POINTING ERRORS OF LARGE TELESCOPES DUE TO WIND

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ABSTRACT

Scaling laws are presented which show the dependence of the tracking error of large telescopes on structural materials, mechanical properties and dimensions of the mount, and wind speed. Based on direct measurements on the Multiple Mirror Telescope, predictions are made for future very large telescopes. It is shown that good tracking can be achieved most of the time even without a traditional dome to block the wind, and this may result in better images by eliminating "dome seeing".

INTRODUCTION

During the last 200 years it has been customary to operate large optical telescopes inside hemispherical domes with small slit areas. The dome serves as weather protection and blocks the wind from hitting the telescope structure, thus minimizing the wind shake of the image. However, the dome is not usually in thermal equilibrium with the ambient air, nor does it allow smooth air flow through the telescope. As a result of the convective air currents set up in the immediate vicinity of the telescope and the turbulence produced by the edges of the slit, the image quality is degraded. This degradation is called "dome seeing", and the effect is noticeable or even dominant at times for most large facilities. If the dome were removed altogether, the laminar air flow associated with good sites would be unperturbed before it passes through the telescope, dome seeing would not occur, and the image quality would be improved and would be determined solely by the atmosphere and the telescope. However, in that case the wind forces and torques would cause the image to move in the focal plane. In some cases it may be possible to remove the effect of image motion due to wind shake when the object is very bright by rapidly guiding a small mirror or even the detector itself. In general, however, it is desirable to minimize the image motion of all objects, especially very faint ones, and the optimum telescope would have no internal wind shake. This cannot be achieved in practice because of the limitations of the motion control servo systems used to track the telescope mount. These systems are less than perfect because of limited resolution of the angle encoders and the finite bandwidth of the control loops. Fluctuating

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wind torques on the telescope disturb the tracking smoothness and cause the image to wander in the focal plane, thus enlarging a long time exposure image. If this wander can be made small enough, then the reduction in image size due to elimination of dome seeing will more than compensate the image enlargement due to wind tracking errors, and the net result will be a better signal-to-noise ratio or a reduction in observing time. In addition, the cost of the facility may be significantly reduced since the "dome" can now be simplified.

Other intermediate solutions are also possible, and two of these deserve careful scrutiny. The first is a shelter with low fixed walls and a roof which rolls off in the downwind direction. The second is a fixed or corotating structure which has at least several (if not all) walls of low thermal capacity which can be made permeable to horizontal winds. These walls act as low-pass filters to wind speeds, allowing low speeds to pass through rather freely but also reducing the wind forces on the telescope by about an order of magnitude at the extreme operating speeds. This insures that air is flushed through the telescope at a reasonable rate to provide good dome and telescope seeing, but the mount tracking errors due to wind torques are still acceptably small. Although no telescope has yet been built which depends on such a sophisticated wind screen, the possibility of achieving both good dome seeing and low wind tracking errors with a simple mechanical structure is very appealing and should be investigated in detail.

This paper predicts the wind tracking errors of large "dome-less" telescopes which are completely exposed to the wind.

WIND FORCES AND TORQUES

An optics support structure which depends on passive internal stiffness to maintain alignment of the telescope optics against gravitational forces will hardly be deformed by wind loads, which normally are only a few percent of gravity. The dominant effect of wind is rigid body motion of the telescope about its tracking axes. Measurements of wind torques on the Multiple Mirror Telescope (MMT) show that (as expected by Kolmogorov turbulence theory) the wind torque per root Hz varies as $[\text{frequency}]^{-7/6}$ and also varies as the square of the mean speed (Woolf and Ulich 1984). Further investigations are required to understand the differences (if any) in statistical "gustiness" among different sites.

TELESCOPE TRACKING ERRORS

Fluctuating wind torques disturb the telescope position servo loops and produce dynamic tracking errors. The magnitude of this error depends on the square root of the integral of the square of the wind torque frequency spectrum (expressed as torque per root bandwidth) multiplied by the torque responsivity spectrum of the servo system (expressed as the frequency-dependent position error per unit torque). Since the wind spectrum is known, one only needs to find the disturbing torque responsivity of the control system. For a typical state-of-the-art servo loop, this function depends on only two parameters, the spring constant of the telescope drive (K) and the rotational moment of inertia of the telescope (J). The locked-rotor resonant frequency of the mechanical system (in radians/second) is given by $[K/J]^{1/2}$. These parameters are, in turn, functions of the mechanical design, the structural material properties, and the dimensions.

