Tilts of the Master Equatorial Tower

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At the center of the DSS-14 antenna, a tower reaches to the focal point of the antenna dish. The master equatorial (ME) instrument is located at the top of the tower. This instrument precisely (with an accuracy that exceeds that of the antenna) follows the commanded trajectory. Through the optical coupling, the antenna focal point follows the ME. One factor of the antenna pointing precision is the movement of the ME base, i.e., the top of the tower. For this reason, measurements of the ME tower tilts have been taken in order to quantify the tilts, to determine possible causes of the tilting, and to update the antenna pointing budget. They were conducted under three antenna operating modes: during tracking, slewing, and antenna stowing. The measurements indicate that the ME tower tilts introduce significant pointing errors that exceed the required 32-GHz (Ka-band) pointing precision (estimated as 0.8 mdeg for a 0.1-dB gain loss). Four different sources of tilt were identified and require verification.

I. Introduction

The 70-meter antenna angular positions are measured in two ways: with azimuth and elevation encoders and by using the master equatorial (ME) instrument. The latter measurements are considered more accurate, since the instrument measures the position of the antenna focal point (or a point close to it), while the encoders are distanced from the focal point. Thus, the encoder readings do not reflect the accurate position of the RF beam since they are impacted by the antenna flexible and thermal deformations and structural imperfections. The ME measurements are more precise than encoder measurements, but the precision depends on the instrument accuracy itself and on the mobility of the ME mounts. The latter is the subject of our investigations.

The ME is mounted on the top of a tower, see Fig. 1(a), and the tower is located inside the antenna structure, along its azimuth axis. The autocollimator, mirrors, and ME allow for measurements of the position of the antenna dish through the optical link, see Fig. 1(b). The tower is designed to keep the ME motionless. Namely, it has a foundation separated from the antenna foundation to prevent ME motions caused by the antenna motions. Also, it is shielded from the wind and from temperature gradients that cause structural deformations.

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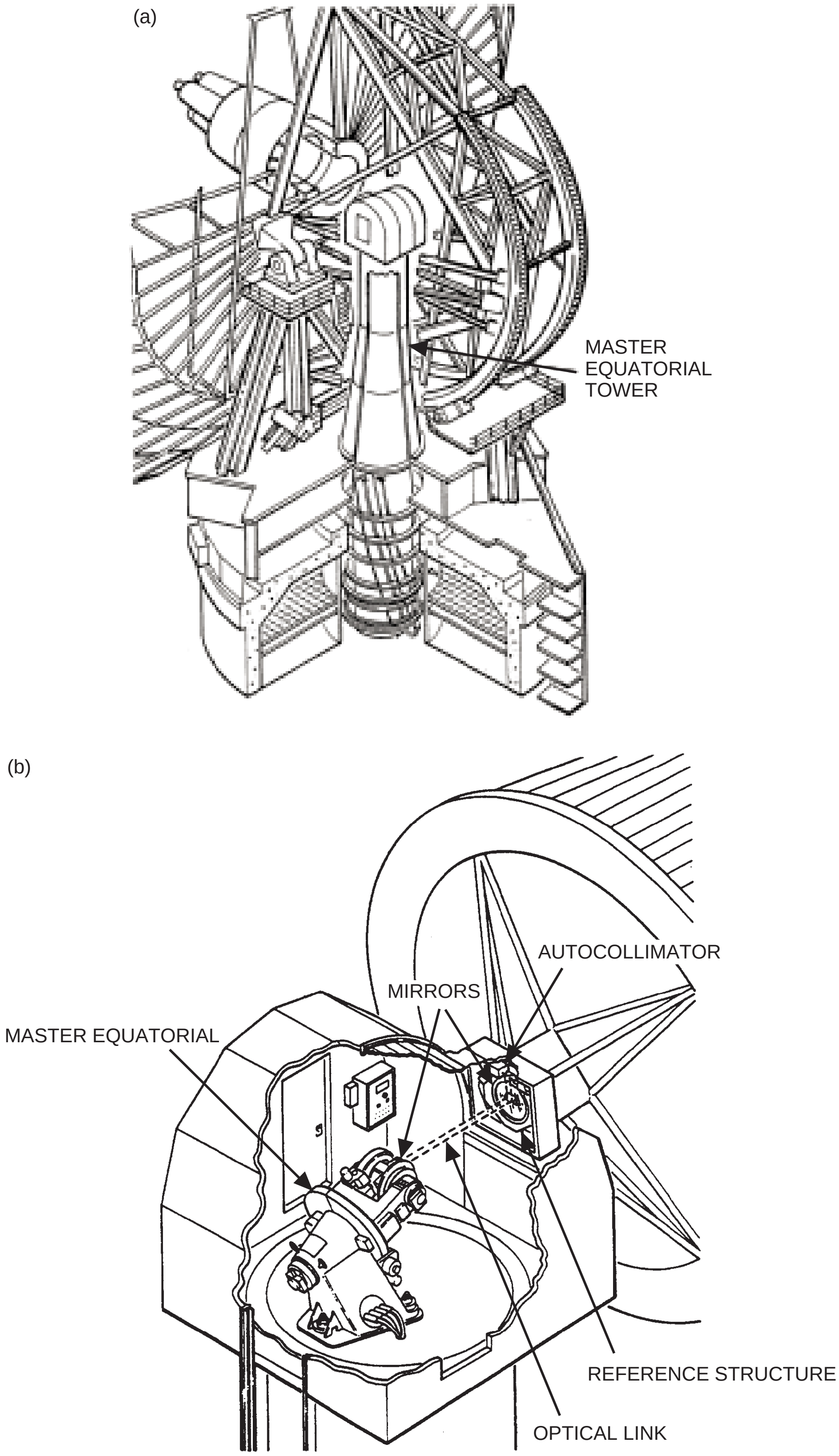

Fig. 1. Antenna and ME tower cross-sections: (a) the ME tower and (b) the ME, autocollimator, and mirrors.

These design features will minimize the ME tower tilts, but in fact the tilts are not completely eliminated. For example, the ME tower-tilt measurements conducted in 1966 and 1967 showed tilts of 0.9-mdeg amplitude for the concrete part of the tower and 1.9 mdeg for the top of the tower [1]. Only slow-varying tilts (over a few hours) were measured.

The purpose of this investigation was to quantify the master equatorial tower tilts of the DSS-14 antenna, to verify if the tower mobility significantly participates in the antenna pointing error budget,[4] and to determine possible causes of the tilting. The current measurements consisted not only of slowly varying trends but also of high-frequency dynamics.

