The Evaluation of Solar Mirror Figure by Moiré' Contouring

J. W. Griffin
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June 1980

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THE EVALUATION OF SOLAR MIRROR FIGURE
BY MOIRÉ CONTOURING

J. W. Griffin
M. A. Lind

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SUMMARY

Moiré topography is applied to the figure assessment of solar mirrors. The technique is demonstrated on component facets of a six-meter diameter, four-meter focal length, parabolic dish collector. The relative ease of experimental implementation and subsequent data analysis suggests distinct advantages over the more established laser ray trace or BCS/ICS techniques for many applications.

This report details the theoretical and experimental considerations necessary to fully implement moiré topography on mirror surfaces. A procedure to de-specularize the mirror is demonstrated which conserves the surface morphology without damaging the reflective surface. The moiré fringe patterns observed for the actual mirror facets are compared with theoretical contours generated for representative dish facets using a computer simulation algorithm. A method for evaluating the figure error of the real facet is presented in which the error parameter takes the form of an average absolute deviation of the surface slope from theoretical.

The experimental measurement system used for this study employs a 200 line/inch Ronchi transmission grating. The mirror surface is illuminated by a collimated beam at 60° . The fringe observation is performed normal to the grating. These parameters yield contour intervals for the fringe patterns of 0.073 mm. The practical considerations for extending the techniques to higher resolution are discussed.

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I. INTRODUCTION

This report describes one method which can be used to evaluate the optical figure of solar mirrors. There are numerous options available either directly from or as modifications of traditional optical shop techniques for measuring mirror figure. The most commonly used techniques in the solar industry include laser ray trace and beam or image characterization systems (BCS or ICS). These and other techniques are discussed in detail elsewhere (Griffin et al., 1980). The moiré method described in this document represents an alternate method of optical component evaluation that is not in common use.

The large range of size, curvature, and physical configuration of solar mirrors contributes to the difficulty of assessing mirror figure quality. Many contemporary optical shop techniques are limited by either or both of the following constraints: 1) infeasibility of physical upscaling due either to mechanical constraints or excessive cost, or 2) insufficient or excessive spatial resolution. The moiré method has the potential of overcoming both these limitations.

The moiré technique has traditionally been used to contour diffusely reflecting objects (see references). With proper surface preparation and experimental arrangements, the technique may be readily extended to specular surfaces. This report details the required experimental modifications and presents the attributes and deficiencies of the moiré method.

DEFINITION OF MIRROR FIGURE

Before beginning a detailed discussion of the technique, it is desirable to define what is meant by the term "figure". In the context of this report mirror figure refers to the exact topography of the mirror surface. Figure errors are manifested as deviation from the desired mirror shape which have a spatial period less than one cm. Figure is distinguished from specularity by the spatial frequency of the local deviations. Spatial periods less than one cm are arbitrarily denoted as specularity errors. Such errors are attributable to material inhomogeneity, adhesion irregularities, forming marks, polishing abrasions, etc. This report addresses only mirror figure.

Moiré Contour Analysis

A cursory overview of the moiré technique and its application to the mirror figure problem is in order prior to establishing the theoretical basis for the measurement scheme. In the moiré method a well characterized line grid is projected obliquely onto a diffusely reflecting surface (i.e., the surface to be contoured). If the projected lines are viewed at some angle other than that of projection and the surface is nonplanar they are seen to be geometrically perturbed according to the surface topography of the object. While the modulated line grid may be analyzed directly to obtain the surface morphology, it is more customary to observe the sample surface through a replica of the illuminating grid. The "interference" between the superimposed, perturbed and reference grids generates fringes of contour denoting the loci of points equidistant from some reference plane.

The surface shape or figure is thus described by a topographical map whose contour interval is a function of three experimental parameters. These parameters are: 1) grating frequency (lines/mm); 2) grating illumination angle; and 3) surface observation angle. Maximum observable surface deviation (i.e., deviation from the grating plane) is a function of grating diffraction limitations and the depth of field of the camera or observation system. The theoretical analysis and data evaluation for the moiré contour fringes is facilitated by using the particular set of experimental parameters described below.

The surface incident line grid is most easily obtained by projection of a collimated light beam through a grating composed of vertically ruled opaque lines whose width equals the spacing between adjacent lines. This grating is commonly a Ronchi ruling. Larger grids are sometimes fabricated by stretching blackened filament (e.g., string or wire) between horizontally mounted combs (e.g., threaded rods). For accurate moiré contouring, the grating lines must be highly parallel and constant in line width and spacing.

Illumination of the grating-test surface may be either by point source or a collimated beam. Since the collimated beam illumination mode is more amenable to simple mathematical treatment it will be discussed to the exclusion of

point source illumination techniques. The production of a collimated beam is most easily performed with a point (or slightly extended) source and a lens or mirror collimator. The degree of collimation necessary is dependent upon the desired contour accuracy. If the contour fringes are to be recorded photographically, careful consideration should be given to the choice of illumination source. For transient analysis and/or large area observation a high intensity arc source (typically carbon or xenon) is optimum. However for smaller surface areas, laser sources are convenient because of the intrinsic ease with which pseudo-point sources may be generated (e.g., with a microscope objective and spatial filter assembly). The collimation optics may consist of either a glass lens or mirror elements depending upon desired beam diameter and cost constraints.

The surface contour fringes obtained with the moiré method present an instantaneous signature of the surface figure. With a small additional effort isometric plots of the surface morphology may be generated. This is in marked contrast to the data reduction requirements for figure extraction utilizing laser ray trace or BCS/ICS techniques.

Constraints in Applying the Moiré Method as a Tool for Solar Mirror Figure Analysis

Although the moiré technique represents a low cost, noncontacting variable resolution technique for the figure assessment of diffusely reflecting surfaces, it is not without its drawbacks. In particular, its application to specular surfaces requires special considerations. The constraint that the surface projected fringes be viewed over a range of angles (inclusive of the calculated angle of reflection) demands that the surface under observation has a high diffuse reflectivity. Since mirror surfaces are characteristically specular, a procedure for applying a noninterfering auxiliary overcoat to the mirror face must be included in the evaluation process. Our experimental investigation has indicated at least three means of accomplishing this surface preparation are feasible.

