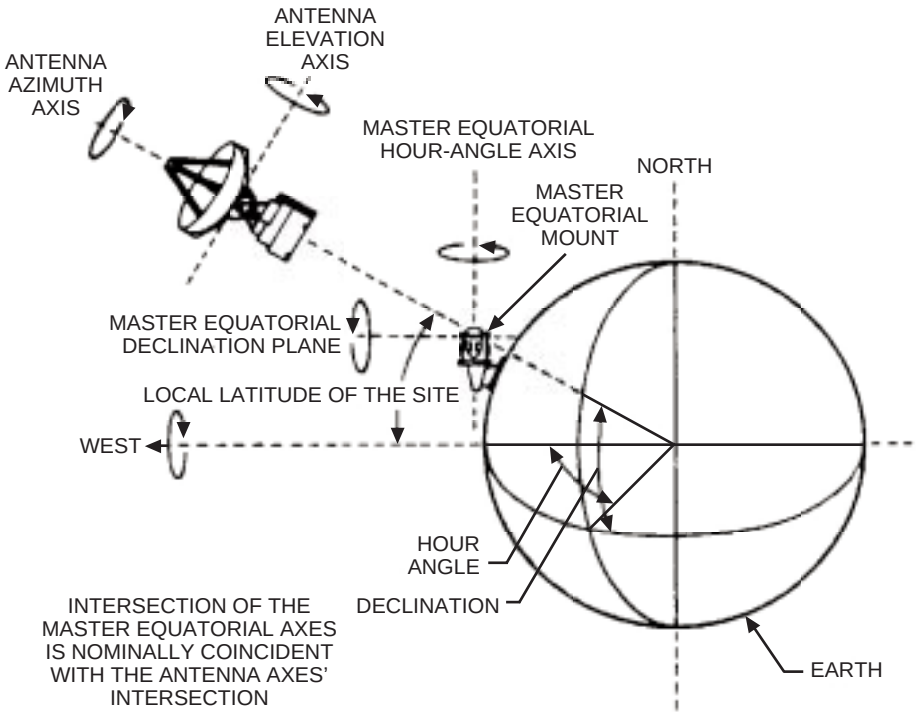

Fig. 1. The master equatorial mount orientation.

autocollimator perpendicularly to the flat ME mirror and reflected back to the autocollimator that generates the angle error voltages for the azimuth/elevation drives. Figure 2 shows how the ME target mirror is linked through the autocollimators to provide error volts to drive the antenna.

Because the positioning of the target mirror controls the azimuth/elevation drives, any imperfections that are present within the ME are translated through the autocollimators to the parabolic dish itself. A preliminary error analysis [1] of the conceptual design of such an instrument was done in 1964, well before the actual instrument was built. The expected accuracy of the master equatorial device was 6 to 7 arcsec at that time. Soon after, further study suggested that the first design could be made more compact. The design specifications were set for a guaranteed defined pointing error of not more than 10 arcsec, with the design goal of 5 arcsec. Following the installation at DSS 14, the first measurements were made on the ME to determine whether the design goal specifications had been achieved. McGinness [2] (1967) utilized a manual opto-mechanical type of autocollimator with special brackets to take measurements and reported that the total error of the ME was between 1.55 and 3.2 arcsec, depending on the method used to combine the error elements. It appeared the design goal had been met with error to spare. Since then, no more of these types of measurements have been conducted for more than 30 years.

A representative of the original contractor, Perkin Elmer, mechanically evaluated the ME mount structures in 1984 and recommended cleaning and lubrication. Water intrusions in 1992 slightly damaged the rain shield and hour-angle worm gear at DSS 14. Mechanical maintenance was performed at that time, which involved rework and bearing replacement of the hour-angle worm gear. At DSS 43, significant hour-angle worm gear rework and mechanical maintenance were performed due to a similar type of water intrusion.

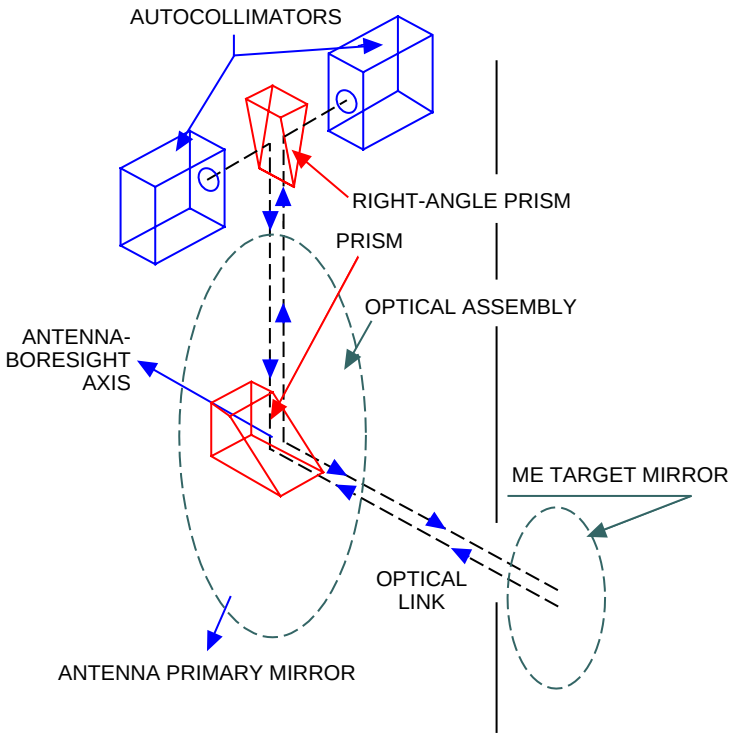

Fig. 2. The optical link between the antenna and the master equatorial instrument.

II. Measurement Setup

The measurement setup is shown in Fig. 3. The pointing vector, perpendicular to the ME target mirror (mounted at the center of the declination axis), is nominally determined by the two angles of this dual-axis mount, namely the primary hour angle (HA), or polar axis, and the secondary axis, or declination axis (DEC). The HA/DEC encoders measure the angular displacement of the shaft ends of each axis in degrees, continuously from 0 to 360. (Often the angle encoders for the secondary polar device axis (declination) instead provide ±90-deg reference.) For the ME, the zero hour angle starts at the local vertical (or meridian crossing) and increments clockwise 360 deg (looking from the north). Zero declination, on the other hand, starts at the plane of the Earth's equator and increments clockwise 360 deg (looking from the east). On a perfect instrument, these two angles correspond to the angular displacement of each respective axis and are the intended reference for these accuracy measurements.