II. Instrumentation and Data Description

During the January–February 2000 period, the tilts of the top of the ME tower in two orthogonal directions (denoted "x" and "y" in Fig. 2) were measured. The data collection system is shown in Fig. 2. An Applied Geomechanics 700 series inclinometer (Model 711) was used to measure tilts at the base of the ME pedestal. The x-tilt direction is directed to the north, and the y-tilt direction to the west. A Fluke Model 2645A data acquisition unit simultaneously collected x- and y-tilts, inclinometer temperature (for drift correction), and temperature from three Fluke thermocouple probes located in the ME tower. Binary antenna azimuth and elevation encoder data were fed into a digital-to-analog (D/A) converter for collection by the data acquisition unit.

The collected data can be divided into three groups:

(1) High-frequency tracking data. Collected at a 10-Hz sampling rate, these data were collected during antenna tracking for a short period of about 1 hour on February 10, 2000.

(2) High-frequency slewing data. Collected at a 10-Hz sampling rate during antenna azimuth and elevation high-rate slewing, these data were collected using 360-deg antenna rotation in azimuth and 84-deg antenna rotation in elevation on January 25 and 29, 2000.

(3) Low-frequency data. These data were collected at a 0.1-Hz sampling rate for a longer period of time, 4 days, from January 10 through January 13, 2000.

The high-frequency tracking data were collected to determine vibrations of the tower due to high-frequency excitations, such as wind or antenna-structure movements during tracking and slewing. The high-frequency slewing data were taken to verify if the tower tilts were dependent upon antenna azimuth and elevation locations. The low-frequency data were taken to investigate slower trends in tower tilts that likely would be caused by the temperature gradient of the tower (affected by the Sun's heat radiation through the shield and air convection) and/or thermal deformations of the antenna.

III. Data Analysis

Data analysis includes Fourier transformations of the time series to reveal frequency contents of the tilts and data smoothing (filtering) to reveal slower trends in the tower tilts. The analysis also estimates tilt values during stowing, slewing, and tracking. These values are given in Table 1.

[4] The Ka-band pointing requirements are not yet strictly defined, but it is known already that the pointing error budget will be about 0.8 mdeg (rms) for 0.1-dB gain loss.

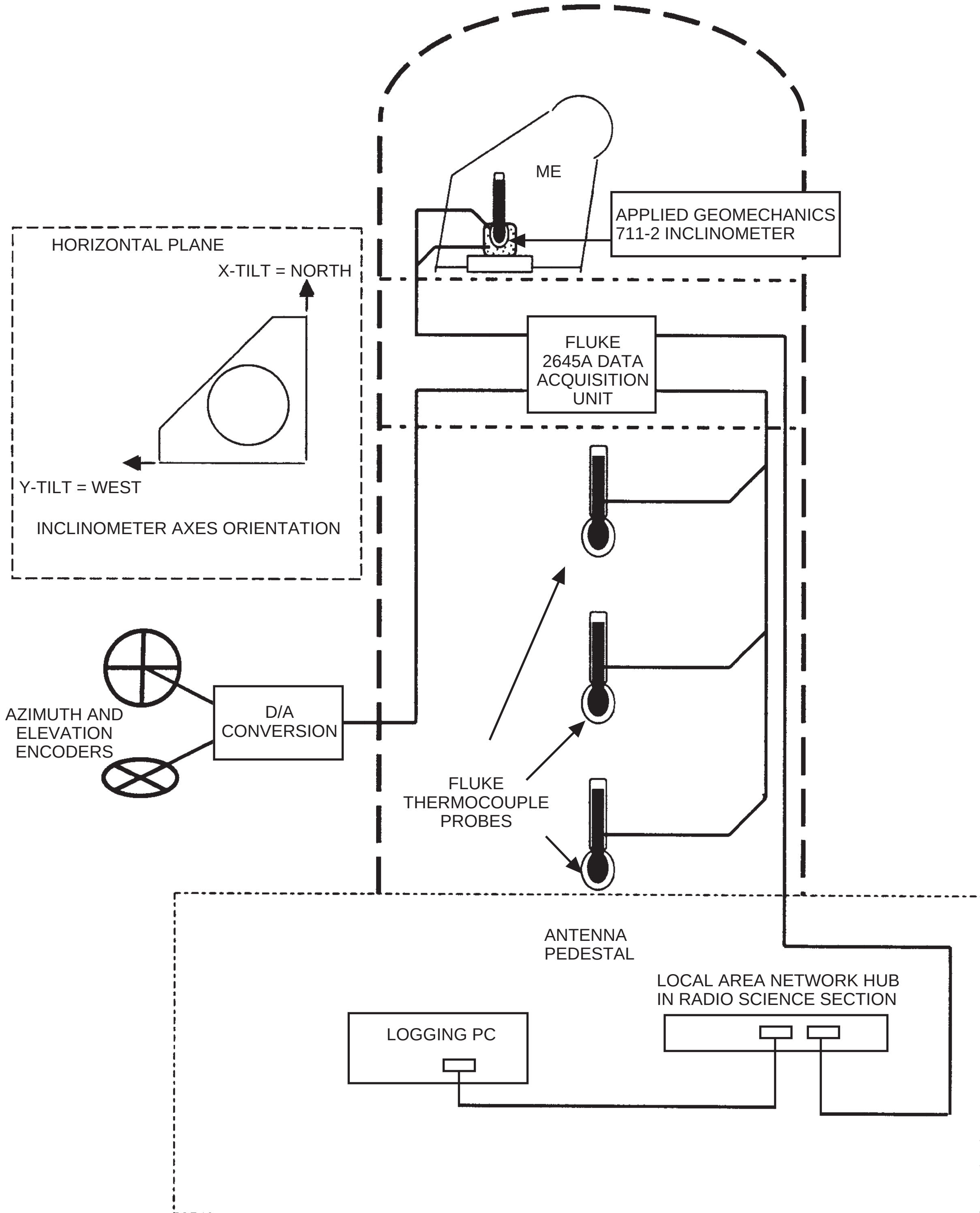

Fig. 2. The data collection system.

Table 1. ME tilt during various antenna operations.

Mode of operation	X-tilt, mdeg	Y-tilt, mdeg
During track (rms)	2.4	1.6
During elevation slewing (rms)	2.1	1.5
During azimuth slewing (rms)	0.7	0.7
During stow (rms)	0.4	0.7
Trend during tracking (peak to peak)	1.5	1.5
Trend during slewing (peak to peak)	0.2	0.2

A. High-Frequency Data During Tracking

The x-tilts (north–south) and y-tilts (east–west) of the ME tower, collected at a 10-Hz sampling rate, are plotted in Figs. 3 and 4. The measurements were taken during antenna slewing in azimuth for the first 900 s, followed by tracking (in azimuth and elevation) for the remaining time. The wind was about 36 km/h at 45 deg from the front of the antenna. The standard deviations were 2.4 mdeg for x-tilt and 1.6 mdeg for y-tilt.

Filtering was used to remove oscillations and to reveal long-range trends. We used zero-phase forward and reverse digital filtering, with averaging filter order of 100. In this case, filtering consisted of running and averaging the data in the forward direction, followed by running and averaging the data in the reverse direction. This kind of filtering produces zero lag. The filtered data are shown in Figs. 3 and 4 by a red line. The trend computed with respect to the mean value was minimal: 0.2 mdeg in x-tilt and 0.06 mdeg in y-tilt.