By far the simplest method of de-specularizing the mirror surface is by dusting with a high reflectivity, micron-sized, solid particulate (e.g., chalk dust). Particulate adhesion may be enhanced by static charging of the mirror surface. The obvious drawback to this procedure is the requisite post evaluation mirror cleaning necessary to restore the mirror specularly. In most cases this could easily be incorporated at low cost into the module production procedure.

An improvement on the above mode of surface preparation is mirror pre-coating with a plastic film (e.g., plastic wrap) followed by application of a diffuse (flat) white overcoat paint. Conformity of the plastic film to the mirror surface is easily achieved especially in the case of parabolic dishes of moderate to short focal length. The chief advantage of this method is that after figure assessment the preparatory surface is easily peeled from the mirror face, thereby circumventing the post-evaluation cleaning requirement of the previous technique.

Another technique of surface preparation presently under consideration for evaluation of large mirrors is a hybrid of the above two schemes. For this method the particulate reflectant is mixed with a liquid vehicle or collodion to form a homogeneous suspension which may be sprayed onto the mirror surface. Following the mirror figure characterization the auxiliary film could be peeled off. If implemented as a post-production quality assurance technique the film could be left intact in order to provide for surface protection during shipping.

Of primary concern to the feasibility of implementing a moiré contour evaluation scheme for the quality assurance of solar mirrors are the size and cost constraints imposed upon the grating and illumination-collimation system. For the evaluation of optical components it is desirable to utilize a grating with excellent physical stability. Consequently optical grade Ronchi rulings are manufactured on planar glass substrates of certified flatness. Currently attainable dimensions are up to 80 x 80 inches with a maximum line frequency of 200 lines/inch. Higher line frequencies (up to 1000/inch) are obtainable for reduced grating dimensions. Currently Ronchi rulings of the sizes of

interest for moiré contouring of mirrors are produced individually using conventional ruling engine techniques. The use of holographic gratings (produced by interference methods) is at this time impractical due to the limited spatial dimensions and high cost.

Another important constraint in the implementation of the moiré technique with collimated illumination is the limitation of optical element diameter (and aperture) for the collimation system. Certainly for large solar mirror elements the required illumination beam diameters exclude the use of glass optics due to excessive fabrication costs. For this application low cost drop forged aluminum parabolic or spherical reflectors (e.g., searchlight reflectors) represent an acceptable alternative. Since these relatively low cost reflective elements are limited in diameter to several feet (~ 5 feet) the moiré contouring of large mirror elements would necessarily be a piecewise procedure.

An attractive alternative to the use of an optical collimation system would be to implement an illumination source with an acceptable, well characterized beam divergence. This could be a point source (arc) located at an extended distance from the grating-mirror surface or possibly the sun itself. Knowledge of the illumination angular divergence distribution would allow deconvolution of the true mirror surface morphology from the observed contour fringe pattern. In most applications a small illumination divergence may be tolerable especially if the illumination and observation angles (measured with respect to the grating normal) are relatively large.

The aspect of possible implementation of direct solar radiation is very attractive from a field applicability point of view. Such a scenario would require only that the heliostat mirror surface be de-specularized via techniques suggested above and the surface juxtaposed with a suitable grating. Solar incidence angles (with respect to the mirror/grating surface) at solar thermal facilities are readily attainable since this data is mandatory for heliostat tracking.

II. EXPERIMENTAL AND THEORETICAL BACKGROUND

The ensuing discussion of the theoretical basis and laboratory implementation of the moiré contour method is based upon use of the following experimental parameters: 1) the grating/object illumination is by collimated light; 2) the grating consists of equally spaced, parallel, vertical lines; and 3) fringe observation is performed at normal incidence to the grating. None of these parameters is a necessary condition for useful implementation of the moiré method, however data analysis is greatly facilitated if these experimental constraints are exercised.

EXPERIMENTAL ARRANGEMENT

A schematic of the experimental arrangement for the moiré contour analysis of solar mirrors appears in Figure 1. The system consists of a laser illumination source, collimation optics, grating/grating rotation stage, and a camera for photographic recording. The laser utilized was an argon-ion type tuned to the 472.7 nm line. The required output power is determined by the size of the area to be illuminated and the characteristics of the photographic medium. A power level of 200 mW was found adequate for illumination of the 6" x 6" grating area and allowed exposure times of 0.5 to 2 sec with ASA 125 films.

Beam expansion and filtering was performed with a 10X microscope objective fitted with a 25 μ m pinhole aperture for spatial filtering. Using folding mirrors the filtered point source was positioned at the focal point of an 8" diameter, 48" focal length f/6 spherical mirror. The resulting collimated beam was aimed to allow oblique illumination of the adjacent Ronchi ruling and mirror surfaces.

The Ronchi ruling utilized was of 6" x 6" size with a line frequency of 200 lines/inch. The grating was positioned (rulings vertical) on a rotation stage (ruled side toward test surface) allowing illumination beam incidence to be varied from 0° to 180° with respect to the grating normal. For all experiments reported, the illumination incidence angle was 60°.

FIGURE 1. Experimental Arrangement for Mirror Figure Assessment by Moiré Contour Technique

The mirrors to be analyzed were positioned on a vertical translation stage with tilt capability to allow positioning of the mirror surface in close proximity to the rear grating surface. This close juxtaposition was found to be a requirement for good fringe visibility and contrast.

Photographic recording of the fringe pattern was performed with a 35 mm camera equipped with a 135 mm, f 3.5 lens. The use of Plus-X panchromatic film (ASA 125) allowed optimum exposure times of 0.5 to 2 sec. The entire optical system was mounted on a pneumatic vibration isolated table for additional physical stability.

