Movement of the Antenna Instrument Tower at DSS 14

H. D. McGinness
DSIF Engineering Section

The motions of the top of the instrument tower and its surrounding windshield have been measured. A relationship between a static horizontal displacement and angular displacement of the tower have been established through the use of optical apparata. Displacements during excitation of the windshield have been determined by the use of accelerometers. The nature of the coupling between windshield and tower is discussed and the conclusion reached that the coupling is primarily an acoustical one.

I. Introduction

The instrument tower is located at the center of the antenna pedestal. The top of the tower is 32 m above ground, and its foundation extends 10.7 m below ground level, being connected to the antenna pedestal only through the soil. The lower part of the tower is enclosed by the pedestal and alidade rooms, whereas the upper 15 m is surrounded and protected by a windshield spaced approximately 15 cm from the tower. The purpose of the tower is to support the precision reference instrument to which the antenna dish is optically connected. Figure 1 shows the configuration of the tower, windshield, and precision reference instrument. It should be noted that the astrodome is connected to the windshield only. The top of the instrument tower is coplanar with the floor of the astrodome; a space of approximately 2 cm separates the two structures. Attached to the edge of the tower top is an annular neoprene ring which bears lightly on the floor of the astrodome and serves to seal the gap so as to allow a temperature-controlled environment within the astrodome.

It is clear that in order for the precision reference instrument to serve its intended purpose, the angular positional stability of the tower should be better than the pointing accuracy of the instrument which is to within 5 arc seconds.

Instrument tower motion has been observed in three ways. When standing in the astrodome, a relative motion between the floor of the astrodome and the tower top is visually quite obvious, especially when the antenna is being accelerated or when the wind is blowing. During the times of relative motion, one can feel motion if he is standing on the instrument tower, thus leading him to wonder how much of the rather large relative motion is contributed by the tower. Instruments including accelerometers and level sensors have been used to detect motion.

There are two general types of tower motion: a long period motion caused by thermal gradients in the structure (reported in Ref. 1), and vibratory motion, which is discussed here.

II. Miscellaneous Experiments

Since the relative motion between the astrodome floor and the tower top has a total excursion of 2 or 3 mm during a moderate wind, and because all observers have been able to feel the tower motion, it was suspected that there was an inadvertent connection between tower and windshield. A rope was dropped through the space between the tower and windshield so that its lower end was at the bottom of the windshield. By sweeping this rope around the entire periphery, it was proved that no such connection existed. The neoprene ring covering the gap in the astrodome floor was removed and no reduction in tower movement was observed.

A sheet of plywood was set horizontally in a JPL laboratory so that it could be vibrated laterally at a frequency of 2.5 Hz and at an adjustable amplitude. Several persons stood and sat on this plywood while it was being shaken. All could feel the motion at amplitudes as small as ± 0.12 mm, and it was generally agreed that it felt like a much larger displacement.

The first mode natural frequency of the tower was measured by displacing its top horizontally, releasing it, and measuring the subsequent accelerations with an accelerometer. This was achieved by bolting a special bracket to the top of the tower, connecting a cable between the bracket and part of the antenna wheel structure, tightening the cable, and then suddenly cutting the cable. The resulting accelerometer record was sufficiently pure to allow a frequency count to be made. It was approximately 3.6 Hz, which was reasonably close to the calculated value.

Another experiment established the relationship between the horizontal and angular displacements of the tower top. While the autocollimator of the precision reference instrument was directed onto a gravity mirror placed on the tower top, the tower was pulled horizontally with a cable and the force measured with a dynamometer. The horizontal motion of the tower was measured with dial gages and compared with angular reading of the autocollimator. Also the windshield was pulled horizontally and the forces and displacements measured. The results of these tests are shown in Figs. 2 and 3.

III. Measurement of Tower Motion With Accelerometers

Two $\frac{1}{10}$-g accelerometers were mounted on the top of the tower. One was aligned with a north–south line and the other was perpendicular to it. Two 1-g accelerometers were clamped to the astrodome structure (to the structural channel at waist level) so as to measure its horizontal acceleration. These were placed parallel to the accelerometers on the tower. It had previously been determined that the astrodome could be shaken at its resonance frequency simply by swaying one's body. All four accelerometers were connected to a Sanborn recorder and the calibrations made by tilting the accelerometers by a known amount.