Due to imperfections of the ME, the mirror-pointing vector does not correspond exactly to the displacements of the shaft ends; nor are the axes perfectly aligned. The pointing error is defined as the hour-angle and declination difference angles between the ME mirror vector (as read by the encoders) and those of a perfect instrument. The principal factors contributing to the defined pointing error are alignment of the mirror, run out of the mirror, lack of perfect orthogonality between the hour-angle and declination axes, dimensional changes from temperature gradients, and normal wear of the moving parts. The measurements conducted in this study were done to determine the overall pointing error of the ME. Little attempt was made to find out how much each of the above principal factors contributes to the overall error.

The measurements setup was based on how the ME was built to work. A spare dual-axis autocollimator was used in two different positions to accomplish the measurements. For the polar axis, the autocollimator was attached to a special bracket fixed to the base of the ME, looking up north through the hollow shaft to the back of the mirror mounted at the center of the declination shaft (Fig. 4). Efforts were made to

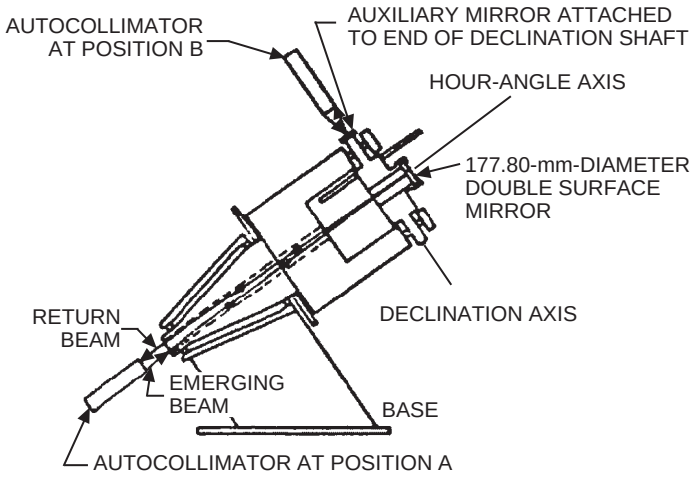

Fig. 3. The autocollimator configuration as a measuring device on the master equatorial.

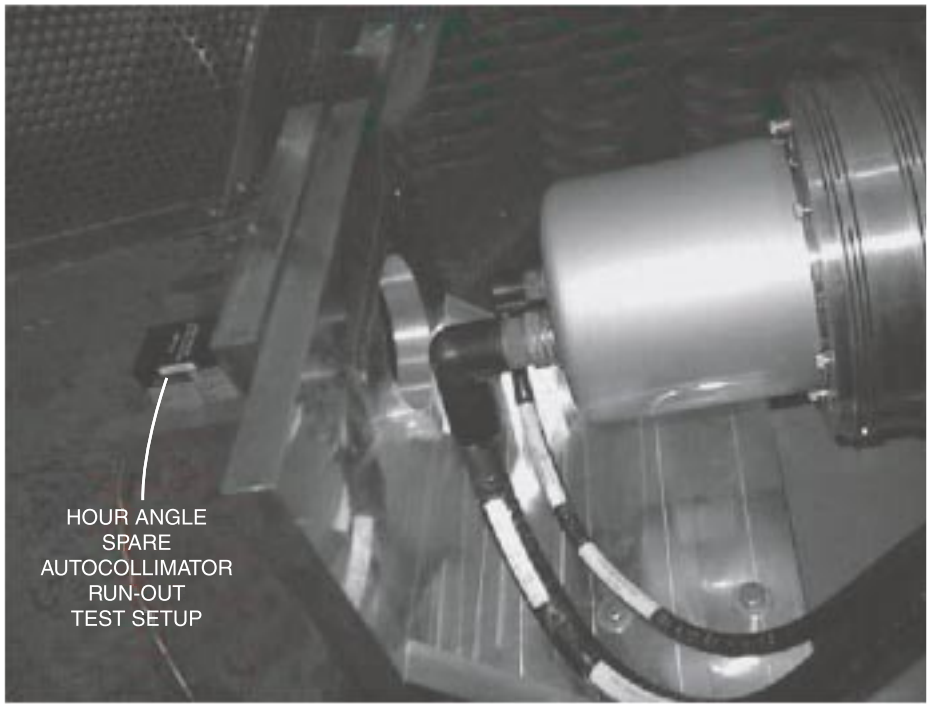

Fig. 4. Hour-angle brackets fixed to the base of the master equatorial.

align the brackets so that the emerging light beam generated from the autocollimator was almost parallel to the polar axis of the ME. To do this, the bracket was adjusted to reduce the amplitude of the recorded sine-curve pattern from the autocollimator output during hour-angle rotation about the polar axis. The declination axis was positioned in the vicinity of either 90 or 270 deg to obtain the best perpendicularity between the mirror surface and the polar axis.

For the declination axis, the autocollimator was attached to another special bracket fixed to one fork leg of the ME, and its emerging beam was reflected back from a 76.20-mm-diameter auxiliary plane mirror attached to the end of the declination axle (Fig. 5). A similar alignment effort was made to reduce the alignment error from the auxiliary mirror and the bracket. Alignment of the rotating axis errors was determined by comparing the autocollimator readings at both 90 and 180 deg apart.

A PC laptop computer with the National Instrument data acquisition card running Lab View was used to take the autocollimator dual-axis readings and the corresponding encoder readings through the normal station cabling down to the alidade. All the data were acquired at a rate of 1 deg/s continuously with the hour angle rotated more than 360 deg and the declination rotated from 90 to −50 deg to cover the tracking ranges.