The power spectrum of the entire data record is shown in Fig. 5. There are 2.6-Hz resonant peaks in both the x- and y-directions along with two low-amplitude peaks of 1.1 Hz and 1.6 Hz. These peaks

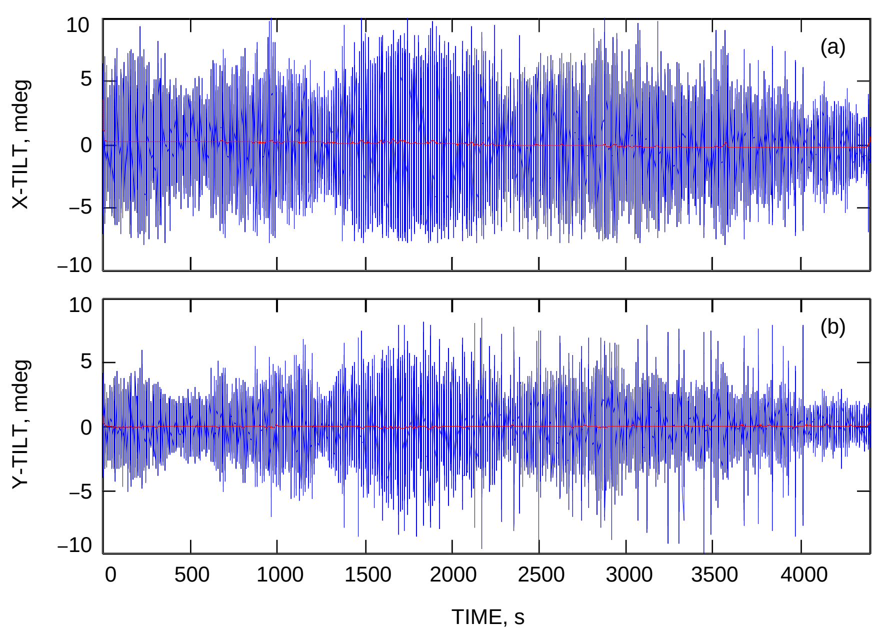

Fig. 3. Tilts of the ME tower collected at a 10-Hz sampling rate during tracking: (a) x-tilts and (b) y-tilts.

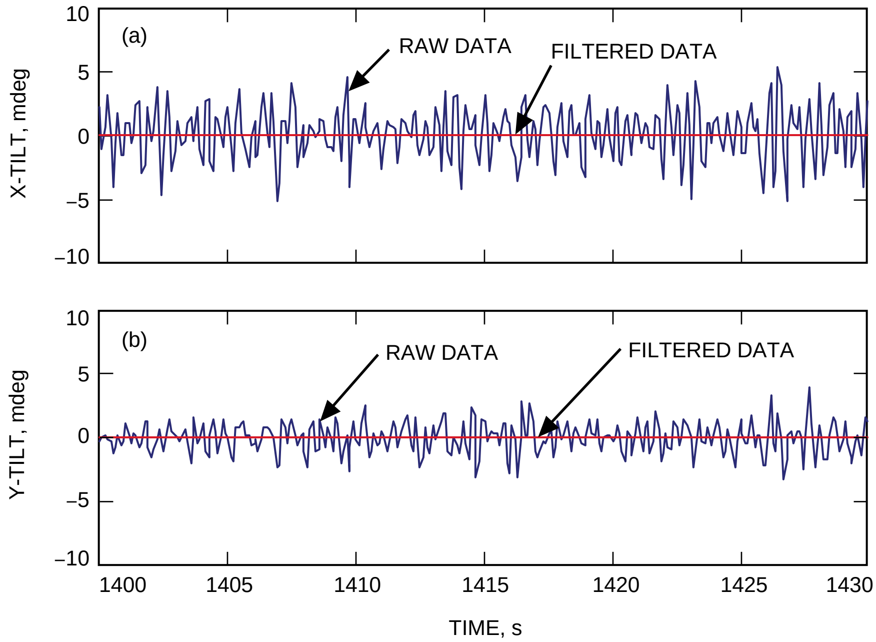

Fig. 4. A sample of the tilt measurements of the ME tower collected at a 10-Hz sampling rate during tracking: (a) x-tilts and (b) y-tilts.

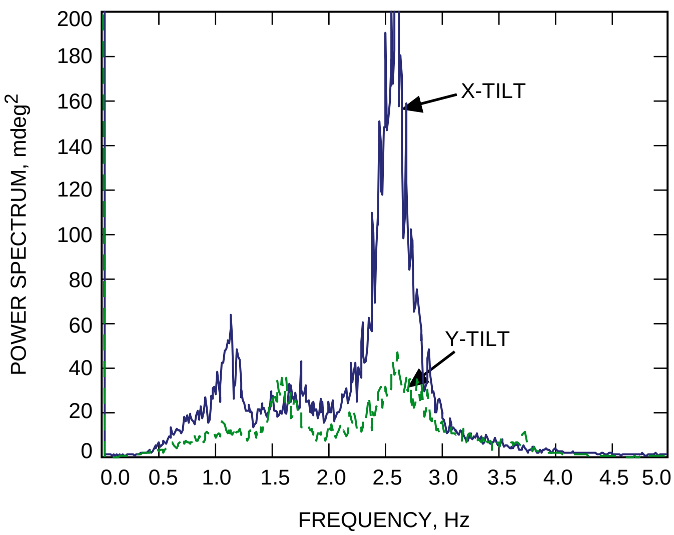

Fig. 5. The power spectrum of the x- and y-tilt data during tracking.

correspond to natural frequencies of the antenna structure and indicate that ME tower vibrations are excited by the antenna's movements. The coupling between the antenna structure and the ME tower is through either the rubber seal at the top of the tower, the tower insulation rubbing, or the foundation.

High amplitudes of the jitter are caused by the antenna motion and can be explained as a combination of the tower tilts and tower accelerations. Inclinometers are designed such that they measure not only tilts but also accelerations. Therefore, it is even possible that the acceleration component dominates the jittery response.

B. High-Frequency Data During Slewing

The second set of the high-frequency data was collected during high-rate slewing at a rate of 0.234 deg/s in elevation and 0.236 deg/s in azimuth (both values were obtained from the encoder data). The data are shown in Fig. 6 for elevation slewing and in Fig. 7 for azimuth slewing. The standard deviations are 2.1 mdeg in x-tilt and 1.5 mdeg in y-tilt for elevation slewing, and 0.7 mdeg in both x- and y-tilt for azimuth slewing.