DERIVATIONS OF RELATIONS FOR THE SURFACE CONTOUR INTERVAL

A schematic of the grating/test surface geometry for moiré analysis appears in Figure 2. The collimated illumination beam obliquely projects a shadow of the Ronchi ruling onto the diffusely reflecting surface to be contoured. This projected grid geometry, when viewed at an angle different from that of projection, is perturbed by the surface topography of the mirror surface. The line perturbation is made evident by viewing the projected grid through the Ronchi ruling. This procedure in essence extracts the difference between the original and perturbed line geometries.

An understanding of the moiré contour generation phenomenon is most easily obtained by borrowing and expanding some basic ideas from communication theory. With this viewpoint the generation of the contours can be understood as the phase modulation and subsequent heterodyne demodulation of a carrier signal (Meadows, et al., 1970).

Derivation for Source and Observer Located at Infinity

For this preliminary derivation, the grating will be assumed to be illuminated and viewed by a source and observer located at infinity. These are just the previously mentioned constraints of collimated illumination and single angle viewing (i.e., the observation angle does not vary across the test surface). Consider a linear grid (Ronchi ruling) with transmittance modulation (optical density) given by

FIGURE 2. Geometry for Moiré Contour Analysis with Collimated Light

$$T(x) = \frac{1}{2} + \frac{1}{2} \sin \left(\frac{2\pi x}{S} \right) \quad (1)$$

where S is the spatial period ($1/\text{spatial frequency}$) of the grid. For an illumination incidence angle θ , the shadow of the grid is projected onto the object surface at the same angle. This results in a spatial (x direction) shift of the projected grid relative to the grating of magnitude $z \tan \theta$. Assuming the surface to be a diffuse scatterer and defining α to be the angle between the incident illumination and the normal to the surface, the intensity of the shadow on the surface is given by

$$I(x,y) = \frac{I_0}{2} \cos \alpha \left[1 + \sin \left\{ \left(\frac{2\pi}{S} \right) [x - z \tan \theta] \right\} \right] \quad (2)$$

where I_0 is the illumination beam intensity. For relatively flat objects with slow slope variation, $\cos \alpha$ is essentially constant and Equation (2) may be approximated as

$$I(x,y) = C \left[1 + \sin \left\{ \left(\frac{2\pi}{S} \right) [x - z \tan \theta] \right\} \right] \quad (3)$$

where $C = (I_0/2) \cos \alpha$.

Notice that the initial grating carrier signal $T(x)$ has now been phase modulated by the surface height to obtain the resultant intensity distribution $I(x,y)$. The demodulation of the phase information is now a straightforward process. If an observer views the test surface through the reference grid, he will see an intensity distribution, $I(x,y)$ given by the product of the grid transmission function, $T(x)$, and the phase modulated grid shadow, $I(x,y)$, or

$$\begin{aligned} I'(x,y) &= I(x,y)T(x) \quad (4) \\ &= (C/2) \left\{ 1 + \sin \left[(2\pi/S)(x - z \tan \theta) \right] \right\} \times \\ &\quad \left\{ 1 + \sin \left[(2\pi/S)(x + z \tan \phi) \right] \right\} \\ &= (C/2) \left\{ 1 + \sin \left[(2\pi/S)(x - z \tan \theta) \right] \right. \\ &\quad \left. + \sin \left[(2\pi/S)(x + z \tan \phi) \right] \right. \\ &\quad \left. + \sin \left[(2\pi/S)(x - z \tan \theta) \right] \sin \left[(2\pi/S)(x + z \tan \phi) \right] \right\} \end{aligned}$$

The last term in Equation (4) can be expanded to give

$$\begin{aligned} I'(x,y) &= (C/2) \left[1 + \sin \left[(2\pi/S)(x - z \tan \theta) \right] + \sin \left[(2\pi/S)(x + z \tan \phi) \right] \right. \\ &\quad \left. - \frac{1}{2} \cos \left\{ (2\pi/S) \left[2x + z(\tan \phi - \tan \theta) \right] \right\} \right. \quad (5) \\ &\quad \left. + \frac{1}{2} \cos \left[(2\pi z/S)(\tan \theta + \tan \phi) \right] \right] \end{aligned}$$

The last term in Equation (5), is dependent only on z and results in the observed contour lines. Note that the numerical value of this term is the same for argument variations of $\pm 2N\pi$ ($N = \text{integer}$). Therefore the fringe separation is given by

$$2N\pi = \Delta z (2\pi/S)(\tan \theta + \tan \phi) \quad (6)$$

or

$$\Delta z = \frac{NS}{(\tan \theta + \tan \phi)} \quad (7)$$

The remaining terms in Equation (5) act as noise and in some situations can mask the contour term. However in general the significance of these noise terms can be minimized by the selection of the proper optical components and experimental arrangement. If the spatial frequencies of the contour fringes and the noise terms are sufficiently different, spatial filtering techniques may also be implemented.

As a final point it should be mentioned that the generated z contour planes are always parallel to the grating surface independent of illumination and/or observation angle. The spatial resolution of the technique is seen to be a function only of θ , ϕ , and S .

Derivation for Source and Observer at Finite Distance from the Grating

The system described above has some rather severe practical constraints particularly when applied to the contouring of large areas. The requirements of source and observer located at infinity are effectively satisfied by use of a collimated illumination system and a large diameter, low aperture viewing system. However the viewed surface area is limited by the maximum feasible diameter of the collimation and viewing optics.