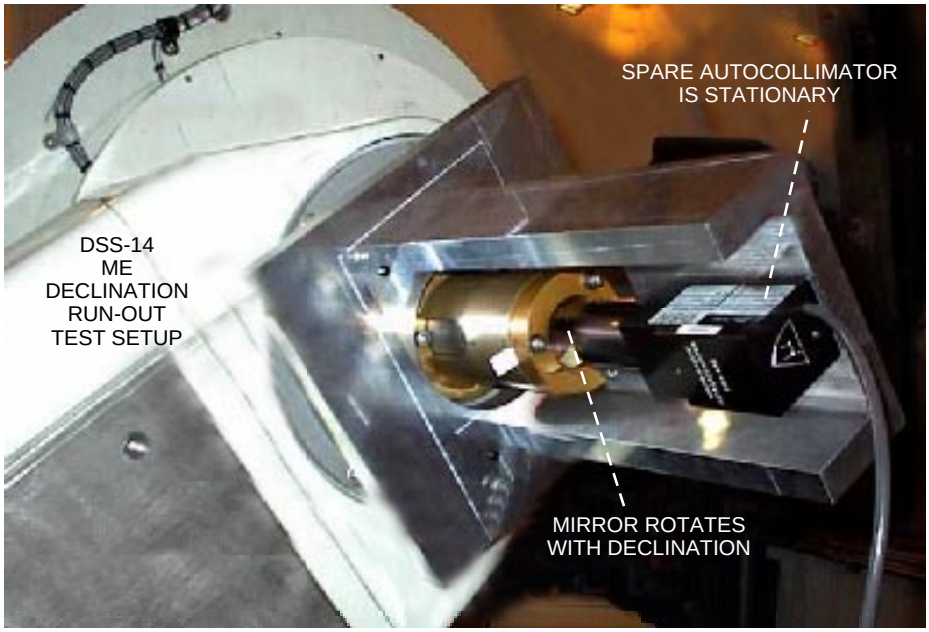

Fig. 5. Declination brackets fixed to one fork leg of the master equatorial.

III. Results and Discussion

Measurements were taken on the polar axis and declination axis. Extra efforts were taken to align the autocollimator and to approach the mirror's true perpendicular position. Initial measurements suggested the ME error in the hour angle was about ±20 mdeg. Later it was found that the declination encoder reading of 90 deg does not represent the mirror's true perpendicular position to the polar axis.

Table 1 gives a few cases measured for errors on the polar and declination axes. Cases 1 through 3 measured the hour-angle axis from 330 deg rotated counterclockwise more than 600 deg and returned. For each case, only one variable was changed so that one could see each effect. The declination axis was positioned to 90.012 deg to obtain the minimum measuring error, suggesting the declination encoder needs resetting to reflect the true perpendicular location of the mirror.

Measurements for Case 1 are shown in Figs. 6 and 7. Figure 6 presents the error with root means square against hour-angle locations. Figure 6(a) shows the actual measurements with a noise level of about 6 mdeg. Figure 6(b) has data smoothing to reveal the trends of the error. The two different colors represent the direction of rotation. The curves have about a 7-mdeg systematic error with a

Table 1. Error measurements of the master equatorial.

Case	Measurement range, deg	Measurement conditions	Error repeatability	
			Systematic, rms	Random, mdeg
		Hour angle		
1	330 to −330 and back (ACS mode)	DEC locked at 90.012 with spring aid (DEC observed 3- to 4-mdeg fluctuations)	7	1
2	330 to −330 and back (ACS mode)	DEC locked at 90.012 (DEC observed 3- to 4-mdeg fluctuations)	7	1
3	330 to −330 and back (ACS mode)	DEC set at 90.012 as it is in tracking (DEC observed 8-mdeg fluctuations)	8	4
		Declination		
4	90 to −30 and back (tracking range, ACS mode)	Hour angle locked at 0.5	10	0.2
5	200 to −152 (main mode)	Hour angle locked at 0.5	10	0.2

1.0-mdeg band of random error. The eccentricity of the curve is about 1.0 mdeg, indicating the misalignment of the measuring device to the rotating polar axis. Figure 7 shows the errors in Cartesian coordinates. Figure 7(a) gives the hour-angle encoder readings, while Figs. 7(b) and 7(c) show the error elements with and without the filtering process, respectively. It can be seen that the sinusoidal distributions have an amplitude from 3 to 4 mdeg, which is consistent with the change of the declination encoder reading during the hour-angle rotation. For this case, the declination was locked with a spring aid.

The cross-elevation (XEL) and elevation (EL) data in Fig. 7 indicate the autocollimator test ports used in the DSS-14 alidade, where the autocollimator error signals were routed from the ME room cable on channel two (as used for the antenna controls' precision 2 or "P2 mode"). The orientation of the data labeled XEL is the autocollimator x-axis error output that is representative of hour-angle (east–west) error when the hour angle is 0 or 180 deg. The orientation of the data labeled EL is the autocollimator y-axis error output that is representative of declination (north–south) error when the hour angle is 0 or 180 deg.

Figure 8 shows Case 2, with everything as in Case 1 except for the removal of the spring aid. Comparing Fig. 8 with Fig. 6, one can see that there are no significant changes occurring, indicating the preload motor is sufficient for its purpose.

In Case 3, on the other hand, the clamp used to lock the declination axis and the preload spring aid were removed. The declination axis was set at 90.012 deg without any extra devices, as it is in operation. It was observed that the declination axis had 8-mdeg fluctuations. The error measurements are shown in Fig. 9. The spike of the unfiltering data in Fig. 9(a) was not repeatable and was caused by the data acquisition devices. Therefore, it was neglected. It can be seen in Fig. 9(b) that the error curves change considerably. The random-error bandwidth has increased to 4.0 mdeg, four times the error band in Case 1. Since the declination axis has no mechanical feature (brake) to "hold" a position, it could be a challenge to keep the declination stable within the submillidegree scale in order to fulfill the pointing-accuracy requirement for 32 GHz (Ka-band).