Recordings of astrodome resonance were made on two occasions. Its frequency was 2.1 Hz and its maximum amplitude was ± 6.55 mm. The oscillograph of the tower accelerometers appeared to be composed of two frequencies, namely, one of 2.1 Hz and one of 10.5 Hz. It was assumed that the amplitude of the 2.1-Hz component was 50% greater than the component of the 10.5-Hz component. The sum of these two vibration components was plotted and found to match the oscillograph very closely. The displacement amplitudes were computed by dividing the measured accelerations by the squares of the circular frequencies. The results are as follows: When the astrodome was resonating at 2.1 Hz and ± 6.55 mm, the tower had a 2.1-Hz amplitude of ± 0.167 mm and a 10.5-Hz amplitude of ± 0.0043 mm. Assuming the dynamic relationship between lateral and angular displacements is the same as the static one shown in Fig. 2, the angular displacement of the tower in arc seconds is obtained by multiplying the lateral displacement in millimeters by 16.3. Thus, the angular motion of the tower was ± 2.7 arc seconds. The oscillograph records indicate that the tower accelerations are proportional to the astrodome accelerations. Hence, the tower displacements would be proportional to the astrodome displacements.

It should be emphasized that an astrodome amplitude of ± 6.55 mm is many times greater than has ever been observed during operation in strong winds. We may conservatively say that the astrodome amplitude does not exceed one-fifth of that obtained during the resonance test. Thus, it is expected that the angular displacement of the tower top will not exceed ± 0.50 arc second from vibratory motion under normal conditions.

According to the oscillographs, the larger amplitude frequency of the tower matches the frequency of the astrodome. Hence, it appears that the tower vibration is a forced one. Since the frequency of the astrodome is 2.1 Hz and the tower is forced at this frequency, which is substantially different from the tower natural frequency of 3.7 Hz, the magnification factor is small; that is, it is approximately 1.30 or 30% more than a static deflection.

IV. Nature of the Coupling Between Tower and Antenna

The preceding experiments indicate that the vibratory motion of the tower produces an error that is small in comparison to that of the precision reference instrument. However, there is an important disadvantage to this vibration. In order to control the tower motion caused by thermal gradients and described in Ref. 1, it is necessary to use a level sensor. Several commercial level sensors which have been tested in this vibratory environment do not work. For example, in Ref. 2, errors are tabulated for a representative level when tested at an amplitude of 0.012 mm over a frequency range from 2 to 10 Hz. Therefore, it is proper to inquire about the nature of the coupling between the antenna and the instrument tower.

It has been noticed that an instrument tower movement is always accompanied by an astrodome movement. Thus, the probability is high that the principal coupling medium is the air between the tower and windshield. However, it cannot be ruled out with certainty that some coupling is constituted by the soil between the pedestal and tower.

The following analysis indicates that the primary coupling is an acoustical one. As the windshield vibrates, it causes a change in the pressure of the connecting air. If the concentric cylindrical tower and windshield are considered to be infinite parallel plates, the one-dimensional acoustic theory may be applied. The change in absolute pressure ΔP may be expressed as follows (Ref. 3):

$$\Delta P = \frac{2\pi \rho_0 a^2 y}{\lambda} \tag{1}$$

where

ρ_0 = mass density of the undisturbed air

a = sonic velocity

y = amplitude of the disturbing source

λ = wavelength

Using the relationship $\lambda = a/f$, where f is the frequency of the source in cycles per unit time, ΔP may be expressed as

$$\Delta P = 2\pi f a \rho_0 y \tag{2}$$

The amplitude of the top of the windshield is greater than that of the lower parts. If it is assumed that the amplitude y is related to the coordinate x as