An alternative experimental arrangement for the implementation of moiré contouring using noncollimated illumination appears in Figure 3. The source (approximated by a point source) and observer are located at heights h_1 and h_2 above the grid respectively and are separated by a horizontal distance d . The intensity distribution of the projected shadow is derived by noting that since the source possesses an angular

FIGURE 3. Geometry for Moiré Contour Analysis with Divergent Light

divergence, the spatial frequency of the grating shadow decreases for increasing z . Mathematically this phenomenon may be expressed by:

$$s' = \left[(h_1 + z) / h_1 \right] s \quad (8)$$

Once again the intensity distribution of the grating shadow at the test surface is given by

$$I(x,y) = \frac{I_0}{r^2} \left\{ \frac{1}{2} + \frac{1}{2} \sin \left[\frac{2\pi h_1 x}{S(h_1+z)} \right] \right\} \cos \alpha \quad (9)$$

where r is the distance from the source to the surface point of interest. If the test surface is relatively flat and the source-object separation, r , is large compared to the variation in r across the surface then Equation (9) may be simplified to

$$I(x,y) = C \left(\frac{1}{2} + \frac{1}{2} \sin \left[2\pi h_1 x / S(h_1 + z) \right] \right) \quad (10)$$

where $C = \frac{I_0}{r^2} \cos \alpha$. If an observer views a surface point through the interposed grating, through a small aperture, the resultant intensity is the product of the spatial surface intensity and the transmission of the grating at the point co-linear with the surface and observation points. The expression is given by

$$\begin{aligned} I'(x,y) &= C \left\{ \frac{1}{2} + \frac{1}{2} \sin \left(\frac{2\pi h_1 x}{S(h_1+z)} \right) \right\} \left\{ \frac{1}{2} + \frac{1}{2} \sin \left[\frac{2\pi}{S} \left(\frac{zd + h_2 x}{h_2 + z} \right) \right] \right\} \\ I'(x,y) &= C' \left\{ 1 + \sin \left[\frac{2\pi}{S} \left(\frac{h_1 x}{h_1 + z} \right) \right] + \sin \left[\frac{2\pi}{S} \left(\frac{zd + h_2 x}{h_2 + z} \right) \right] + \sin \right. \\ &\quad \left. \left[\frac{2\pi}{S} \left(\frac{h_1 x}{h_1 + z} \right) \right] \sin \left[\frac{2\pi}{S} \left(\frac{zd + h_2 x}{h_2 + z} \right) \right] \right\} \quad (11) \end{aligned}$$

where $C' = C/4$. The last term in the brackets can be expanded to yield

$$\begin{aligned} I''(x,y) &= C' \left\{ 1 + \sin \left[\frac{2\pi}{S} \left(\frac{h_1 x}{h_1 + z} \right) \right] + \sin \left[\frac{2\pi}{S} \left(\frac{zd + h_2 x}{h_2 + z} \right) \right] + \frac{1}{2} \cos \right. \\ &\quad \left. \left[\frac{2\pi}{S} \left(\frac{h_1 x}{h_1 + z} - \frac{zd + h_2 x}{h_2 + z} \right) \right] - \frac{1}{2} \cos \left[\frac{2\pi}{S} \left(\frac{h_1 x}{h_1 + z} + \frac{zd + h_2 x}{h_2 + z} \right) \right] \right\} \quad (12) \end{aligned}$$

Notice that no term in the above expression is dependent only on z . A strict z -dependence may however be obtained by setting $h_1 = h_2$. The result is

$$I''(x,y) = C' \left\{ 1 + \sin \left[\frac{2\pi}{S} \left(\frac{hx}{h+z} \right) \right] + \sin \left[\frac{2\pi}{S} \left(\frac{zd + hx}{h+z} \right) \right] - \frac{1}{2} \cos \left[\frac{2\pi}{S} \left(\frac{(2hx + zd)}{h+z} \right) \right] + \frac{1}{2} \cos \left[\frac{2\pi}{S} \left(\frac{zd}{h+z} \right) \right] \right\} \quad (13)$$

The last term in the above expression,

$$\frac{C'}{2} \cos \left[\frac{2\pi}{S} \left(\frac{zd}{h+z} \right) \right] \quad (14)$$

is z -dependent and will yield the desired contour information. The shortcoming of the above expression however is that now the fringe intensity does not vary sinusoidally with z . Therefore the spatial z separation between two object points may no longer be determined by merely counting the number of fringes between the two points. To determine the z increment, Δz , between z_1 and z_2 (both coincident with fringe maxima) one must know the number of fringes, n_1 , between z_1 and the grating surface ($z = 0$) and the number of fringes, n_2 , between z_2 and the grating surface. At z_1 the phase of the contour term will be

$$2\pi zd_1 / [S(h + z_1)] = 2\pi n_1 \quad (15)$$

and at z_2 the phase will be

$$2\pi zd_2 / [S(h + z_2)] = 2\pi n_2 \quad (16)$$

So $\Delta z = z_2 - z_1$ is given by

$$\Delta z = \frac{n_2 Sh}{d - Sn_2} - \frac{n_1 Sh}{d - Sn_1} \quad (17)$$

The implementation of the above equation requires that the test surface be placed in contact with the reference grating which may not be possible or desirable. An approximation to the above expression may be made however if the experimental arrangement insures that h is always much greater than z_1 . The argument of the contour term (Equation 14) may then be expanded in a Taylor series with the result

$$\frac{2\pi zd}{S(h+z)} = \frac{2\pi d}{S} \left(\frac{z}{h} - \frac{z^2}{h^2} + \frac{z^3}{h^3} - \dots \right) \approx \frac{2\pi zd}{Sh} \quad (18)$$

and the contour term takes the form

$$\frac{C'}{2} \cos \left(\frac{2\pi zd}{Sh} \right) \quad (19)$$

with the result that

$$\Delta z = z_2 - z_1 \approx \frac{NSh}{d} \quad (20)$$

where N is the number of fringes between the two points. This is similar to the previous result obtained for the collimated case in Equation (7) except that the $1/(\tan \theta + \tan \phi)$ factor is replaced by h/d . In general however the contour pattern intensity distribution is described by equation 14 which exhibits a cosine variation with a spatial frequency dependence given by $d/S(h+z)$. So as z increases, the contour spatial frequency (and therefore the resolution) decreases. If the first order fringe occurs at $z = 0$, then the final fringe occurs for large z causing the argument of Equation (21) to approach $2\pi d/S$. There are therefore d/S fringes available for contouring.