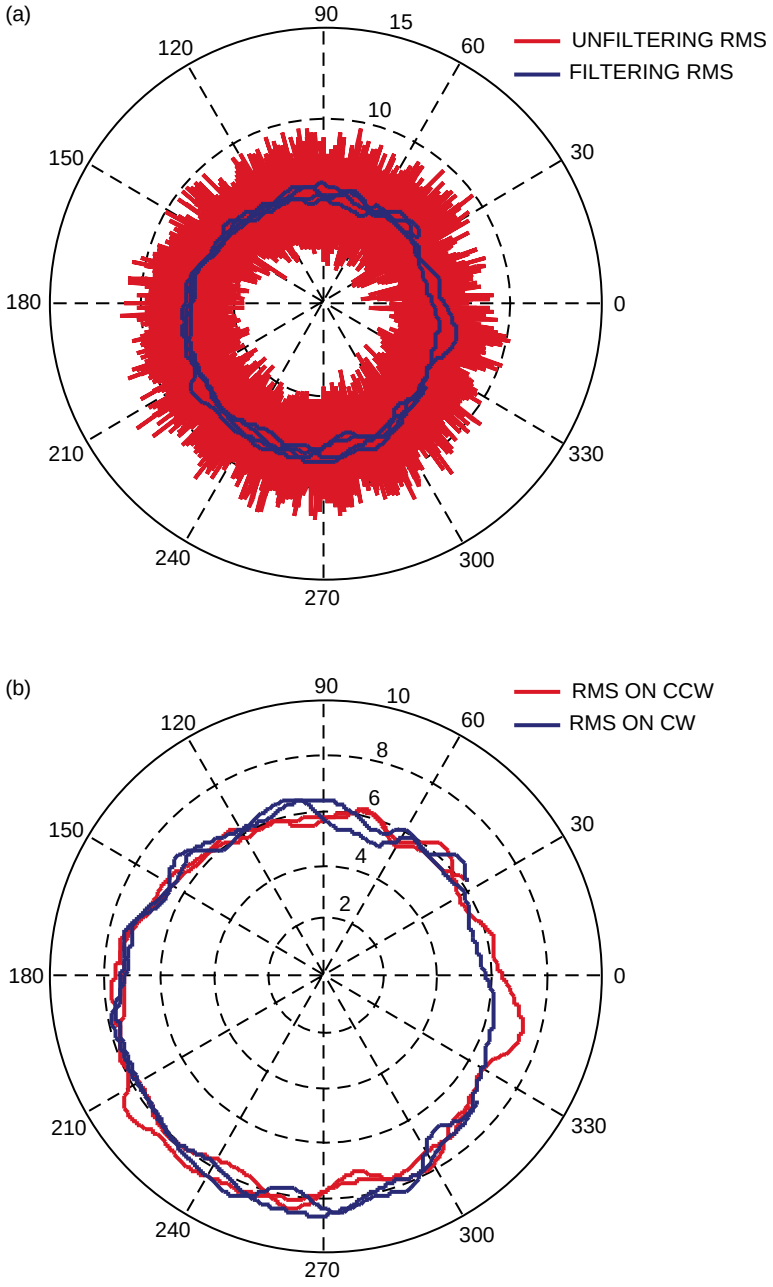

Fig. 6. Hour-angle accuracy versus position in the polar coordinate (from 330 to –330 deg and back): (a) error repeatability and (b) error repeatability with filtering. Declination was locked at 90.012 deg with a spring aid to the preload motor.