The power spectra of the x- and y-tilts are shown in Figs. 8 and 9 for elevation slewing and azimuth slewing, respectively. Elevation slew figures show resonance at 1.1, 1.75, and 2.3 Hz, while azimuth slew figures show resonances at 1.6, 1.75, 2.6, 3.1, and 3.3 to 3.5 Hz. Note that the azimuth slew resonance frequencies are consistent with resonance frequencies excited during tracking.

The slewing data show that the bulk of the tower vibrations are excited through the antenna slewing motions, since the stowed antenna showed low-amplitude jitter. Additionally, antenna elevation slew motion excites more ME tower vibrations than does azimuth slew. The resonant frequencies excited by the azimuth slew are consistent with the track data since during the track the antenna moved faster in azimuth, while elevation slowed to a stop at the track's midpoint. The added natural frequency was in the range of 3.3 to 3.5 Hz. This is the first (lowest) frequency of the tower itself.[5] Spectral analysis shows, however, that the tower vibrates predominantly with the antenna natural frequencies, indicating that the antenna excites the tower movement.

In order to highlight the correlation between the antenna and tower movement, we note that during a short period of time (from 370 to 414 s) the antenna did not move during the elevation slew experiment (see Fig. 6). The tower vibrations were significantly smaller, with rms values of 0.4 mdeg in x-tilt and 0.7 mdeg in y-tilt.

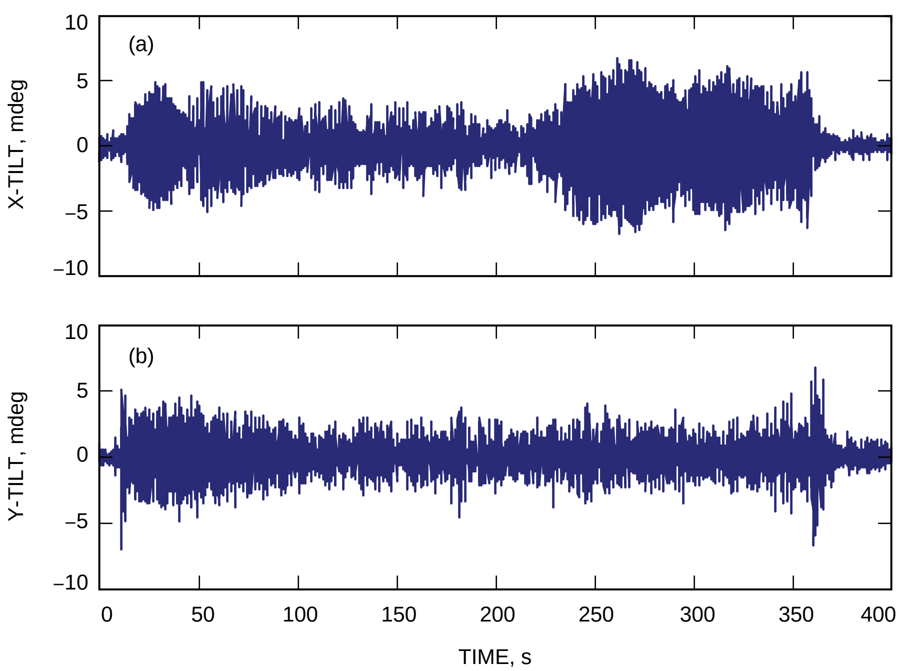

Fig. 6. The ME tower tilts during elevation slew: (a) x-tilt and (b) y-tilt.

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[5] "Experimental Modal Analysis of the DSS-14 Antenna Instrument Tower," in *DSS-14 70-m Antenna Earthquake Investigation*, JPL Document 890-251 (JPL internal document), Jet Propulsion Laboratory, Pasadena, California, vol. 2, appendix H, September 8, 1992.

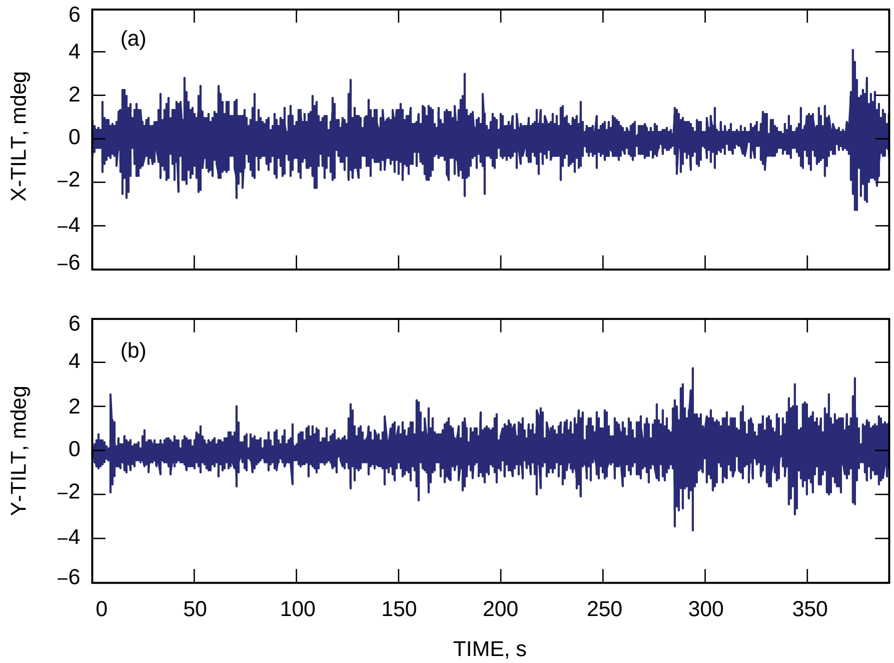

Fig. 7. The ME tower tilts during azimuth slew: (a) x-tilt and (b) y-tilt.

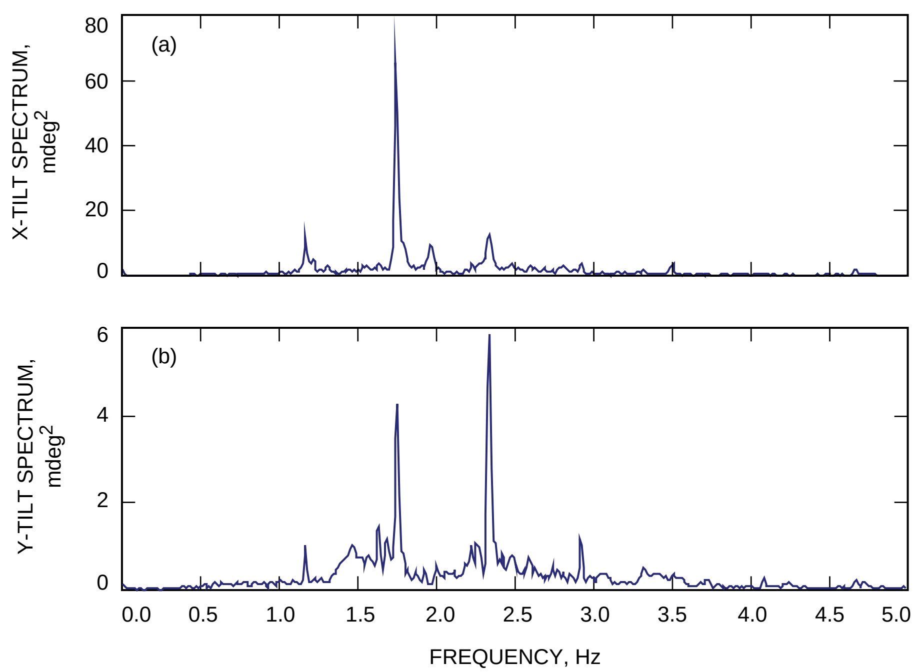

Fig. 8. The power spectra of the ME tower tilts during elevation slew: (a) x-tilt and (b) y-tilt.

