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Measurement, Modeling and Adjustment of the 10.4 m Diameter Leighton Telescopes

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ABSTRACT

The design of the Leighton telescopes and the unique techniques used in their fabrication make these telescopes particularly amenable to precise modeling and measurement of their performance. The surface is essentially a continuous membrane supported at 99 uniformly distributed nodes by a pin joint triangular grid space frame. This structure can be accurately modeled and the surface can be adjusted using low-resolution maps. Holographic measurements of the surface figure of these telescopes at the Caltech Submillimeter Observatory (CSO) and the Owens Valley Radio Observatory (OVRO) have been made over several epochs with a repeatability of 5-10 μm over the zenith angle range from 15 to 75 degrees. The measurements are consistent with the calculated gravitational distortions.

Several different surface setting strategies are evaluated and the "second order deviation from homology", H_d, is introduced as a measure of the gravitational degradation that can be expected for an optimally adjusted surface. H_d is defined as half of the RMS difference between the deviations from homology for the telescope pointed at the extremes of its intended sky coverage range. This parameter can be used to compare the expected performance of many different types of telescopes, including off-axis reflectors and slant-axis or polar mounts as well as standard alt-az designs. Subtle asymmetries in a telescope's structure are shown to dramatically affect its performance. The RMS surface error of the Leighton telescope is improved by more than a factor of two when optimized over the positive zenith angle quadrant compared to optimization over the negative quadrant.

A global surface optimization algorithm is developed to take advantage of the long term stability and understanding of the Leighton telescopes. It significantly improves the operational performance of the telescope over that obtained using a simple "rigging angle" adjustment. The surface errors for the CSO are now less than 22 μm RMS over most of the zenith angle range and the aperture efficiency at 810 GHz exceeds 33%. This illustrates the usefulness of the global surface optimization procedure.

Keywords: radio telescopes, radio holography, structural modeling, surface adjustment, telescope design

1. INTRODUCTION

Many factors affect the performance of large reflector antennas, including wind, temperature and gravity. The papers by von Hoerner[1, 2] and Baars[3] review these effects and their contribution to the RMS surface errors. Modern telescopes use sophisticated structural models to optimize the design taking these effects into account (see for example Baars et al.[4, 5]). The forcing functions for the wind and temperature effects are essentially random and the structure must be designed to perform satisfactorily under "typical" conditions. On the other hand, the gravitational distortions are well-behaved and predictable using modern structural analysis programs. Von Hoerner showed that you could apply the homology concept to design reflectors in which the deviations from the best-fit paraboloid are much smaller than the gross gravitational deformations.

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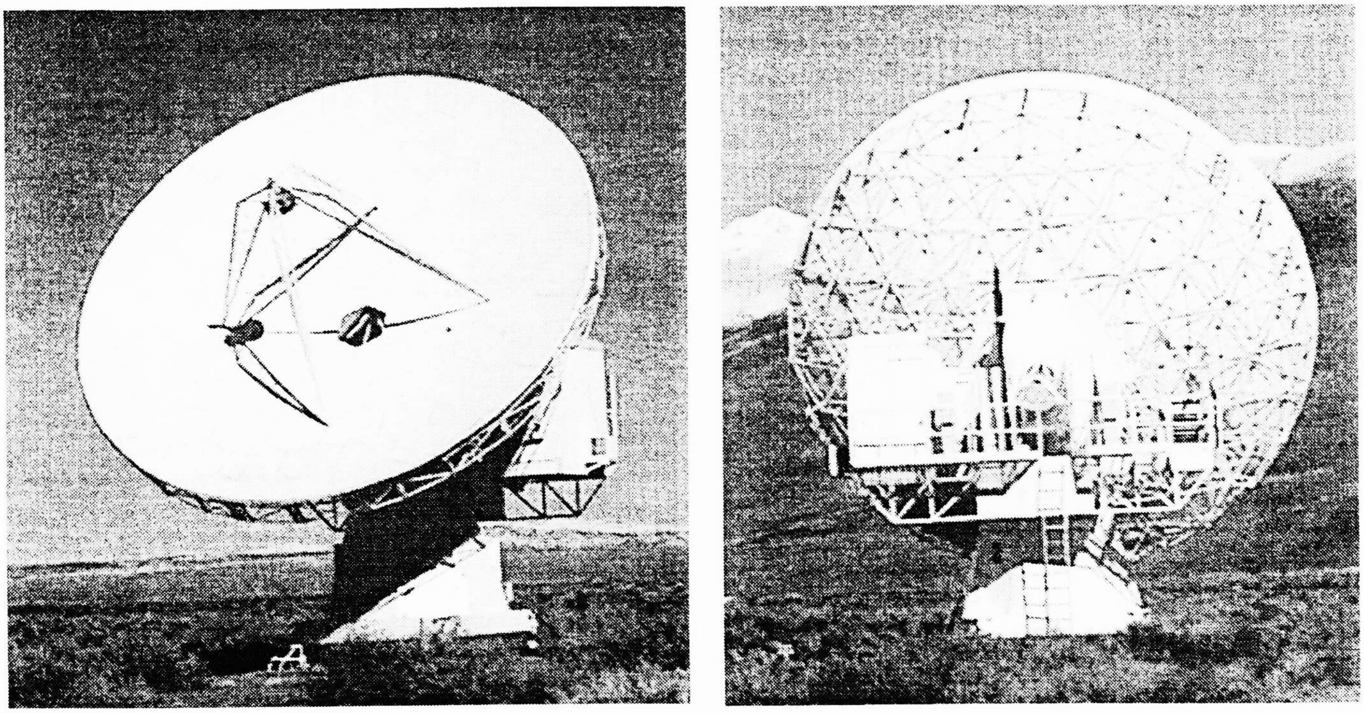

Figure 1. Front and back views of a Leighton telescope at OVRO.

The improvements in structural design have resulted in telescopes with homology ratios much greater than five[6, 7, 8]. Even with these improvements, gravitational distortions still dominate the reflector performance for most large radio telescopes.

The performance achieved by a telescope depends upon how the surface is set or tuned. Proper tuning of the surface can reduce the degradation caused by the gravitational distortions. This requires a thorough understanding of the gravitational deformations of the telescope, a strategy for determining the optimal shape, and a method for measuring the surface before and after adjustments have been applied. This paper discusses these issues in the context of the Leighton 10.4 m diameter telescopes used at the Caltech Submillimeter Observatory (CSO) and at the Owens Valley Radio Observatory (OVRO).