In view of the contour interval dependence on z when implementing the moiré method with divergent illumination, the remainder of this report will deal only with the collimated illumination mode. In the analysis presented the test surface dimensions were within the capability of available collimation optics. The photographic fringe observation system utilized was located at such a distance that the variation in observation angle across the test surface was minimal. With these experimental parameters the use of the z independent contour interval relation is justified.

III. EXPERIMENTAL PROCEDURE

The mirrors investigated in this report were three facets of a multi-faceted, 4 meter focal length, 6 meter diameter parabolic dish collector. The facets were formed by bonding high reflectivity aluminum sheet onto a pre-formed low density (foam) substrate block. The rough physical dimensions were nearly equal for all three facets. A diagram of a representative element appears in Figure 4. A photograph of the three facets appears in Figure 5.

FIGURE 4. Nominal Face Dimensions of the Parabolic Facets

COATING OF MIRRORS

The implementation of moiré contour analysis requires that the surface under investigation be a diffuse reflector. While contour fringes could be observed on these unmodified mirrors, the contrast and intensity were deemed unsatisfactory for quantitative mirror analysis. This necessitated a mirror

FIGURE 5. Photograph of Parabolic Facets Investigated in Present Study

surface modification which would maintain the mirror topography and at the same time would allow quick restoration of the reflective surface to its virgin condition. It was found that a manually applied thin plastic film overcoated with a flat white diffuse layer would faithfully replicate the surface under study. The thin film chosen was a 0.5 mil clear plastic wrap. Its excellent adhesion characteristics facilitated its application to the aluminum surface and even over extended time intervals (weeks) no separation was observed. The auxiliary film was overcoated with a flat white diffusely reflecting paint. A minimum allowable coat thickness was applied because of the adverse effect upon the film-mirror adhesion characteristics. This was attributed to the nonelastic character of the dried paint. Even for light paint coatings slight film separation was observed at the mirror edges due to nonuniformity of mechanical support at the boundary. This was insignificant since the fringes resulting from these small film ripples were of much higher spatial frequency than the dominant mirror contour fringes attributed to the figure.

Implementation of the above mirror preparation resulted in high intensity, high contrast fringes which were easily recorded on photographic emulsion. The smoothness of the flat white overcoat resulted in a preferential forward scattering (specular component) of the illuminating light. This was manifested as a slow, minor variation in the observed brightness of the mirror surface. This phenomenon is attributable to the spatial variation in mirror surface slope with the more obliquely illuminated sections scattering less light in the observation direction. This minor effect can be masked with a proper choice of photographic parameters (i.e., film type, exposure time, etc.).

EXPERIMENTAL PARAMETERS

The grating utilized was a Ronchi type consisting of black baked-on rulings on a 3.2 mm glass substrate. Due to the limited depth of field of the optical observation system (to be discussed later), optimum fringe visibility was observed with the ruled surface toward the test mirror. The grating holder was mounted on a mirror mount affixed to a vertical axis rotation

stage. The normal (zero degree) illumination incidence position was established by retro-reflecting the illumination beam back through the reflective optics onto the spatial filter. The grating was then rotated to establish the desired beam incidence angle. The choice of illumination angle is the result of a tradeoff between two factors; desired contour interval and fringe visibility (intensity and contrast). For the present study a minimal contour interval was desirable in order to map the mirror surface with high resolution. However, at incidence angles greater than 60°, the fringe quality rapidly degrades. The reason for this degradation will be discussed in a later section. Note that for a given incidence angle, the fringe contour interval may be decreased by simply observing the fringes at non-normal incidence ($\phi \neq 0$). While this is certainly feasible, this requires a spatial correction of the mirror contour data since the mirror is viewed in oblique projection. This requirement is undesirable from a data reduction time standpoint. Another point of minor importance is that it is much easier to establish a camera geometry which views the grating normally. The camera lens is easily positioned along the axis of a retro-reflected auxiliary laser beam which impinges normally onto the grating surface.

For all measurements the grating-test surface was illuminated at an incidence angle (with respect to the grating normal) of 60°. Observation was performed normal to the grating (zero degree incidence). The contour interval for these parameters is calculated from the relation

$$\Delta z = \frac{S}{\tan \theta + \tan \phi}$$

The grating frequency was 200 lines/inch so that line spacing was 1/200 inches or 0.127 mm. This results in a contour interval ($\theta = 60^\circ$, $\phi = 0$), Δz , of 0.0733 mm. The actual experimental value was determined by measurement of the fringe period of a flat wedged plate of known slope. A dimensional schematic of the reference wedge appears in Figure 6. The observed fringe pattern appears in Figure 7. Deviation between the theoretical and observed contour intervals was within 5%. The slight curvature of the contour fringes on the reference wedge was attributed to an accumulation of intrinsic errors. Among

FIGURE 6. Schematic of Reference Wedge

FIGURE 7. Fringe Pattern for a 0.466° Reference Wedge

these were illumination beam divergence or convergence (very slight), non-flatness of the Ronchi ruling substrate, line spacing variation, and nonflatness of the wedge surface. Since the curvature of the reference fringes amounted to only a small fraction of a fringe this anomaly was considered unworthy of further investigation.

The surface modified test mirrors were mounted behind the Ronchi grating on an optical jack. An elevation screw in the jack platform introduced tilt capability to allow positioning of the mirror surface nearly parallel to the grating plane. The mirrors were positioned so that they contacted the grating at as many points as possible (typically three). The choice of the contact points was constrained by the requirement for a fringe pattern with a maximum degree of unilateral symmetry about the vertical axis. Note that this practice introduces a degree of uncertainty in the orientation of the mirror surface with respect to the grating plane. This uncertainty requires a correction of the obtained mirror topography data to allow an absolute figure error assessment. This is a major shortcoming of the technique. This aspect will be further discussed in a later section.