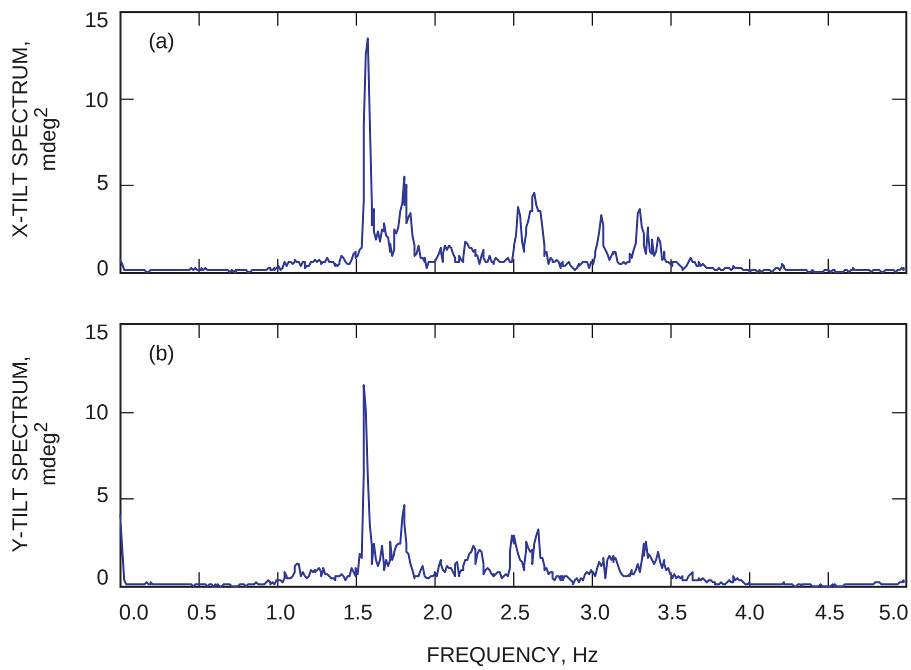

Fig. 9. The power spectra of the ME tower tilts during azimuth slew: (a) x-tilt and (b) y-tilt.

Additional data were collected while slewing the antenna by 360 deg (a full circle from 180 deg to 180 deg) both clockwise and counterclockwise. The purpose of this experiment was to determine if there exists an obstacle at a particular azimuth angle that causes ME tower tilt. After removing the jitter, the resulting ME tower tilts are shown in Figs. 10(a) and 10(b). The plots do not show any particular azimuth-angle position with repeatable tower tilts. However, both figures show periodic tilts of ± 0.2-mdeg amplitude and 360-deg period, with the y-tilt shifted approximately by 90 deg with respect to the x-tilt. This kind of tilting can be explained by a nonvertical position of the antenna azimuth axis. The tilted antenna structure causes the tower harmonic tilts.

C. Low-Frequency Data

From January 10 through January 13, 2000, ME tilt measurements were collected with the inclinometer set at high gain, the inclinometer's internal low-pass filter turned off, and a 10-s sampling interval. The resulting data plot is shown in Fig. 11. In this and subsequent figures, the following notation was chosen to denote each day: day 1 is January 10, 2000; day 2 is January 11, 2000; day 3 is January 12, 2000; and day 4 is January 13, 2000.

The data show the tower jitter on top of slow-varying tilts. The slow-rate tilts were recovered through data filtering and are shown in Fig. 12. The same data on slow-varying tilts of the tower are shown in the x- and y-coordinates in Fig. 13. The data are contained within a circle of radius 2.2 mdeg. Similar data were collected by McGinness in 1967 [1] and are shown in Fig. 14. The data are contained in a circle of radius 1.9 mdeg. The current data are consistent with the McGinness data since the bulk of tilts currently measured are contained in the 1.9-mdeg circle, except for a single peak that departs from the circle (see Fig. 13).

Tower vibrations (after removing the trends) are shown in Fig. 15. Their rms value is as high as 2 mdeg (or 6-mdeg peak to peak) during antenna operations.

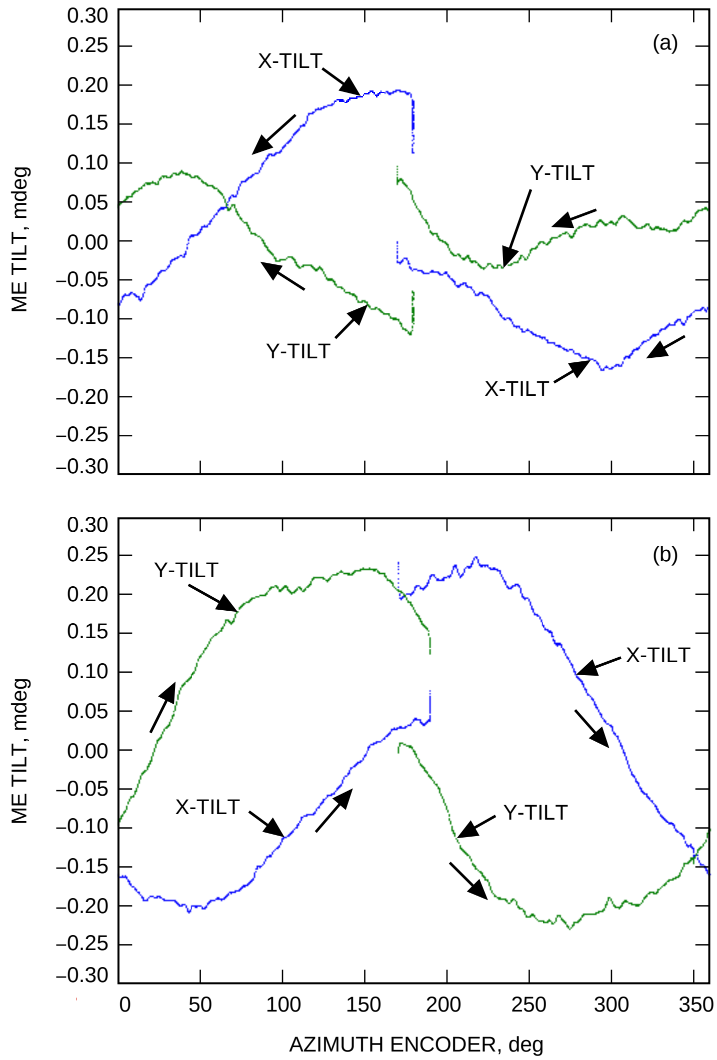

Fig. 10. Slow-varying ME tower tilts during antenna slew: (a) counterclockwise slew and (b) clockwise slew.