Prof. Robert Leighton developed these telescopes in the 1970's for use in the OVRO millimeter interferometer array. The array initially consisted of three of these telescopes. After their excellent performance was demonstrated at millimeter wavelengths, Prof. Leighton fabricated a fourth telescope for the CSO. This telescope is now named after Prof. Leighton in honor of his many contributions to astronomical instrumentation and measurements during his career at Caltech. Three more telescopes were added to the OVRO array for a total of six telescopes.

The design and fabrication of the Leighton telescopes is described in detail in the paper by Woody et al.[7] Many innovative ideas were incorporated into the design and fabrication of the Leighton telescopes. Some of the innovations are very subtle and only when the details of the structure are studied does their significance become apparent. This paper is a result of trying to understand the intricacies of Prof. Leighton's design and realizing that an extension of the standard surface setting procedure was required for these telescopes to reach their full potential.

The pictures in Fig. 1 show two views of one of the Leighton telescopes at OVRO. The important features of the telescopes for this paper are the hexagonal panels and the triangular spaceframe backing structure. The view of the back of the reflector shows the uniform spacing of the backing structure nodes and the neutral corners where three panels meet in free space and are fastened together. The truncated triangular tipping platform that supports the backing structure is also visible in this picture. The telescopes have proven to be very stable and in the case of the CSO have an operational surface error of less than 22 µm RMS over most of the zenith angle range. The telescopes operating outside at OVRO have a surface error of ~35 µm during the night and ~50 µm during the day.

An important step in optimizing the surface figure is verifying the accuracy of the structural calculations by measuring the surface distortions as a function of zenith angle. Section 2 presents the holographic measurements obtained over a wide zenith angle range and compares the results to the structural calculations. Optimal setting of the surface depends not only upon knowing the gravitational deformations but also upon the intended use for the telescope, i.e. what are you trying to optimize. Section 3 develops a generalized formalism for optimizing the surface tuning for different telescope configurations and different observational requirements. It is found that the symmetry or the lack of symmetry can significantly affect the optimal tuning and final performance achieved. The "second order deviation from homology", H_d, is defined that indicates the achievable performance you can expect from a optimally tuned telescope. The tuning procedure and results for setting the CSO surface are described in Section 4. A summary and conclusions are given in section 5.

2. CALCULATED AND MEASURED GRAVITAIONAL DEFORMATIONS

The primary quantity of interest for radio telescopes is the phase error across the aperture plane. In this paper we will only deal with the path length errors caused by gravitational deformations of the primary surface. The theory of gravitational deformation of large radio telescopes is well developed[8, 9, 10]. Radio telescopes usually qualify as elastic structures in which the gravitational deflections are small. The gravitational deformation of an elastic structure in any orientation can be calculated using linear superposition of the three principle deformation maps obtained for gravity applied along the three orthogonal axis in the reflector's coordinate frame. These principle maps are based upon starting with a perfect surface, i.e. a paraboloid, at zero gravity and then applying gravity. It is only necessary to carry out detailed structural calculations for gravity applied along three orthogonal directions. The deformation for an arbitrary orientation is given by

$$S(x,y)_g = D_x(x,y)\hat{g}\cdot\hat{x} + D_y(x,y)\hat{g}\cdot\hat{y} + D_z(x,y)\hat{g}\cdot\hat{z} + T(x,y)\,. \tag{1}$$

$D_x(x,y)$, $D_y(x,y)$, and $D_z(x,y)$ are the principal deformations for gravity applied along the X, Y and Z directions respectively, $\hat{g}$ is the gravity unit vector and $T(x,y)$ is the fixed tuning or adjustment applied to the surface. The coordinate system is fixed to the reflector with Z along the optical axis and X parallel to the elevation axis for an elevation over azimuth (alt-az) mount.

Most radio telescopes have mechanisms for moving the position of prime focus receivers, or equivalently the secondary mirror, to correct for the first three aberrations; tilt in X and Y and focus in Z. The gravitational deformations are a simple function of the zenith angle and the secondary mirror can track the optimal prime focus position. The performance of a telescope structure is usually evaluated in terms of its deviation from homology, that is a best fit paraboloid is removed from the calculated surface deformations[8]. Throughout this paper the terms surface distortion, deformation or deviations will mean half of the effective path length errors after subtracting the best fit paraboloid.

There are several caveats that should be kept in mind when applying the principle of the linear superposition of forces used in equation (1). Non-linear and hysteretic deformations must be small and it is also assumed that the support of the tipping structure does not change as the structure moves. This is true for balanced structures which are essentially supported by bearings at two points with the third support point carrying no load, but it is not strictly true for unbalanced structures. The position or vector direction for the application of the balancing force provided by the drive system usually changes as a function of the zenith angle and thus does not meet the strict requirements for a simple linear superposition of forces in the reflector's reference frame. Unbalanced structures are not treated in this paper, although the distortions of an unbalanced alt-az telescope operating only over the 0-90 deg zenith angle range can be reasonably well approximated using linear superposition of the zenith and horizontal orientation maps.

Most radio telescopes use alt-az mounts in which the gravity component parallel to the elevation axis is zero and only the $D_y(x,y)$, and $D_z(x,y)$ deformation maps are required to fully characterize the effect of gravity. Figure 2 shows the calculated deformations for the Leighton telescopes looking at the zenith and the horizon. The rms of these maps is 29 and 41 μm respectively for Gaussian aperture weighting with 10dB edge taper giving a standard deviation from of homology of $H_0 = 36$ μm. The raw map errors are 95 and 247 μm before removing the best-fit paraboloid and hence the homology ratio is ~5.

It is important to verify that the maps is Fig. 2 accurately reflect the deformations of the actual structure before the surface figure can be optimized using the strategies described in the next section. This requires measuring the surface as a function of zenith angle. The standard method for accomplishing this is to use "holography" with satellite and astronomical sources[11, 12, 13]. At OVRO the six Leighton telescopes in the millimeter interferometer are routinely measured using the brightest quasars and planets at 1.3 mm and 3 mm wavelengths. The CSO uses a shearing interferometer with a bolometric detector to make holographic measurements of the telescope surface using the planets[14]. This system operates well at millimeter and sub-millimeter wavelengths. Most of the maps reported here are based on the CSO shearing interferometer operating from 0.8 to 1.7 mm. Both methods use the same secondary mirror and observing frequencies as are used for astronomical observations.