IV. DATA

Partial surface contours for the three parabolic mirror facets were generated. Photographs of the observed fringe patterns appear in Figures 8A-8C. Due to the collimated illumination mode and narrow angle observation, all fringe intervals correspond to a contour interval of 0.0733 mm. The z-axis increment between any two fringe coincident points, z_1 and z_2 , may be calculated by simply taking the product of the fundamental fringe interval and the number of fringes between the points (inclusive of point z_2).

Fringe maxima coordinates (i.e., coordinates of maximum photographic density) were digitized to enable plotting a three dimensional isometric (45°) representation of the mirror topography. These isometric diagrams appear in Figures 9A-9C. The z surface variation is highly exaggerated to enable a better conceptualization of the parabolic figure.

DISCUSSION

The maximum mirror surface deviation from the grating plane was nearly the same for all three samples. For Facet #1 the maximum dish depth was roughly 7 fringes or $7 \times 0.0733 \text{ mm} = 0.51 \text{ mm}$. For Facet #2 the depth was approximately $7 \frac{1}{2}$ fringes or $7.5 \times 0.0733 \text{ mm} = 0.55 \text{ mm}$. And for Facet #3 the surface deviation was roughly 6 fringes or $6 \times 0.0733 \text{ mm} = 0.44 \text{ mm}$.

More revealing than maximum surface deviation is the degree of fringe symmetry. Note that a perfect paraboloidal mirror will only produce fringes with unilateral symmetry (about the vertical axis) for certain grating orientations. In particular, symmetric fringes will result only when the grating normal at the horizontal centerpoint lies in the plane defined by the parabolic axis of revolution for the mirror and the orthogonal vector from this axis to the geometric center of the mirror element. This situation is depicted in Figure 10a. Note that this fringe symmetry is characteristic of a rotationally symmetric test surface. It is no simple task to align the grating and mirror in the above configuration. Consequently fringe asymmetry will usually be observed even for a perfect mirror.

FIGURE 8. Contour Fringe Distribution Produced by Sample Facets

A. Facet #1

B. Facet #2

C. Facet #3

FIGURE 9. Isometric Mirror Surface Plots

A. Grating Orientation Required for Symmetric Fringes on a Perfect Mirror

B. Fringe Asymmetry Introduced by Incorrect Ruling Orientation

FIGURE 10. Requirements for Fringe Symmetry

It should be noted that deviation of the grating rulings from vertical will also introduce fringe asymmetry. This situation can be caused by a slight rotation of the grating about the correct normal axis or by nonparallelism of the rulings and substrate sides. The above conditions are depicted in Figure 10b. This type of alignment error is most easily prevented by pre-determination of the ruling axis and subsequent mounting of the grating with this axis vertical.

Since fringe symmetry is a sensitive function of grating orientation, its value as a mirror figure indicator is uncertain. A more reliable indicator of surface figure is the presence or lack of fringe continuity. For the spherical and parabolic mirror facets encountered in solar collectors and heliostats the lines of contour should be relatively smooth functions devoid of sharp kinks and/or discontinuities. The presence of these anomalies is an indicator of surface defects attributable either to manufacturing deformation or subsequent in-field damage. The calculation of the magnitude of these spatially limited figure defects is straightforward.

Consider the hypothetical fringe pattern depicted in Figure 11. Points P and P' denote the expected and observed locations of a fringe maximum respectively. Note that if the fringe pattern is scanned from right to left the kinked fringe is encountered too soon, indicating that the point P is too low. The z deviation, E_z , of point P from its expected position is given approximately by

$$E_z = \frac{E}{\Delta C} \Delta h \quad (23)$$

where Δh is the contour interval, ΔC is the distance between adjacent fringes, and E is the distance between the actual and expected fringe positions. The calculation of error values for additional points along the kinked fringe permits a spatial mapping of the mirror defect. The detailed quantitative assessment of all mirror defects evidenced by fringe discontinuity is a laborious procedure. A more reasonable method for quantitative mirror analysis is reserved for later discussion. At present, however, a cursory qualitative evaluation of the mirrors is worthwhile.

FIGURE 11. Quantitative Evaluation of Surface Figure Error by Fringe Kink Analysis

QUALITATIVE FACET EVALUATION

Facet #1

The fringe pattern produced on the surface of Facet #1 exhibits some symmetry. The symmetry axis is inclined approximately 9° to the vertical. This is attributable to grating misorientation. Kink fringe discontinuities are evident over the entire mirror surface but are most pronounced at the upper edge. This may be attributable to the aluminum/substrate laminating process at which time the edges experience a shear force due to a cutting or forming operation. This defect may also be the result of mirror/substrate boundary separation at the edges due to ineffective bonding or a mechanical support discontinuity.

Facet #2

The fringe pattern observed on the surface of Facet #2 possesses some characteristics common to the fringes of Facet #1. Note the fringe discontinuities at the upper and lower mirror boundaries. If one "subtracts" the kinks from the upper left fringe pattern a high degree of unilateral symmetry is again observed for a symmetry axis tilted approximately 6° with respect to the vertical. Once again this may be due to grating misalignment. The presence of the large fringe discontinuity in the upper left quadrant is indicative of a major mirror defect. Since the mirror surface (before coating) appeared undamaged this anomaly is likely due either to superstrate separation or a forming error.

Facet #3

The fringe pattern of Facet #3 exhibits characteristics common to both Facet #1 and Facet #2. Notice that this facet does exhibit a high degree of symmetry about the vertical axis. This symmetry may be attributed to either a fortuitous grating/mirror orientation or simply the result of a nonuniform surface combined with a grating misorientation. With the exception of the usual fringe kinks at the top and bottom, the fringe pattern for this facet is relatively well behaved.

CONCLUSION

It is apparent that the usefulness of a fringe pattern in its raw form is largely limited to the qualitative evaluation of mirror surface topography. While quantitative assessment of localized mirror surface perturbations is possible, it requires substantial data acquisition and processing times. This practical limitation may be alleviated if auxiliary data for the surface under consideration can be generated. This concept is discussed in the next section.