The slow-rate tilts have a periodicity of 1/2 day. The temperature gradient of a stowed antenna would cause a tilt variation of 1-day period. The tracking antenna causes additional variations of temperature, which changed the 1-day period.

IV. Possible Sources of Tilting

Based on the previous data analysis, the following are identified as possible causes of tilting:

(1) Tower bending through the rubber seal coupling on the top of the tower and through rubbing of the tower insulation against the tower shield

(2) Tower tilting due to flexibility of the tower foundation and caused by the rubber seal coupling on the top of the tower and through rubbing of the tower insulation against the tower shield

(3) Coupling through the antenna and tower foundation

(4) Temperature gradient

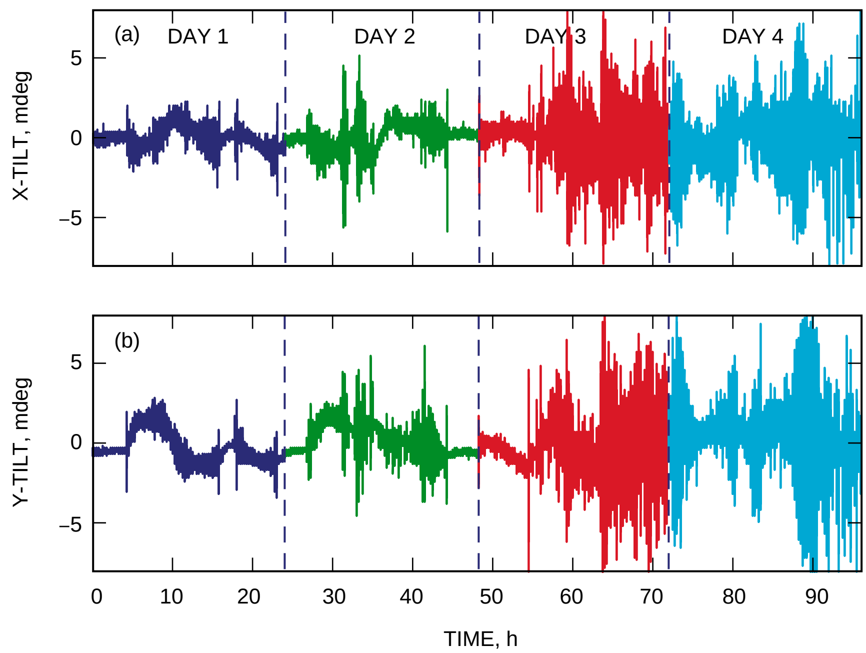

Fig. 11. Tilt measurements of the ME tower collected at a 0.1-Hz sampling rate: (a) x-tilt and (b) y-tilt.

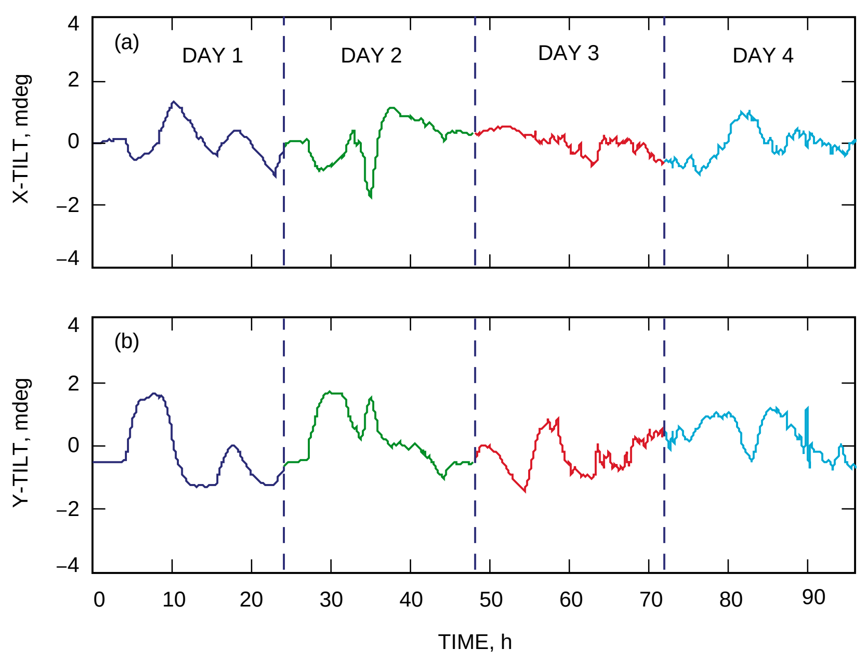

Fig. 12. Slow-rate trends in the tilts of the ME tower: (a) x-tilt and (b) y-tilt.

Using the existing data, these causes were verified through analysis. In particular, in order to verify if tower bending and structural coupling on the top of the tower cause the tower tilting, approximate coupling forces were computed. For this purpose, a horizontal force that causes 1-mdeg tower bending at the top was calculated (see Appendix A). It takes 2387 N (537 lbf) to bend and tilt the tower by 1 mdeg (a rigid foundation was assumed). In this computation, we used a simplified model of the tower: a steel tube 21.64 m (71 ft) in length, 3.45 m (11.3 ft) in diameter, and 0.95 cm (3/8 in.) in wall thickness.

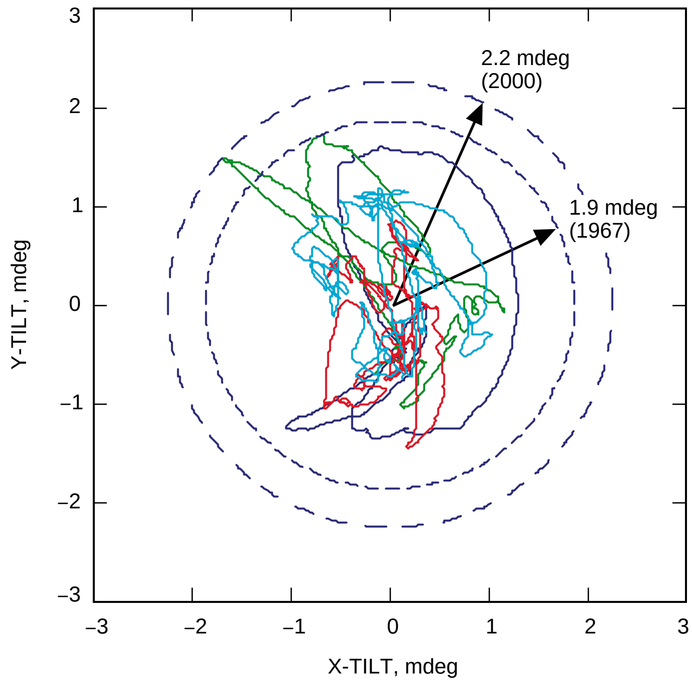

Fig. 13. The same data used in Fig. 12, shown in the x- and y-coordinates.