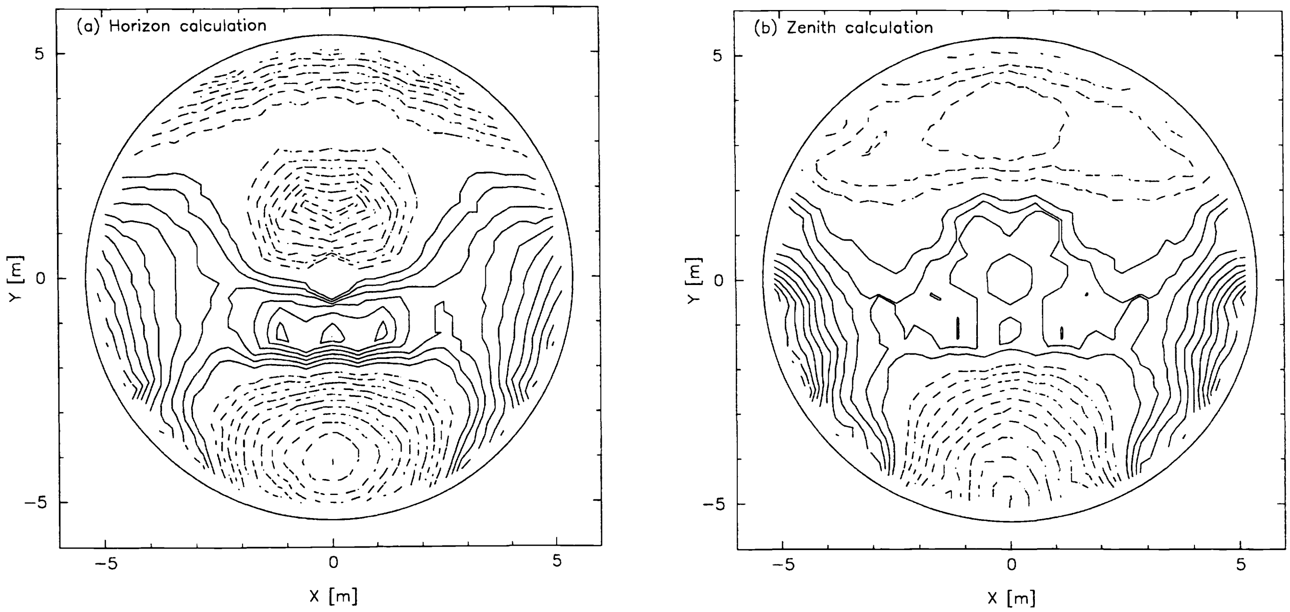

Figure 2. Calculated gravitational distortion maps at the horizon (a) and at the zenith (b). The contour interval is 10 μm with the zero contour suppressed.

These systems work extremely well and provide very repeatable and accurate maps of the aperture phase errors for the telescopes including the primary and secondary. The RMS difference between 21x21 pixel maps made at the same zenith angle on successive days is ~7 μm. The repeatability after a year is <15 μm. The CSO operates at frequencies as high as 850 GHz and the shearing interferometer has been essential in setting the surface to the high accuracy required for these observations.

Gravity will produce low order aberrations in the surface figure. Hence, quick low-resolution maps can be used to "freeze" the telescope in a narrow zenith angle range in order to study the gravitational deformations. The surface deformations of the Leighton telescopes have been measured over the zenith angle range from 20 to 75 degrees. Figure 3 shows five maps of the CSO obtained using Mars and Saturn to cover the full zenith angle range in one night. The spatial resolution of these maps is ~1 m. The surface of the Leighton telescopes is essentially a continuous meniscus supported at 99 points and hence can be characterized using these low-resolution maps[7]. This will be discussed further in section 4. These five maps were used to determine a best-fit model of the gravitational distortions consisting of the zenith and horizon distortion maps. The RMS deviation of the measured data from the best-fit gravitational model is 7 μm. This is the average RMS error of five measurements of the displacement of each node after removing a best-fit sinusoid. This includes the measurement errors and hence indicates both that the telescope follows the linear superposition model and that the holographic measurement errors are small.

The structural calculations can be compared to the measured distortions by looking at the change in shape between the zenith and horizon. This difference is shown in Fig. 4 for the best-fit model and the structural calculations. The RMS of the difference map for the best-fit model is 45 μm while the structural calculations predict only a 32 μm RMS difference. Thus ~30 μm of the measured difference is not accounted for by the structural calculations. This is only 10% of the difference for the gross deformations. The required positioning of the secondary is also predicted to an accuracy of ~10%. Thus the structural calculations predict the gross deformations with ~90% accuracy.

Simple structural stiffness errors do explain the discrepancy since scaling the calculated maps does not reduce the difference between the calculated and measured maps. Several effects that might explain the difference between the measured and calculated surface maps. There could be mistakes in the structural model used for the calculations or there may be additional distortions not caused by gravity. Incomplete modeling of the tipping structure supporting the reflector spaceframe is a likely source of modeling errors. The measurements show a distinct left-right asymmetry that could be a thermal effect.