V. THEORETICAL CALCULATIONS

To aid in the quantitative assessment of the parabolic facets, the theoretical contour fringe pattern for mathematically perfect facets was calculated. Based on a limited knowledge of the parabolic collector geometry, facet surface coordinates were generated to permit the calculation of the locus of points equidistant from a reference plane of any desired orientation. This locus is equivalent to a moiré contour fringe. If the criterion spacing between mirror and reference plane is incremented, another locus of points may be generated. In this manner, a fringe pattern equivalent to the moiré contour geometry may be formed and used as a basis for quantitative evaluation of the mirror facets. A detailed discussion of the technique follows.

CALCULATION OF PARABOLOIDAL COLLECTOR SURFACE COORDINATES

The facets examined in this study were components of a 3.95 m (12.96 feet) focal length, 5.9 m (19.4 feet) diameter paraboloidal concentrator. Included rim angle, as viewed from the focal point, was 82°. A dimensional schematic of this mirror appears in Figure 12.

The geometry for generation of theoretical paraboloid surface coordinates appears in Figure 13. The mathematical expression for a paraboloid (parabola of revolution) is given by

$$z = \frac{x^2 + y^2}{4F} \quad (24)$$

where F is the focal length. This expression may be used to derive the maximum dish depth (z coordinate of the rim) for the parabolic concentrator. $z_{\max}$ is given by

$$z_{\max} = (x_{\max})^2 / 4F \quad (25)$$

For a 5.9 m diameter dish, $x_{\max} = 2.95$ m. If the focal length, F, is taken to be 3.95 m, the resulting dish depth is 0.55 m or 1.81 feet.

FIGURE 12. Schematic of Paraboloidal Collector

FIGURE 13. Geometry for Generation of Paraboloid Surface Coordinates

A matching of theoretical and experimental contour fringes requires that coordinates be generated for exactly the same surface areas as those of the mirror facets. The method by which this was accomplished is illustrated in Figure 14. Note that the angle subtended by the sample area is less than that subtended by the entire facet surface. This is a result of the limited size of the Ronchi ruling (6"x6").

The calculation of coordinates for a theoretical facet requires an input of three variables; the mirror focal length, F , and the minimum and maximum z values for the particular facet. The determination of z bounds for the mirror facets is nontrivial and is reserved for later discussion. Nevertheless, assuming these values are known $\Delta\theta_{\max}$ is given by

$$\Delta\theta_{\max} = 0.1524/\sqrt{4Fz_{\min}} \quad (26)$$

for F in meters. $\Delta\theta_{\max}$ is then divided into 49 equal increments to allow the calculation of 50 surface coordinates $P(x_1, y_1, z_{\min})$, $P(x_2, y_2, z_{\min})$... $P(x_{50}, y_{50}, z_{\min})$ in the $z_{\min}$ plane (i.e., in the $z_{\min}$ plane θ runs from $\pi/2 + (\Delta\theta_{\max}/2)$ to $\pi/2 - (\Delta\theta_{\max}/2)$). This operation is repeated for $z_{\min} \leq z \leq z_{\max}$ by sequentially incrementing the current z value by $[(z_{\max} - z_{\min})/49]$ and calculating the corresponding $\Delta\theta$ value. The (x, y) coordinates for a point on the mirror surface are

$$x = -2\sqrt{Fz} \sin \theta \quad (27)$$

$$y = 2\sqrt{Fz} \cos \theta \quad (28)$$

The end result is a 50X50 matrix of theoretical facet surface coordinates. It should be mentioned that the surface coordinates should be generated at as high a spatial resolution as is possible. In this case, computer data storage capacity established a maximum matrix size of 50X50.

FIGURE 14. Geometry for Generation of Facet Surface Coordinates

CALCULATION OF PARABOLOID SURFACE - REFERENCE PLANE SEPARATION DISTANCES

Following the calculation of paraboloid coordinates, the distances from these points to a specified reference plane are computed. This plane is equivalent to the Ronchi ruling in the experimental arrangement. The reference plane is defined by specifying the elevation (α) and azimuth (β) angles of its normal and a contained point $R(x_0, y_0, z_0)$. These parameters are illustrated in Figure 15. The contained point should be chosen so as to prevent reference plane intersection with the paraboloid area (theoretical facet) under consideration. The distance from a calculated surface point to the reference plane is given by

$$d = \left| \frac{Ax' + By' + Cz' + D}{\sqrt{A^2 + B^2 + C^2}} \right| \quad (29)$$

where x' , y' , and z' are the paraboloid coordinates and $Ax + By + Cz + D = 0$ is the equation of the plane. The equation of the plane which is perpendicular to the vector $\vec{v}(v_1, v_2, v_3)$ and which passes through the point $R(x_0, y_0, z_0)$ is

$$v_1 (x-x_0) + v_2 (y-y_0) + v_3 (z-z_0) = 0 \quad (30)$$

The components for a normal vector specified by its elevation and azimuth angles, α and β , are

$$v_1 = \cos \alpha \cos \beta \quad (31)$$

$$v_2 = \cos \alpha \sin \beta \quad (32)$$

$$v_3 = \sin \alpha \quad (33)$$

For convenience, the contained point may be chosen to lie on the x-axis in which case $y_0 = z_0 = 0$. A , B , C , and D in Equation 29 are then given by

FIGURE 15. Parameters for Defining Reference Plane

$$A = \cos \alpha \cos \beta \quad (34)$$

$$B = \cos \alpha \sin \beta \quad (35)$$

$$C = \sin \alpha \quad (36)$$

$$D = -x_0 \cos \alpha \cos \beta \quad (37)$$

Equation 29 may then be reduced to

$$d = \left| x' \cos \alpha \cos \beta + y' \cos \alpha \sin \beta + z' \sin \alpha - x_0 \cos \alpha \cos \beta \right| \quad (38)$$

For the reported calculations, x_0 was chosen as 0.25 m to insure that the reference plane would never intersect a facet surface.