$$y = A\left(1 - \cos\frac{\pi x}{2\ell}\right) \tag{3}$$

where

A = amplitude at the top of the windshield

x = distance along windshield axis with origin at bottom of windshield

ℓ = length of the windshield

then the change in absolute pressure may be written as

$$\Delta P = 2\pi f a \rho_0 A\left(1 - \cos\frac{\pi x}{2\ell}\right) \tag{4}$$

The total instantaneous force F acting on one side of the tower may be obtained by integrating ΔP over the surface of the tower:

$$F = 2\pi f a \rho_0 D A \int_0^{\ell} \left(1 - \cos\frac{\pi x}{2\ell}\right) dx$$

$$= 2\pi f a \rho_0 D A \ell \left(1 - \frac{2}{\pi}\right) \tag{5}$$

where D is the diameter of the instrument tower.

Equation (5) represents the instantaneous force on one side of the tower caused by a pressure increase. Simultaneously, there would be a pressure decrease on the opposite side of the tower; hence, the total simultaneous force acting on the tower would be twice that of Eq. (5), namely,

$$F_{\mathrm{TOTAL}} = 4\pi f a \rho_0 D A \ell \left(1 - \frac{2}{\pi}\right) = 4.55 f a \rho_0 D A \ell \tag{6}$$

This total force is distributed over approximately half the length (that portion surrounded by the windshield) of the cantilever tower. In order to compare with experimentally measured values, it is necessary to convert F_{TOTAL} of Eq. (6) to an equivalent concentrated force applied at the tower top, since the static deflection measurements were made when the force was so located. A comparison of the end deflections of two cantilever beams, one loaded with an end concentrated load W, and the other loaded with a distributed load per Eq. (3) of total magnitude W, gives the required modification factor, which is 0.75. The equivalent end force F_E is

$$F_E = (0.75)\, 4.55 f a \rho_0 D A \ell = 3.42 f a \rho_0 D A \ell \tag{7}$$

Substituting the following values into Eq. (7),

$f = 2.1$ hertz

$a = 335$ meters/second

$\rho_0 = 1.22$ kg/meter^3

$D = 2.75$ meter

$\ell = 15.2$ meter

there is obtained:

$$F_E = 122\,000\,A \tag{8}$$

where A is the amplitude of the top of the windshield in meters and F_E is in newtons.

For $A = 0.00655$ meter, Eq. (8) becomes

$$F_E = 122\,000\,(0.00655) = 800 \text{ newtons} \tag{9}$$

This value of 800 newtons is an effective static force derived from a consideration of the one-dimensional acoustic equation. From Fig. 2, the relationship between static force and horizontal tower displacement z is

$$z = \frac{F}{5663610} \tag{10}$$

where z is in meters and F in newtons.

Substituting the calculated value of $F = 800$ into Eq. (10), there is obtained:

$$z = \frac{800}{5663610} = 0.000141 \text{ meter} \tag{11}$$

From the accelerometer tests, the tower amplitude was 0.000167 m when the astrodome amplitude was 0.00655 m. But under this vibration, the magnification factor was 1.3. If the value 0.000167 is divided by 1.3, there is obtained 0.000128, which checks well with the calculated value of 0.000141.

V. Conclusions

The results of the accelerometer tests show that the amplitude of tower vibration produces a tower angular error that is small in comparison to the error of the precision instrument mount. The above analysis of an acoustical coupling between the tower and windshield, although based on boldly simplifying assumptions, gives an answer that matches the measured value to within 10%. If this is indeed the nature of the coupling, how can it be reduced? The outside of the tower is already covered with a heat insulation urethane foam. In the low frequency range at hand, it is thought that the addition of sound absorbing materials would be useless. The addition of holes in the tower would reduce the coupling but only by the percentage of area reduction. Since the only real problem caused by the vibration is the difficulty of making a level sensor work, it is best to concentrate our efforts toward developing a level sensor which will function in this kind of vibratory environment.