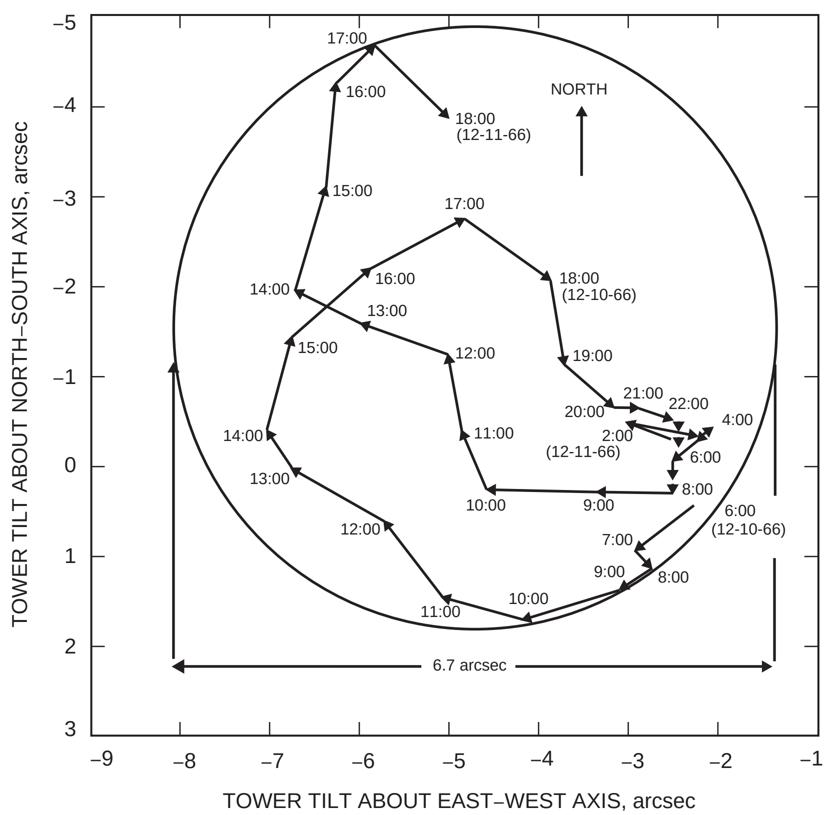

Fig. 14. Slow-rate trends in x- and y-tilts of the ME tower taken by McGinness in 1967.

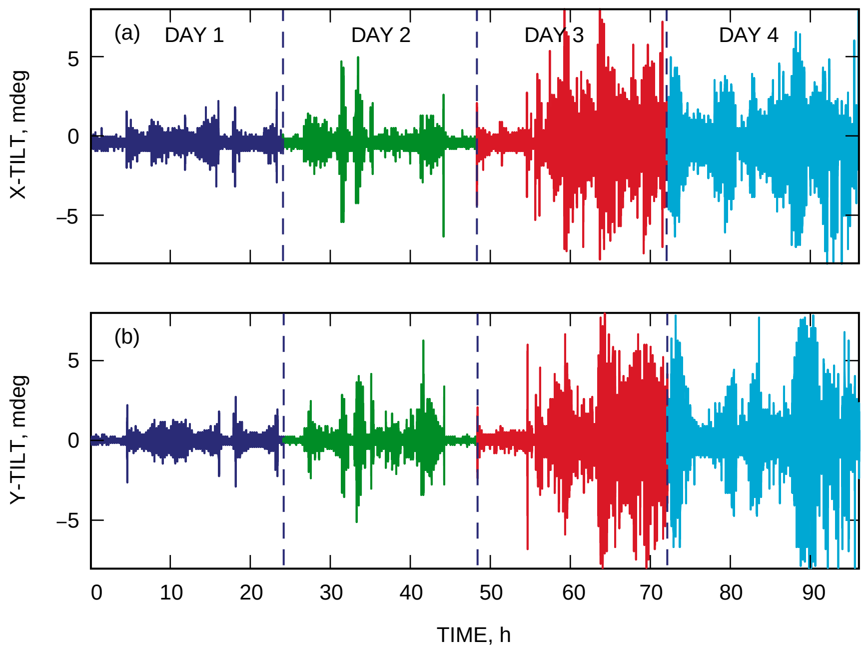

Fig. 15. ME tower jitter: (a) x-tilt and (b) y-tilt.

Thus, a 1.5-mdeg tilt would require 3580 N (805 lbf), which seems to be a force much larger than the one transferred by the seal from the antenna to the tower. Also, the twisting force of the seal at the top of the tower has been calculated. In order to twist the tower by 1 mdeg, a tangential force of 3478 N (782 lbf) is required. These forces seem to be too large to be produced by the rubber seal.

Second, we verified if the tower is tilting due to flexibility of the tower foundation. We assumed a rigid tower and a flexible foundation, and we took the foundation stiffness from the existing engineering data.[6] In Appendix B, we calculated that, in this case, a horizontal force of 9100 N (2050 lbf) causes a 1-mdeg tilt of the tower. The obtained force in this case is large indeed, indicating that the rubbing seal is less likely to cause the tilts (both of slow and of high frequencies).

Third, the coupling between the antenna and tower foundations was considered. From the engineering data,[7] we found that a 113-km/h wind loading of the antenna structure causes 0.67 mdeg of tower tilt, see Appendix C. The wind during our experiment did not exceed 36 km/h; thus, the tilt due to wind load was less than 0.05 mdeg, i.e., insignificant. These data, therefore, indicate a weak coupling through the foundation between the antenna structure and the ME tower.

Fourth, the ME tower itself can be under temperature-gradient influence. The most probable gradient is along the tower rather than across the tower structure. However, the longitudinal (vertical) temperature gradient causes no tilts. It is the horizontal (across-tower) gradient that causes tower bending and tilting. The temperatures in the ME room and along the ME tower (at the top, in the middle, and at the bottom of the tower) were measured. The temperature probes (shown in Fig. 2) were placed 6, 12, and 18 m below the ME room. Temperature plots are given in Fig. 16. They show a diurnal pattern with the highest temperature between 5:00 and 6 p.m. and the lowest between 8:00 and 9:00 a.m. The room

[6] *Structural Calculations for 210 ft JPL Advanced Antenna System*, Holmes and Narver Inc., Los Angeles, California, October 4, 1963.