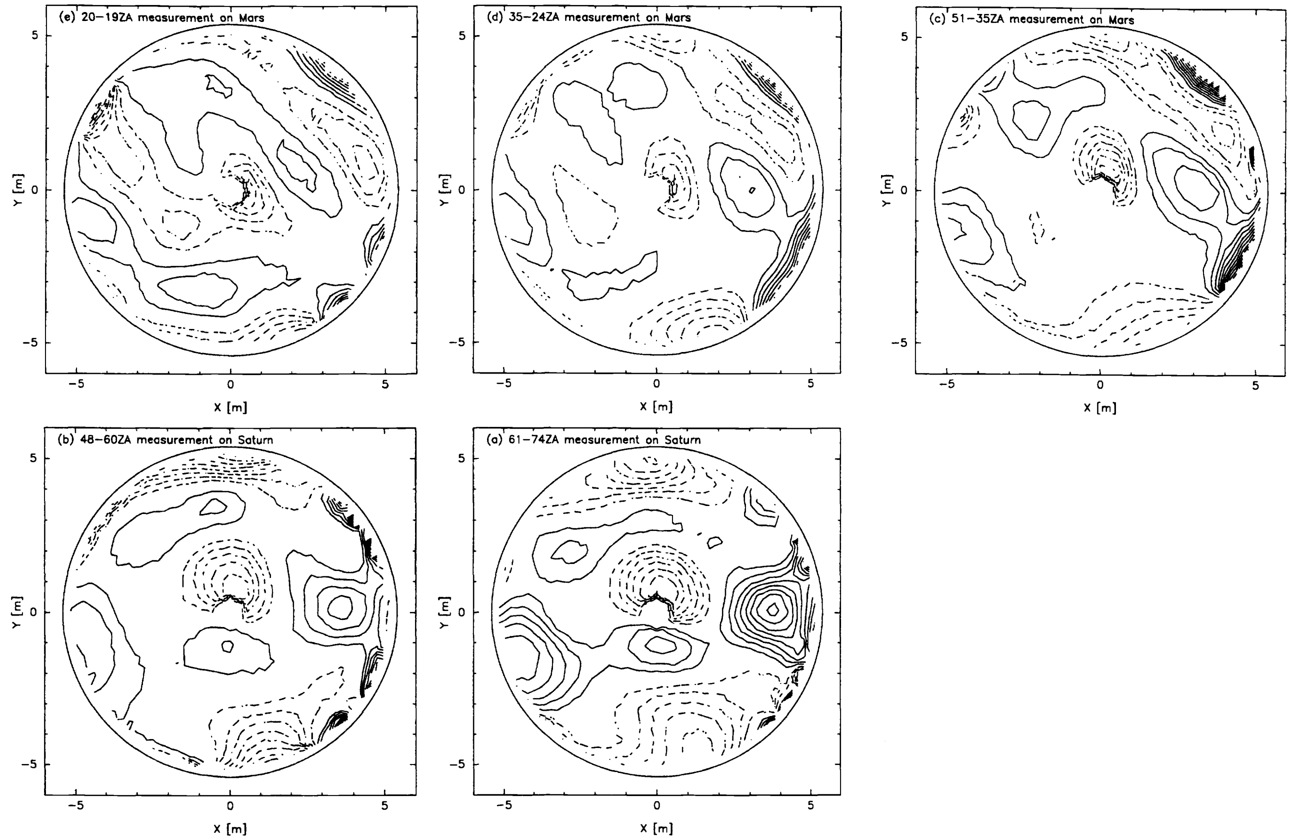

Figure 3. Measured CSO surface deviations at five different zenith angles. The contour interval is 10 μm with the zero contour suppressed. The resolution of these maps is ~ 1 m.

The heat rising from the Naysmyth receiver room on the right side or compressors on the left side could distort the reflector at the zenith.

3. SURFACE SETTING STRATEGIES

The performance of a telescope during observations will depend not only on the gravitational deformations but also on how the panels are set. The structure is not built perfectly in zero gravity and then gravity applied, which is what the computer models calculate and is plotted in Fig. 2 for the Leighton reflector. A fixed "tuning" map, T, must be included to obtain the actual surface errors. Radio telescope surfaces are often set to minimize the surface error at some "rigging angle". As will be shown below there are other more general strategies that result in significantly better performance for radio astronomy applications. The structural calculations for the Leighton telescopes will be used below to illustrate the improvement that can be achieved using these strategies.

The effect of gravity on the surface can be represented as a family of curves showing the displacements of a representative subset of the backing structure nodes as a function of zenith angle (ZA). The full 2-dimensional maps are not necessary since the primary quantity of interest is the aperture efficiency that is determined by the statistics of the displacements and not the shape of the distortions[15]. The node displacements for the Leighton telescope are shown in Fig. 5(a) without any tuning. Each node follows a sinusoid with its own phase and amplitude. A distinct feature of the node plot for the Leighton reflector is the lack of symmetry about ZA = 0. A structure that has reflection symmetry across the XZ-plane will have a node plot that appears symmetric, i.e. the nodes will occur in symmetric pairs. Note that although the Leighton node plot is asymmetric, the maps at –90 and +90 deg are still mirror images of each other, as they must be.

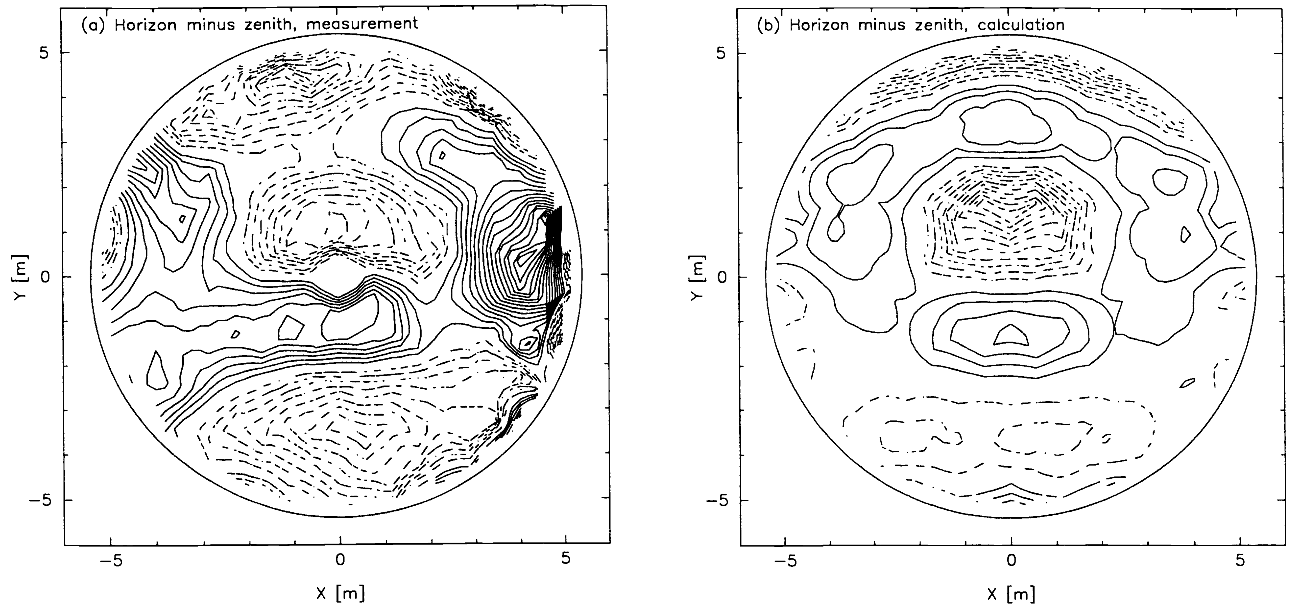

Figure 4. Horizontal deviation map minus zenith map: (a) best-fit model from maps in Fig. 3, (b) structural calculations. The contour interval is 10 μm with the zero contour suppressed.