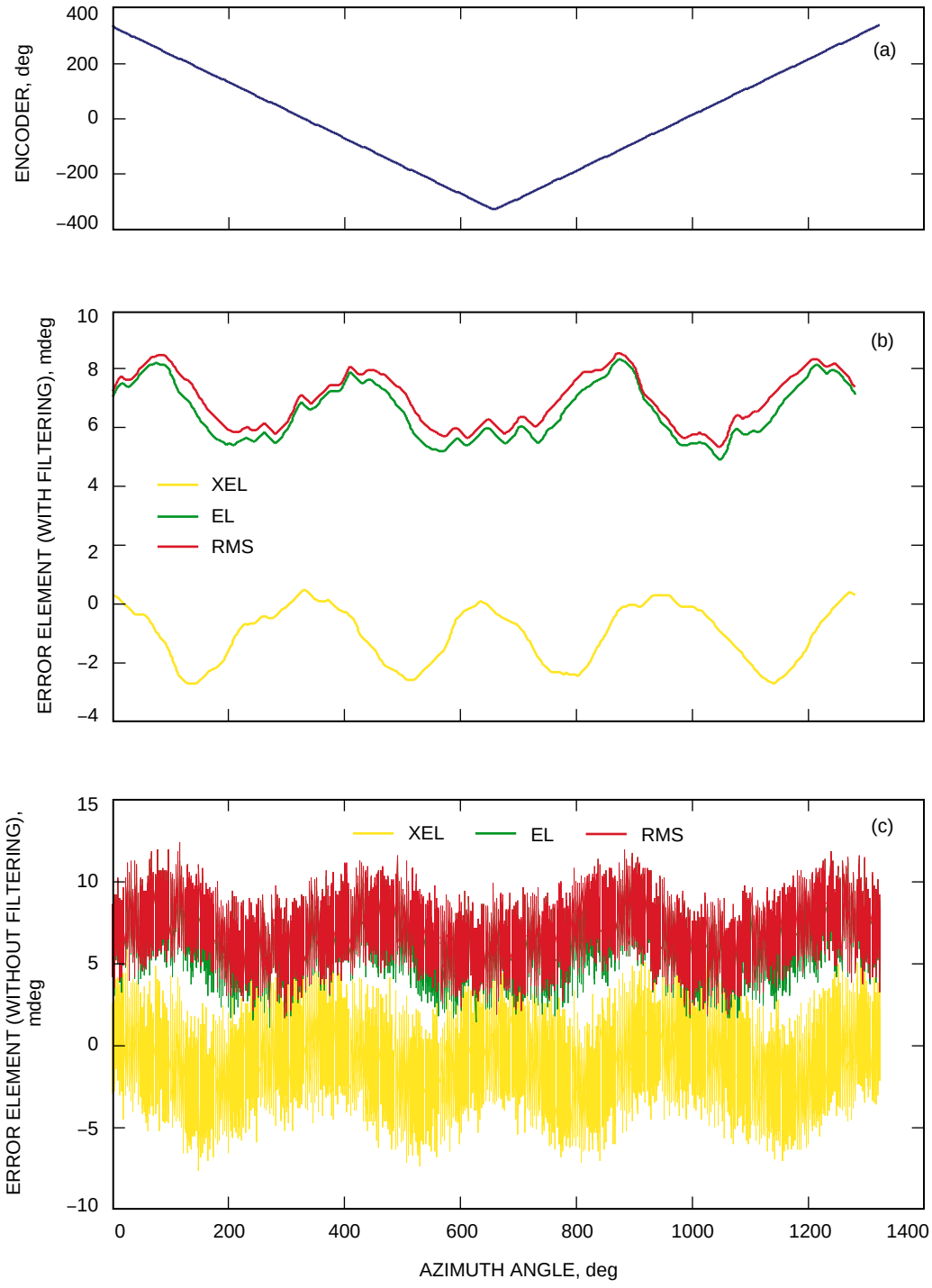

Fig. 7. Hour-angle accuracy versus position in Cartesian coordinates (from 330 to −330 deg and back): (a) hour-angle encoder readings, (b) error elements with filtering, and (c) error elements without filtering. Declination was locked at 90.012 deg with a spring aid to the preload motor.

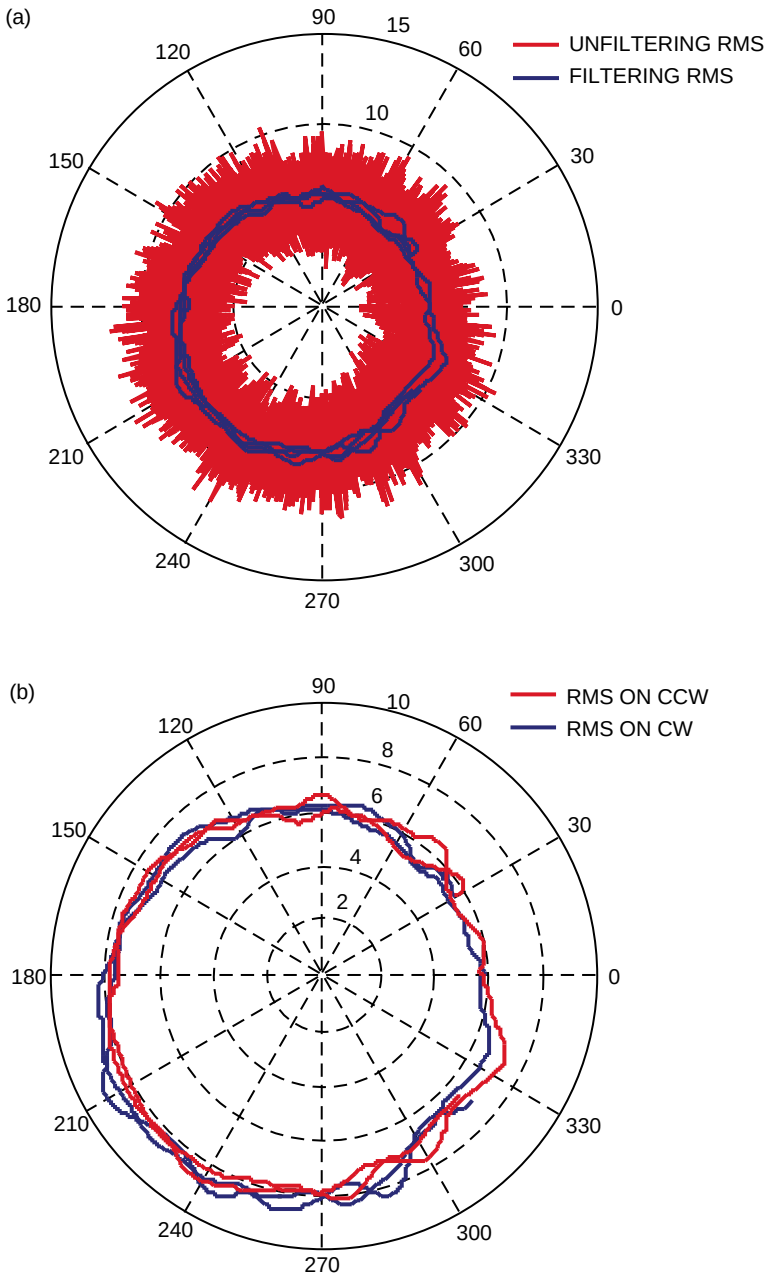

Fig. 8. Hour-angle accuracy versus position in the polar coordinate (from 330 to –330 deg and back) without the spring aid: (a) error repeatability and (b) error repeatability with filtering. Declination was locked at 90.012 deg.