[7] *Preliminary Soil Study Foundation Investigation Advanced Antenna System Goldstone Lake, CA*, F 61-451, Donald R. Warren Engineers, Los Angeles, California, August 1961.

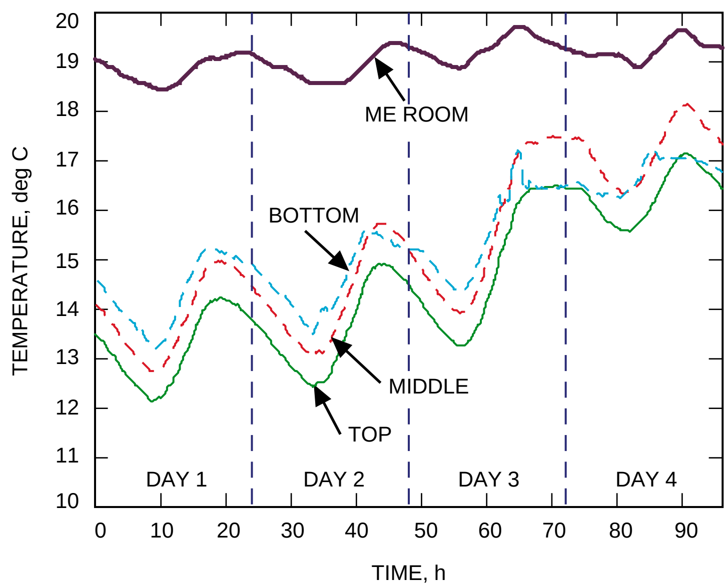

Fig. 16. Temperature in the ME room and the ME tower.

temperature varied about ±0.5 deg C, while the tower temperature varied about ±1.3 deg C. The tower temperature plots display an increasing trend of 1.3 deg C per day. Also, the temperature at the top of the tower is lower than at the bottom by about 1 deg C. The cross-tower temperature gradient has not been measured.

V. Conclusions

The collected data show both slow-varying movements and fast-varying vibrations of the ME tower. The values of the slow-varying tilts are predominantly in a 1.9-mdeg circle in the x- and y-directions. These data are consistent with the McGinness data that are contained in the same circle. The current measurements also allowed us to evaluate high-frequency data. The rms value of the tower vibrations is up to 2 mdeg at frequencies ranging from 1 to 3.5 Hz.

The data indicate that the tower movements are coupled with the antenna movements because the tilts were much smaller when the antenna was motionless and because the tower vibration spectra showed the antenna (rather than the tower) natural frequencies.

The most probable couplings are forces between the tower and the rubber seal, the tower and the insulation, the tower and the antenna foundations, and the thermal gradient across the tower. The possible rubber-seal coupling forces and insulation coupling forces are weak, and the tower-foundation stiffness as well as the tower-structure stiffness are high, so large forces are required to produce tilts as in the data. The coupling through the foundations also can be a source of high- and low-frequency tilting, but the available engineering data indicate that small tilts due to soil coupling are expected. The probable reasons for the low-rate tilting are the antenna thermal deformations transferred into the tower. Also, the cross-tower temperature gradient may cause tilting, but it is a low probability that such a gradient exists.

Future investigations will determine the reason for the ME tilts and the means of tilt reduction. Conclusions regarding the tilt causes are not yet decisive; they were drawn indirectly from the collected data, by analyzing the symptoms, and by using available simplified models. In order to confirm our findings, we need to identify all possible antenna-tower couplings and measure tower tilts caused by each coupling. For example, ground motions will be measured to determine cross-foundation coupling. In order to verify the source of the low-rate tilts, the temperature gradients will be measured along the tower height and around the tower cross-section. Finally, the correlation between antenna and tower motion will indicate possible mechanical couplings.

Acknowledgments

The authors thank Ben Saldua for his assistance in the calculations of soil stiffness and for information on the tower tilts in the wind, and Jun Liu for frequent discussions on the tower-tilt issues.

Reference

[1] M. D. McGuinness, "210-ft Antenna Tower Positional Stability," *Space Programs Summary 37-50*, Jet Propulsion Laboratory, Pasadena, California, vol. II, pp. 151–58, 1967.

Appendix A
Estimating the Tower Bending

The force required to bend the ME tower 1 mdeg is computed. In this analysis, we assume a rigid foundation. The tower cross-section is circular and of slightly increasing radius, but the radius is assumed to be constant. Its value of $R = 172.7$ cm is the mean value of the variable radius. The Young modulus of the ME tower (steel) is 2.1×10^7 N/cm^2; the thickness, t, of the tower wall is $t = 0.95$ cm; and the height of the steel part of the tower is $h = 2164$ cm.

The horizontal force, F, acting at the top of the tower causes the tilt, ϕ, of the top of the tower:

$$\varphi = \frac{Fh^2}{2EI} \tag{A-1}$$

where I is the second moment of the cross-section. For the circular ring of radius r and thickness t, the moment is

$$I = \frac{\pi}{4}(R^4 - r^4) = 1.52 \times 10^7 \text{ cm}^4 \tag{A-2}$$

where $r = R - t$.

From Eq. (A-1), one obtains the force

$$F = \frac{2\varphi EI}{h^2} \tag{A-3}$$

Assuming $\varphi = 1$ mdeg $= 1.75 \times 10^{-5}$ rad, one obtains $F = 2387$ N (537 lbf).

Appendix B
Estimating the Rigid Tower Tilt

Here we assume a rigid tower and a flexible foundation. From the Holmes and Narver engineering document,[8] the stiffness of the tower foundation is obtained as a scaled stiffness of the antenna structure:

$$k = 1.68 \times 10^{10} \text{ lbf ft/rad} = 2.3 \times 10^{8} \text{ N m/rad}$$

The height of the tower from the middle of the foundation to the top is $h = 43.9$ m. A horizontal force applied to the top of the tower produces the following torque:

$$M = Fh \tag{B-1}$$

Assuming a rigid tower, the torque is related to the tower tilt, θ, as follows:

$$M = k\theta \tag{B-2}$$

Introducing Eq. (B-1) to Eq. (B-2), one obtains

$$F = \frac{k\theta}{h} \tag{B-3}$$

Assume $\theta = 1$ mdeg $= 1.745 \times 10^{-5}$ rad; then, from Eq. (B-3), the force required to tilt the tower for this angle is $F = 9100$ N $= 2050$ lbf.

[8] Holmes and Narver Inc., op. cit.

Appendix C

Estimating Tower Tilt Due to Antenna Movement

The design specification for the antenna wind load is a 113-km/h wind. For this wind, the tower tilt was calculated by Donald R. Warren Engineers.[9] The antenna-structure wind load causes a pressure increase within the soil and, consequently, the rotation of the ME tower footing. In the calculations, it was assumed that the ME tower is fully shielded from lateral loads of any kind. The tower rotation in a 113-km/h wind was 2.4 arcsec, or 2/3 mdeg.

[9] Donald R. Warren Engineers, op. cit.