The asymmetry must be taken into account in optimizing the surface tuning. The source of the asymmetry in the Leighton telescope is not obvious. As seen in Fig. 1 the reflector is a rotationally symmetric paraboloid with a symmetric tiling of the hexagonal panels and a quadrupod to support the secondary. The triangular spaceframe is shifted up ~ ½ a grid spacing in the *Y*-direction which breaks the symmetry. The symmetry is also broken by the attachment to the tipping structure at nine points in a truncated triangle pattern. Many telescope configurations are not completely axisymmetric, such as off-axis reflectors, tripod supported secondaries, and elevation bull gears with less than ±90 ZA range.

Tuning the surface corresponds to shifting the individual node curves in Fig. 5(a) up or down. The mean square distortion for a structure obeying equation (1) is

$$\sigma_g^{\,2} = \sum_{i=1}^{N} w_i (D_{x,i}\hat{g} \cdot \hat{x} + D_{y,i}\hat{g} \cdot \hat{y} + D_{z,i}\hat{g} \cdot \hat{z} + T_i)^2 . \tag{2}$$

The weighting coefficients, w_i, normalize the contribution of each adjustment point, including the fraction of the total illumination affected by adjustments at point *i*. The choice of tuning adjustments, T_i, has a large effect on the performance of a telescope during observations.

The optimal tuning can be calculated once an objective measure of the telescope's performance is defined. Observations of a geosynchronous satellite requires that a telescope perform well only over a small region of the sky and the antenna gain in the center of this region is a good measure of it's performance. On the other hand, the worst gain over the full sky is a reasonable measure of the performance for a general-purpose astronomical telescope. Other performance measures are possible and the choice will depend upon the intended use for the telescope. The best tuning is then found by determining the set of T_i which optimizes the chosen measure of performance.

The standard "rigging angle" adjustment optimizes the surface at a specified orientation. This is accomplished by applying the tuning

$$T_{ra,i} = -D_{x,i}\hat{g}_{ra} \cdot \hat{x} - D_{y,i}\hat{g}_{ra} \cdot \hat{y} - D_{z,i}\hat{g}_{ra} \cdot \hat{z} , \tag{3}$$

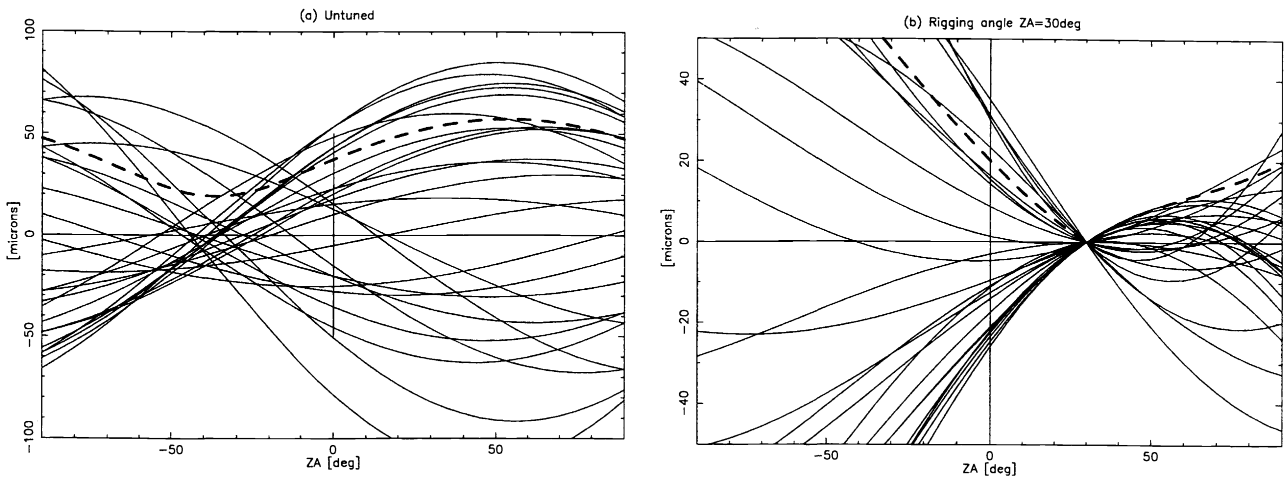

Figure 5. Displacements of a representative set of nodes as a function of zenith angle. The RMS deviation of all nodes is plotted as a thick dashed line. The raw displacements before applying any surface tuning are shown in (a) and the displacements after adjusting the surface for a rigging angle of 30 deg are shown in (b).

where $\hat{g}_{ra}$ is the gravity vector at the rigging angle. Levy gives formulas for picking the rigging angle that gives equal RMS deviations for the zenith angles at the extremes of the desired observing range for an alt-az telescope[16]. Von Hoerner calculates an "optimum" rigging angle for axisymmetric alt-az telescopes as a function of the ratio of variances for the vertical and zenith deformation maps[9]. Figure 5(b) shows the node paths and surface RMS error for the Leighton reflector tuned to be perfect at 30 deg.

Another strategy is to minimize the average surface error of an alt-az telescope over a selected zenith angle range. Integrating equation (2) from θ_1 to θ_2 and minimizing the contribution of each node results in a tuning given by

$$T_{ma,i} = [(\cos(\theta_2) - \cos(\theta_1))D_{y,i} + (\sin(\theta_1) - \sin(\theta_2))D_{z,i}]/(\theta_2 - \theta_1). \tag{4}$$

A strategy more appropriate for a general-purpose telescope intended to cover most of the sky is to minimize the worst case surface error over a selected zenith angle range. An approximate solution to this problem is to simply set the tuning equal to minus the average of the deflection maps at the extremes of the selected zenith angle range[13, 17], i.e.

$$T_{mwc,i} = -\tfrac{1}{2}\left((\cos(\theta_1) + \cos(\theta_2))D_{y,i} + (\sin(\theta_1) + \sin(\theta_2))D_{z,i}\right). \tag{5}$$

This tuning produces equal surface variances at the extremes of the zenith angle range and the displacement of each node has equal magnitude and opposite sign at the ends of the range. Figure 6(a) and (b) show the result of applying this tuning to the Leighton telescopes for 0 to 90 deg and –90 to 0 deg respectively. This tuning reduces the worst case errors at the extremes of the zenith angle range at the cost of not having an ideal surface at any orientation.