References

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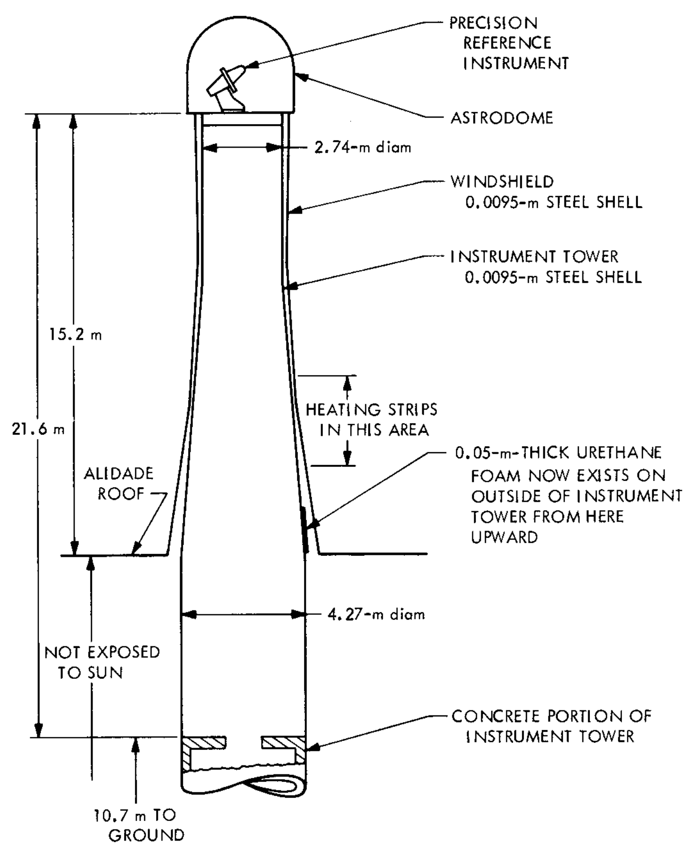

Fig. 1. Instrument tower configuration

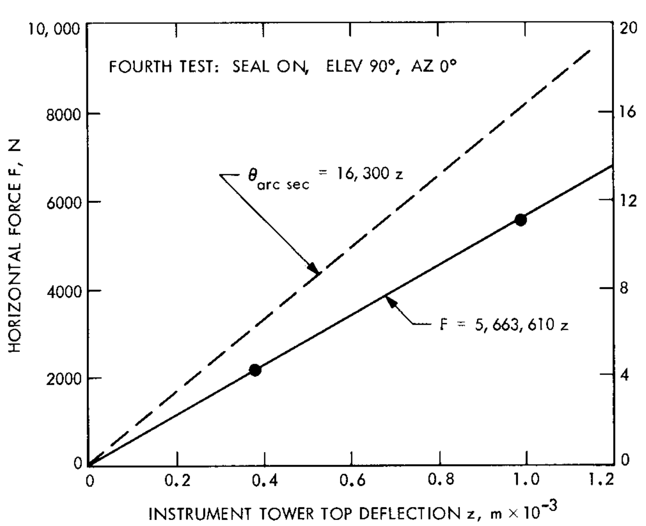

Fig. 2. Horizontal force versus tower deflection and angular deflection versus horizontal deflection

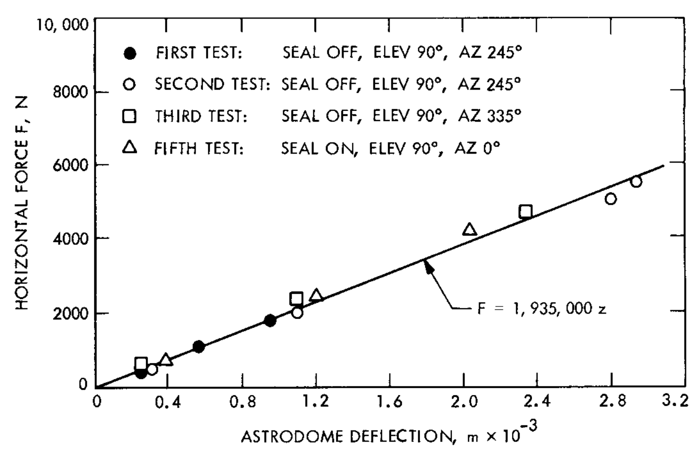

Fig. 3. Horizontal force versus astrodome deflection