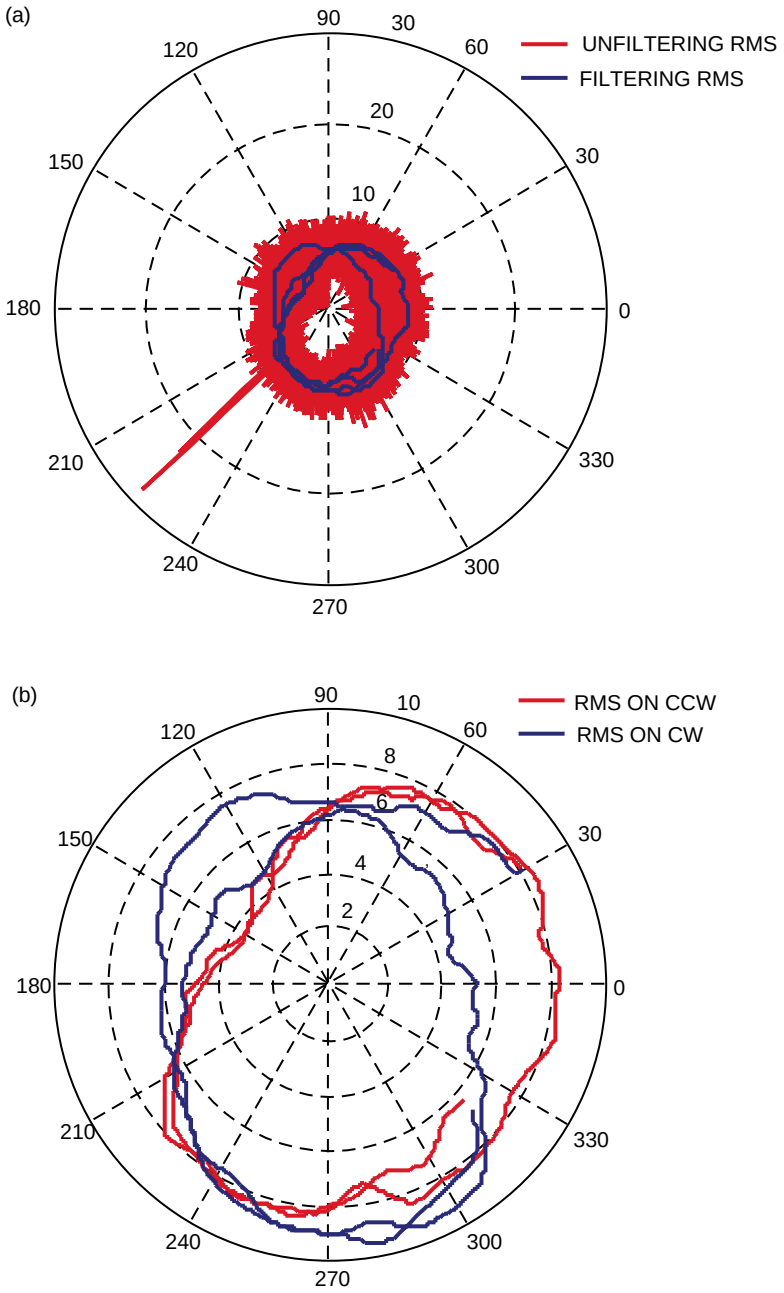

Fig. 9. Hour-angle accuracy versus position in the polar coordinate (from 330 to –330 deg and back) with no clamp on the declination axis: (a) error repeatability and (b) error repeatability with filtering. Declination was set at 90.009 deg.

We also mounted an auxiliary mirror on the decination axis, opposite the existing ME target mirror. It showed very good repeatability, but the overall error was too big since the declination axis was locked at 89.998 deg, away from the true perpendicular position. The results showed no new findings and are not presented in this article. The noise level using the auxiliary mirror, however, was significantly lower (by one-third) than that using the ME mirror because the surface quality of the new mirror is about twice as good as the one used on the ME.

Cases 4 and 5 are error measurements on the declination axis with the hour angle locked at the vicinity of 0 deg. The declination axle was located in the vertical plane so that the declination axis rotation was least affected by any unbalanced weight. Figures 10 and 11 show the measurements from −50 deg to 90 deg (310- through 360-deg and 0- to 90-deg read-out angles), covering all of the tracking range. The error curves in red and blue in Fig. 10 represent the declination rotation clockwise (CW) and counterclockwise (CCW), respectively. The repeatability of the error is considered very good. However, the overall error of 10 mdeg suggested that there was pronounced mounting error in these two cases. The large amplitudes of the sinusoid curves of the error elements in Fig. 11 clearly indicate this. With more than 360-deg declination rotation, as shown in Fig. 12 for Case 5, the eccentricity pattern is about 4 mdeg, indicating the misalignment of the mirror and the autocollimator. Because there were two parts of the declination alignment, in one sense the parts had to reference each other to be aligned, and it was very time consuming.

It is worthwhile to mention again that the position of the declination axis used for Cases 4 and 5 was so chosen that any unbalanced weight is almost ruled out. That is to say, at certain hour-angle orientations, there might exist some random errors that did not appear in this measurement. For a clear vision of the performance of the declination axis, further investigation is needed, with measurements at several different orientations of the hour-angle axis.

Since the scale of the measurements is so small and the measurements were taken at a place other than in a laboratory environment, the results are affected by many things in situ. The noise level, for example, is larger than errors measured and had to be filtered as often as every 10 s in order to obtain smooth curves, as shown in the figures. This would filter noises as well as the vibrations due to the systems.

Looking at Table 1, one can see the overall errors of the ME are considerably larger than the instrument specifications, although most of them are systematic. If we can assume the systematic error can be completely removed, the random errors are less than 1 mdeg with a clamp on the declination axis. However, the declination axis cannot be locked under any circumstances during a tracking mission. In other words, Case 3 is the only case that is close to a tracking condition, in which a random error is about 4 mdeg. The magnitude of this random error is considered to be typical because several similar tests without a clamp on the declination axis gave similar indications. This suggests that, in addition to the error contributors mentioned before, the servo/control and wire wraps of the ME play a significant role in the error buildup. Therefore, the overall random error of the ME is considered to be about 4 mdeg, far beyond the requirement for Ka-band pointing precision.

The master equatorial instrument is no double for a high-precision instrument. What it does is to move a target mirror in very precise hour-angle and declination coordinates to provide a reference for the antenna to drive with. This was certainly a challenge 35 years ago, as complex mechanisms were designed for positioning and adjusting two axes with customized designed drives built in to the two axes. After reading the drawings, it appears that the systems were designed and built with minimum maintenance expected. Access to the internal mechanisms without disassembly is, therefore, very limited.