The performance is much better when operating over the positive zenith angle quadrant than over the negative quadrant despite the raw RMS surface error plotted in Fig. 5(a) being larger in the positive quadrant. The reason for this can be understood by examining the node plot in Fig. 5(a). Most of the node displacement sinusoids have an extremum in the positive quadrant while they are crossing zero in the negative quadrant. Thus the net node excursions are larger in the negative quadrant than in the positive quadrant and shifting the sinusoids up or down is less effective in reducing the peak RMS at –90 and 0 deg. The same difference in the peak RMS for the two quadrants also shows up when applying the standard rigging angle tuning. Rigging angle tuning in the negative quadrant yields a peak RMS more than twice as large as the positive quadrant tuning displayed in Fig. 5(b).

Equation (5) is the exact solution to minimizing the peak variance for axisymmetric alt-az telescope. In this case the zenith deflection map is symmetric, $D_z(x,-y)=D_z(x,y)$ and the horizon deflection map is anti-symmetric, $D_z(x,-y)=-D_z(x,y)$ and hence the cross correlation of the zenith and horizon deflection maps is zero. It can be shown that the maximum variance

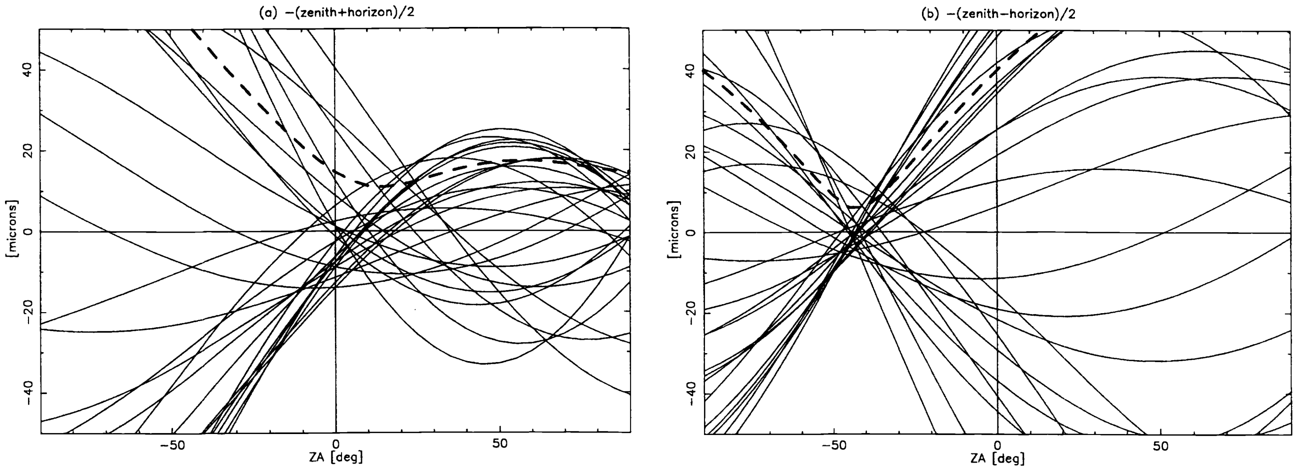

Figure 6. Node displacement plot for equal RMS deviations at 0 and 90 deg in panel (a) and equal RMS deviations at -90 and 0 deg in panel (b).

occurs at both ends of the zenith angle range and any other tuning will increase the maximum variance. The peak RMS distortion for optimization over the full 0 to 90 deg is given by

$$\sigma_{\max} = \tfrac{1}{2}\left(H_y^2 + H_z^2\right)^{\frac{1}{2}}. \tag{6}$$

Following the convention of von Hoerner[8] H_y and H_z are the RMS deviations for the horizon and zenith deflection maps relative to a perfect surface in zero gravity. This $\sigma_{\max}$ is $\sqrt{2}$ smaller than the standard deviation from homology, H_0, defined by von Hoerner.

A global search must be used to minimize the peak variance for telescopes that are not axisymmetric. Equation (5) can be used as the starting point for an iterative search for the optimal tuning. Another method is to look at the each node and adjust its tuning to minimize its deviation over the zenith angle range of interest and use this as the starting point for a global search. Figure 7(a) shows the global optimization for operation over the full ZA range. The RMS is a very flat function of ZA with a minimum of 10 μm and a maximum of 16 μm. Figure 7(b) shows the results when optimizing over the 5 to 60 deg range. The peak RMS is reduced to 12 μm over this range.

Global optimization for operation over the negative quadrant is far worse. The results are essentially the same as shown in Fig. 6(b) with a peak RMS of 40 μm. This is a factor of 2 ½ degradation in performance compared to optimization over the positive quadrant. This is dramatic considering the subtle deviations from symmetry for the Leighton telescope structure. This could be an important consideration when designing off-axis or other obviously asymmetric telescopes. The node displacement plots are very useful for identifying troublesome nodes during the design optimization process. Nodes that have the same sign of displacement for the zenith and horizon deflection maps do not affect the operational performance as much as nodes whose displacement changes sign for the two maps.

The peak RMS for global optimization over the 0 to 90 deg range is only 45% of H_0 for the Leighton telescope. A more useful measure of the performance potential is half of the RMS difference between the gravitational distortion maps at the extremes of the operational tracking range given by

$$H_d = \frac{1}{2}\left\{\sum_{i=1}^{N} w_i \left[(\hat{g}_1 - \hat{g}_2)\cdot(D_{x,i}\hat{x} + D_{y,i}\hat{y} + D_{z,i}\hat{z})\right]^2\right\}^{\frac{1}{2}}. \tag{7}$$

H_d accounts for the degree to which the deviations from homology can be "tuned out" and hence can be called the "second order deviation from homology". Axisymmetric alt-az telescopes operating over the full 0 to 90 deg range will have