MATERIALS

There are for many practical reasons now only three materials suitable for fabricating telescope structures. These are steel, aluminum, and carbon-fiber-reinforced-epoxy (CFRP). Steel is economical and easy to fabricate, but it has significant thermal deformations. Aluminum has the same stiffness per unit mass as steel, but it is about 5 times as expensive and has even larger thermal expansion. Thus aluminum is not to be preferred over steel. CFRP, on the other hand, has 3 times the stiffness per unit mass compared to steel and thermal expansion about 15 times smaller. Resonant frequencies can be made about 1.7 times higher, and the wind tracking error can be made about 1.4 times smaller. In addition, the gravity deformations are 3 times smaller and the thermal time constant is 1.7 times shorter than for steel. However, CFRP is now very expensive and joints are particularly difficult to fabricate. It seems that the slight improvements offered by CFRP are not worth the extra cost. The exception to this rule might be the case where the lower thermal expansion of CFRP would allow passive position control of optics which could only be matched by an active control system mounted on a steel structure. In conclusion, steel is generally preferred for economy.

SCALING LAWS

The torsional spring constant K varies as GS^2T, where G is the modulus of elasticity in shear, S is the linear dimension scaling factor (diameter and length) of the optics support structure, and T is the wall thickness of the members which comprise the optics support structure. The torsional moment of inertia J varies as DS^4T, where D is the material density. The mass depends on DS^2T, and the locked-rotor frequency varies as $[G/D]^{1/2}/S$. Thus the resonant frequency and the servo bandwidth are independent of the structure wall thickness T but decrease linearly as the dimensional scale factor S is increased. By performing the previously described spectral calculations, the position error due to unit wind shake is found to be proportional to $J^{1/3}K^{-4/3}$, or to $D^{1/3}G^{-4/3}S^{-4/3}T^{-1}$. Since the actual wind torque is proportional to S^3V^2, where V is the mean wind speed, the actual one-dimensional root-mean-squared position error E_w varies as $D^{1/3}G^{-4/3}S^{5/3}T^{-1}V^2$. For the MMT (which has a steel structure with resonant frequencies of 4 Hz in both axes), S = 7 meters, and the measured value of E_w in the worst case for V = 10 meters/second is 0.14 arc seconds, which is about one-half the typical image motion due to seeing. The wind speed exceeds 10 meters/second about 20% of the time at the MMT. The worst-case wind torques measured on the MMT are equal to that calculated for the same telescope completely exposed to the wind. Thus the measured worst-case tracking errors are also appropriate for a "dome-less" telescope. The average wind tracking error is lower than the worst-case value by a factor of about two.

VERY LARGE TELESCOPES

If the steel MMT were scaled larger in all three dimensions (S = 15 meters and T a factor of two larger), then E_w for this 15 meter telescope would be 0.25 arc seconds, which is comparable to the seeing motion and larger than desired. The thermal time constant of the steel structure would still be only about 30 minutes, resulting in typical night-time thermal differences of 0.2°C and telescope seeing of about 0.1 arc second. The dominant compliance in the MMT is not in the optics support structure but rather in the gear drives. An optimized design could double the effective spring constant (halve the torsional compliance) and reduce the wind error E_w by a factor of 2.5. Thus for the MMT the wind error could be reduced to 0.06 arc seconds at V = 10 meters/second and for a 15 meter MMT-style telescope the worst-case E_w = 0.10 arc seconds. The cost of building stiffer drives is not negligible but seems worthwhile compared to the improved performance, and it is probably smaller than the cost savings gained by the simpler shelter. In conclusion, it is possible to build a 15 meter telescope which has wind tracking errors no more than half as large as the typical image motion due to seeing for at least 80% of the time even if this telescope is completely exposed to the wind.

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REFERENCES

Woolf, N. J. and Ulich, B. L. 1984, Proceedings of the European Southern Observatory Workshop on "Site Testing for Future Large Telescopes", No. 18, 163-183.

DISCUSSION

B. Mack: What natural frequency would the large telescope be, would it be 2Hz, 5Hz or 10Hz?

B. Ulich: The locked-rotor resonant frequency of a fast 7.5m aperture telescope would be about the same as the MMT, which is about 4Hz in both axes. An optimized drive system could raise that to about 6Hz. For a 15m equivalent aperture MMT the corresponding frequencies are about 1.5Hz for the scaled-up MMT drive design and 2.3Hz for an optimized drive system.