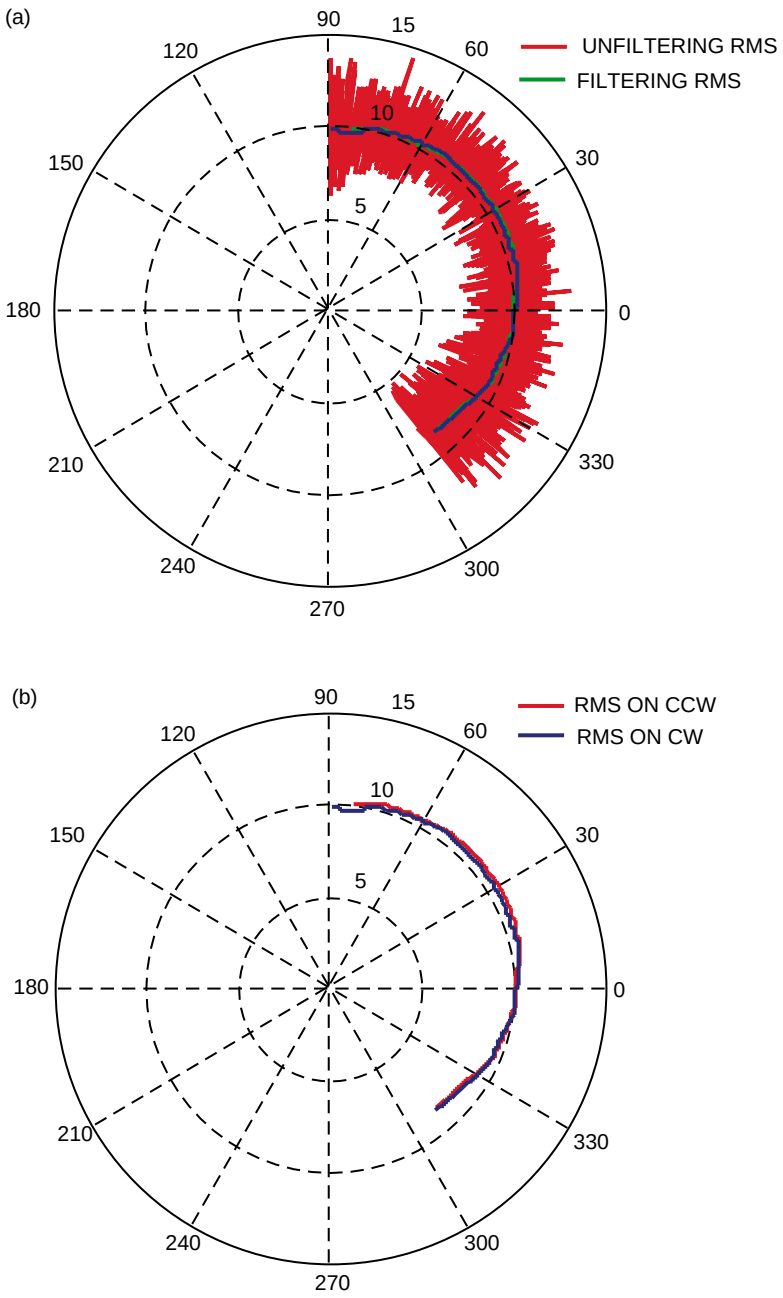

Fig. 10. Declination accuracy versus position in the polar coordinate (from 90 to 310 deg and back): (a) error repeatability and (b) error repeatability with filtering. Hour angle was locked at 0.547 deg.

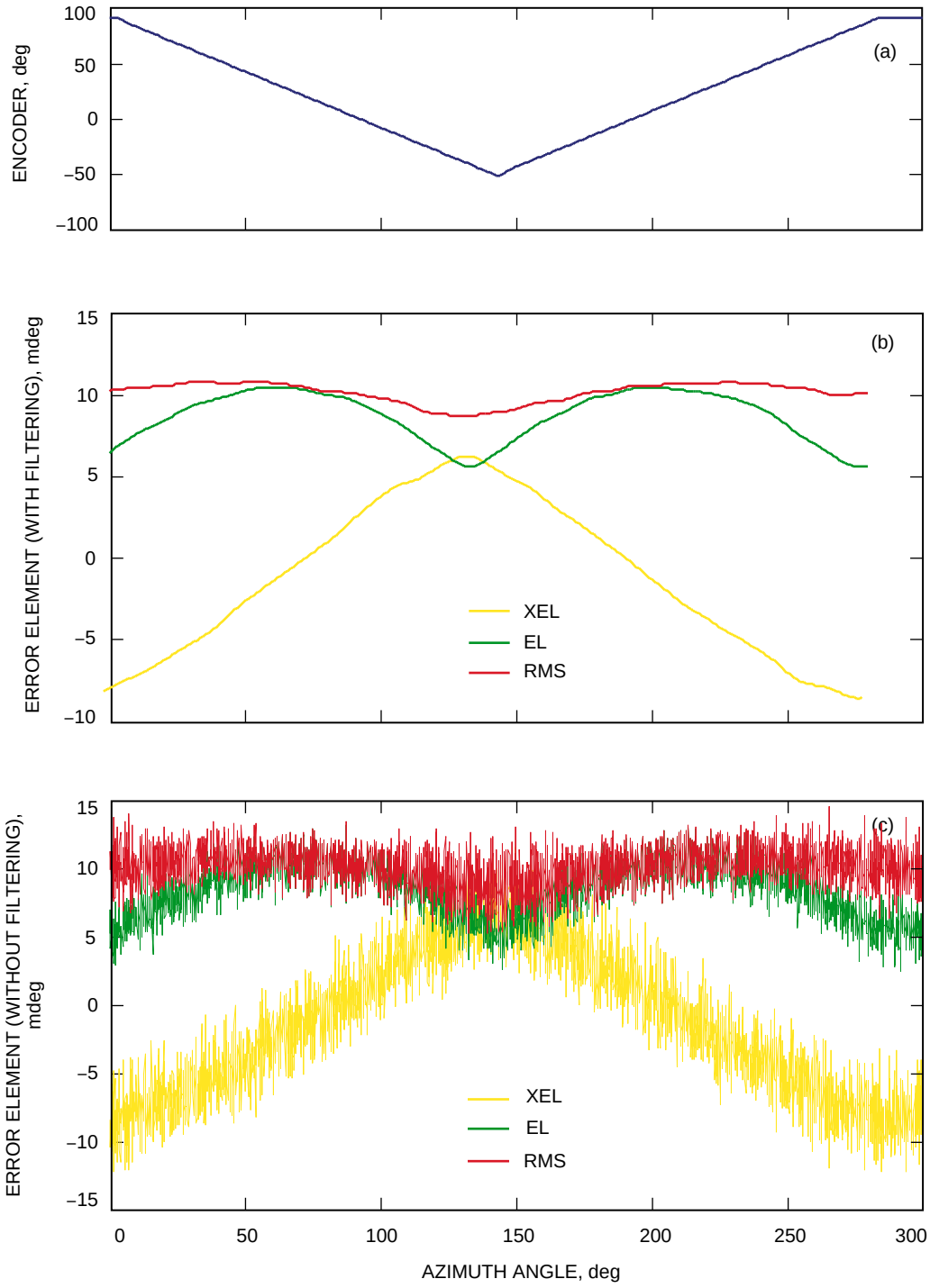

Fig. 11. Declination accuracy versus position in Cartesian coordinates (from 90 to 310 deg and back): (a) declination encoder readings, (b) error elements with filtering, and (c) error elements without filtering. Hour angle was locked at 0.547 deg.