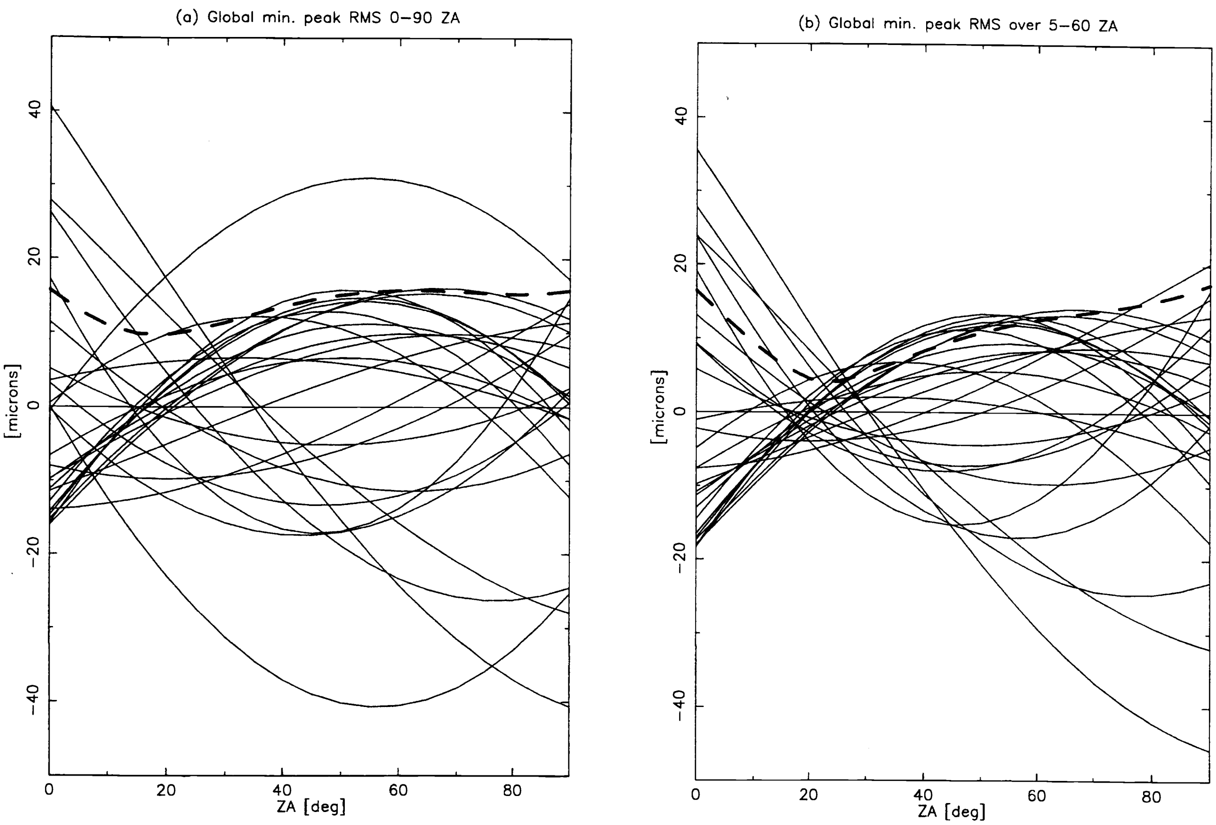

Figure 7. Node displacements for global minimization of the peak RMS surface deviation over 0 to 90 deg in panel (a) and over 5 to 60 deg in panel (b).

$H_0 = H_0/\sqrt{2}$. Telescopes that are not axisymmetric can achieve significantly better performance when operated in the favorable quadrant. H_d for the Leighton telescope is 16 μm which is the same as the peak RMS deviation for the globally optimized tuning plotted in Fig. 7. H_d also properly evaluates the potential performance of telescopes operating over reduced or expanded elevation ranges. Analogous to the homology ratio we can define a "tuneability ratio" t= H_0/H_d. The tunability for the Leighton telescope for the 0 to 90 zenith angle range is 2.2 compared to 1.4 for an axisymmetric structure.

Telescope mount configurations other than the alt-az geometry present difficult challenges. The peak RMS deviation can not be improved significantly over the untuned performance when the gravity vector sweeps out a large angular range. Polar and slant-axis mounts are in this category. The full gravity vector can reverse directions in a polar mount and equation (7) gives $H_d \sim H_0$. An off-axis reflector mounted on a slant-axis appears to have a better geometry[18]. The $g/\sqrt{2}$ gravity component parallel to the slant-axis is stable and its effect can be completely removed by tuning, but the $g/\sqrt{2}$ component perpendicular to the axis sweeps through 180 deg in covering the full sky. Any tuning to improve the performance at one end of the range will degrade the performance at the other extreme. The second order deviation from homology is close to what the same reflector mounted on an alt-az mount would achieve, i.e. $H_d \sim H_0/\sqrt{2}$.

4. SURFACE ADJUSTMENT PROCEDURE

The global optimization algorithm described above has been applied to both the OVRO and CSO telescopes. We will emphasize the procedure used to set the CSO surface because of the more exacting requirements it must meet for sub-millimeter observations. The zenith angle range for the optimization is 5 to 60 deg. The surface adjustment was carried out in two steps; first the small errors were measured and corrected, then the large-scale deformations were measured and corrected.

The design and fabrication of the Leighton telescopes makes optimization of the surface relatively easy[7]. The backing structure spaceframe forms an equilateral grid with a node spacing of 1.14 m when projected onto the aperture plane. The surface is tiled with 84 approximately hexagonal panels supported at 99 nodes. The three panels that meet above one of the nodes share a common adjustable standoff. When three panels meet in the middle of a grid triangle they are fastened together. These "neutral corners" are not connected to the backing structure. Thus three of the corners of each hexagonal panel are supported by stiff standoffs and the other three are tied to neighboring panels. The panels are all placed on the backing structure and the surface figure is cut into the whole structure using a custom built machining fixture. The accuracy of the final surface in the fabrication shop is <15 μm RMS on all size scales. The panels used for the CSO have an additional six-legged "spider" structure that can be used to fine tune the curvature of each panel. The errors for the CSO reflector were reduced to ~10 μm in the shop through a process of surface "polishing" and panel curvature adjustment. This fabrication technique insures that all of the panel edges are accurately aligned and that the small-scale errors are less than 10 μm. The reflector surface resembles a thin meniscus mirror more than it does panels on a traditional radio telescope.

Experience shows that the Leighton telescopes can be disassembled and reassembled in the field with a resulting surface accuracy at zenith of ~25 μm. The CSO operates at wavelengths as short as 0.3 mm and it was necessary to recover the excellent small-scale accuracy that was achieved in the lab after the telescope was installed in the dome on the top of Mauna Kea. This was accomplished using a measuring fixture with non-contacting transducers mounted on an arm that extended from the vertex to beyond the rim. With the telescope at the zenith and the feedlegs removed the measurement arm was suspended between a bearing at the vertex and a platform attached to the dome. Measurements were taken as the telescope rotated in azimuth beneath the arm to provide surface deviations at 32 different radii as a function of azimuth. Tiltmeters were used to monitor the orientation of the azimuth axis and measurement arm. Azimuthal "ring" maps were obtained that had an accuracy of better than 5 μm RMS. These maps were used to adjust the spiders and correct errors that occurred during shipping and reassembly. The small-scale defects were less than 10 μm after these corrections. Despite not having any absolute radial measurements, this method works very well for the hexagonal panels used by the Leighton telescopes. It would not work as well for telescopes that have panels arranged in rings since the transition between successive rings would not be sensed.