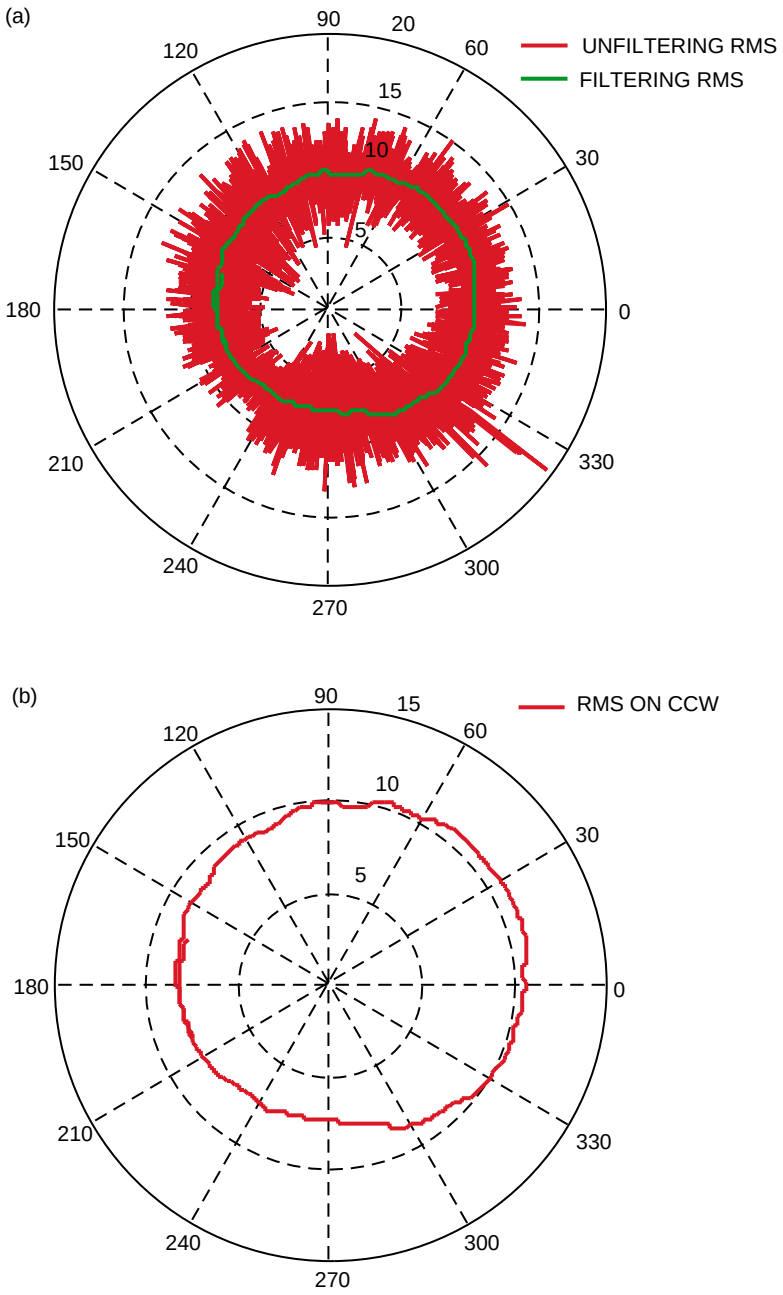

Fig. 12. Declination accuracy versus position in polar coordinates (from 200 to –152 deg): (a) error repeatability and (b) error repeatability with filtering. Hour angle was locked at 0.547 deg.

IV. Conclusions and Recommendations

Based on the measurements and our understanding of them, it is concluded that

(1) The master equatorial instrument is still a precision instrument, with a pointing error of about 4 mdeg with an assumption that all systematic errors can be completely eliminated.

(2) It was understood that, within 360 deg (one complete revolution of an axis), up to four harmonic components of the systematic errors could be removed. Noise with a frequency higher than that of the fourth-order correction model, however, cannot be eliminated even if that is systematic. Therefore, we also need to include the high-frequency portion of the systematic noise in the pointing error. When the noise goes higher, to the level at which the antenna does not respond, it will not count in the pointing error anymore. These two threshold values should be determined.

(3) The measuring method can be improved by taking data directly from the ME room, reducing noise from the long cabling. Both encoders on the hour-angle and declination axes need to be recorded in order to see the correlation between the sinusoid curve and the declination oscillation.

(4) The pointing error of the ME is considerably larger than the original specifications. However, it does not significantly affect the performance of existing 1.7-GHz (L-band) and 8.5-GHz (X-band) communication. If the antenna is to be upgraded for Ka-band, the ME also has to be upgraded for better pointing (the ME will not meet Ka-band pointing accuracy for Ka-band, which for the 70-m antenna is 0.8-mdeg for a 0.1-dB gain loss).

(5) A search for a new instrument to replace the ME was carried out along with this study. An off-the-shelf instrument was found with a pointing accuracy of within 1 arcsec. The mechanical structure of the instrument was evaluated and was found to be much simpler than the master equatorial currently in use, reflecting up-to-date technology. Therefore, it is clearly indicated that a replacement should be pursued if the antenna is to be upgraded for Ka-band.

References

[1] "Master Equatorial Preliminary Design Analysis," *Space Programs Summary 37-26*, vol. III, Jet Propulsion Laboratory, Pasadena, California, pp. 73–80, 1964.

[2] H. McGinness, "Internal Alignment of the 210-ft Antenna Master Equatorial," *Space Programs Summary 37-46*, vol. III, Jet Propulsion Laboratory, Pasadena, California, pp. 115–119, 1967.