The OVRO millimeter array only operates at wavelengths longer than 1 mm and detailed measurements of the small-scale errors were not necessary, but measurements were made of the panel warping under different solar illumination conditions. The panels form a perfect hexagonal array when projected onto the aperture plane and warping of the panels produces grating lobes in the far-field beam. The average panel shape was determined by measuring the beam at these reciprocal lattice points and reconstructing the unit cell much like X-ray crystallography with the added benefit of phase information. The measurements showed that direct solar illumination makes the panels concave and contributes ~25 μm to the surface RMS. At night the panels became convex adding ~10 μm to the surface RMS. The OVRO panels are painted white to minimize the daytime distortions. The same measurements on a telescope with bare aluminum panels showed that the day RMS increased by ~35 μm. The CSO operates only at night and the bare aluminum panels are insulated on the back to minimize the heat flow through the panels. The thermal warping of the CSO panels at night contributes less than 5 μm to the surface RMS.

The setting of the surfaces of the Leighton telescopes is based on the holographic measurements of the aperture phase errors and the global optimization strategy described in section 3. The calculated gravitational deflection together with the global optimization determines what the surface should look like as a function of zenith angle. The corrections to be applied are determined by comparing the measured surface to the calculated optimum shape at the same elevation. It is not sufficient to simply adjust the surface to be perfect from the measurements since this will have the effect of applying rigging angle tuning at the zenith angle at which the measurements were made. The procedure was iterative using under-correction to avoid "chasing our tails". We were able to accurately predict the adjustments necessary to achieve the desired tuning. This required proper modeling of the panel stiffness since each panel is attached to three rigid standoffs and also to three neutral corners.

The CSO adjustments were carried out over many observing runs spread out over several years with the goal of minimizing the RMS surface error over the 5 to 60 deg zenith angle range. The shearing interferometer evolved during this time and our understanding of how to optimize the surface improved. The structure is very stable and periodic readjustments do not appear to be required. The OVRO telescopes have been measured many times but the surfaces have been adjusted only once or twice during the two decades that they have been in operation.

Figure 8 shows the measured and calculated surface errors for the CSO as a function of zenith angle. The plotted measurements are from the holographic measurements with an estimated 5 μm measurement error removed and 10 μm added

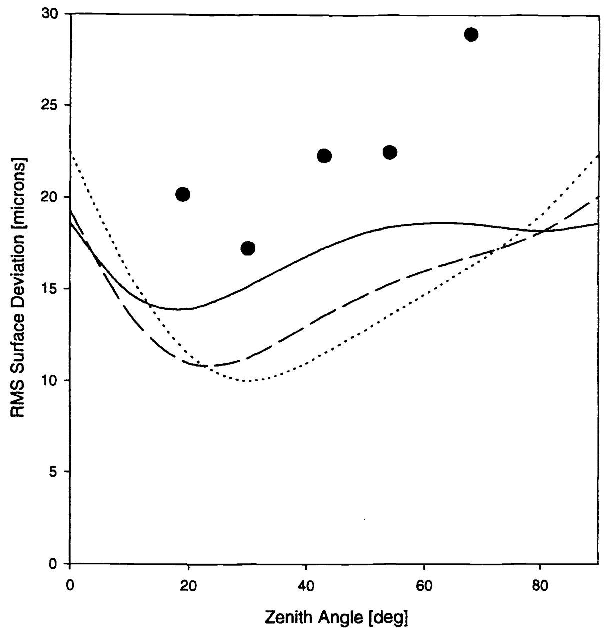

Figure 8. RMS surface deviations. Measured deviations are shown as filled curcles. The calculated RMS deviations for optimization over 0 to 90 deg is plotted as a solid line, optimization over 5 to 60 deg is plotted as a dashed line and rigging angle tuning for 30 deg is plotted as a dotted line. Ten μm has been added in quadrature to the measurements and the calculations to account for the small scale surfaces errors.

back in quadrature to account for small-scale errors not measured by the low-resolution maps. The surface deviations are less than 22 μm over 20 to 60 deg zenith angle range. The observed aperture efficiency of 33% at 810 GHz is consistent with these surface errors. The expected performance for several different tunings is also plotted in Fig. 8. These curves are based upon the structural calculations with 10 μm added in quadrature to account for the small-scale errors.

5. SUMMARY AND CONCLUSIONS

The gravitational deformations determine how the shape of a telescope's surface changes with orientation but the operational performance also depends upon the setting of the surface. Proper tuning of the surface figure requires accurate measurements of the surface errors over a wide zenith angle range to verify the validity of the structural calculations. The standard procedure of optimizing the surface at a particular rigging angle may not be the optimal setting for a general-purpose astronomical telescope. Minimizing the peak RMS surface error over the operational zenith angle range is a more useful strategy for astronomical telescopes. A global optimization procedure is shown to give better performance than rigging angle tuning.

The "second order deviation from homology", H_d, is introduced to accurately indicate the performance that a telescope will achieve after the surface figure has been optimized. H_d is defined as half of the RMS difference between the gravitational distortion maps at the extremes of the operational tracking range. It gives a better measure of the achievable performance than the "standard deviation from homology", H_0. Two telescopes with similar RMS deviations for the principal deformation maps will have the same H_0 but their optimized performance can be quite different. The "tuneability", $t = H_0/H_d$, is analogous to the homology ratio and indicates the improvement possible over a limited angular range relative to the average surface error over the full 360 degrees.

The combination of small gravitational distortions, good stability and the ability to make accurate surface measurements over a wide zenith angle range makes the Leighton telescope an excellent platform for implementing and evaluating the global optimization tuning algorithm. Investigation of the Leighton telescopes reveals that subtle deviations from symmetry in the structure produces large changes in the peak RMS after optimization. This could be important in the design of off-axis telescopes and other asymmetric configurations. In particular the peak RMS for optimization over the negative zenith angle range with a tuneability t=.9 is 2 ½ worse than the corresponding optimization over the positive zenith angle range where t=2.2.

The CSO surface errors are less than 22 μm RMS and the aperture efficiency is greater than 33% at 810 GHz over most of the zenith angle range after setting the surface using the global optimization strategy. The variation in surface accuracy varies by only ~25% over the 5 to 60 deg range, giving a relatively flat gain curve. These results demonstrate both the success of the surface tuning procedure and the quality of the design and construction of the Leighton telescope.

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