DETERMINATION OF UPPER AND LOWER FACET BOUNDARIES

Assuming that the parabolic collector is formed from facets with nearly equal face dimensions, it is possible to calculate $z_{\min}$ and $z_{\max}$ values for all elements. The procedure is illustrated in Figure 16. Given a constant face height, C , the relationship between x , z , and C is

$$(z_n - z_{n-1})^2 + (x_n - x_{n-1})^2 = C^2 \quad (39)$$

Since in the x - z plane $x = 2\sqrt{Fz}$, this may also be written as:

$$(z_n - z_{n-1})^2 + 4(\sqrt{Fz_n} - \sqrt{Fz_{n-1}})^2 = C^2 \quad (40)$$

This equation may be solved for z_n given z_{n-1} using iterative methods. A FORTRAN IV program (ZBND) for iterative solution of Equation 40 appears in the appendix. For the reported calculations, z_0 was chosen to equal zero and the subsequent z_n were generated by iterative solution of Equation 40. The calculated $z_{\min}$ and $z_{\max}$ values for all facets are tabulated in Table 1.

DETERMINATION OF REFERENCE PLANE ORIENTATION

The $z_{\min}$ and $z_{\max}$ values for each facet may be utilized to calculate a "best" orientation for the auxiliary reference plane (surrogate Ronchi ruling). The technique is outlined in Figure 17. The reference plane is chosen to be parallel to the line joining the upper and lower facet centerpoints. The slope of this line is

$$M = \frac{\Delta z}{\Delta x} = \frac{(z_{\max} - z_{\min})}{(x_{\max} - x_{\min})} = \tan \phi \quad (41)$$

The grating normal elevation angle, α , is then $(90^\circ - \phi)$. These values are tabulated in Table 1 for all facets. The azimuth angle, β , is set to zero. This method of defining the reference plane approximates the actual experimental technique.

FIGURE 16. Technique for Determining $z_{\min}$ and $z_{\max}$ Boundaries for Theoretical Facet

FIGURE 17. Determination of Elevation Angle for Best Reference Plane Orientation ($\beta=0$)

TABLE 1. Facet Boundaries for Parabolic Collector. (All values generated using ZBNDs. Input parameters: Focal = 3.95 m, ZMAX = 60.0 cm, FFH = 9.843 cm, ZINIT = 0.000 cm, DELZ = 1.0 E-10)

<u>Facet Number</u>	<u>Lower Z Boundary (cm)</u>	<u>Upper Z Boundary (cm)</u>	<u>Alpha (degrees)</u>
1	0.000	0.061	89.643
2	0.061	0.245	88.929
3	0.245	0.552	88.216
4	0.552	0.980	87.504
5	0.980	1.531	86.793
6	1.531	2.203	86.083
7	2.203	2.997	85.375
8	2.997	3.912	84.669
9	3.912	4.946	83.966
10	4.946	6.101	83.265
11	6.101	7.374	82.567
12	7.374	8.765	81.873
13	8.765	10.274	81.182
14	10.274	11.899	80.496
15	11.899	13.640	79.813
16	13.640	15.496	79.134
17	15.496	17.465	78.461
18	17.465	19.546	77.792
19	19.546	21.739	77.128
20	21.739	24.042	76.469
21	24.042	26.453	75.816
22	26.453	28.973	75.168
23	28.973	31.599	74.526
24	31.599	34.330	73.890
25	34.330	37.165	73.260
26	37.165	40.102	72.636
27	40.102	43.141	72.019
28	43.141	46.279	71.408
29	46.279	49.515	70.803
30	49.515	52.848	70.205
31	52.848	56.277	69.614
32	56.277	59.799	69.030
33	59.799	63.414	68.452

GENERATION OF SURFACE CONTOURS

With the theoretical facet boundaries established, calculation of the surface coordinates proceeds in a straightforward manner. These coordinates, in conjunction with the previously determined reference plane parameters, are used to generate the surface-plane interseparation distances. The distances are stored in a 50X50 matrix array to permit easy data manipulation.

Following the completion of all calculations, a search is made for the minimum interseparation distance. This distance is subtracted from all matrix values to produce a normalized spatial separation distribution.

Unlike the continuous fringe intensity distribution (typically sinusoidal) produced with the experimental moiré method, the fringes generated with the computer simulation technique are created in a discrete manner. The simulation requires two input parameters; the theoretical contour interval, Δh , and a dispersion halfwidth term, D . Note that if only surface points producing contour multiple $(n\Delta h)$ plane-paraboloid separation distances are plotted, the result is fringes of infinitely narrow width. To alleviate this anomaly, a dispersion halfwidth, D , is introduced which allows all points lying in the interval $(n\Delta h - D) \leq d \leq (n\Delta h + D)$ to be plotted where n is the fringe order. This procedure simulates the finite fringe width.

The contour plotting operation proceeds by specifying the range of d for a particular fringe ($d \leq D$ for zero order fringe, $(\Delta h - D) \leq d \leq (\Delta h + D)$ for first order fringe, etc.); searching the entire matrix for data values in this range; converting the matrix coordinates to a desired output scale and finally, plotting the point. The range of d is then incremented ($n \rightarrow n+1$) by Δh and the process is repeated. The algorithm is terminated when no data point is contained in the criterion interval (i.e., $d < N\Delta h - D$, where $N-1$ is the highest order fringe plotted).

PHASE MATCHING OF MOIRÉ CONTOUR PATTERNS

The simulated facet fringe distribution generated by the above algorithm may be useful, from a qualitative evaluation standpoint, but its usefulness as a quantitative tool requires that the experimental and theoretical contours be

indexed. This process is termed "phase matching" and consists of simply "forcing" a simulated fringe to coincide with an experimental fringe at some point on the mirror. This is accomplished in the following manner.

The phase matching operation is illustrated in Figure 18. A point on the lowest order experimental fringe is chosen and its equivalent matrix coordinates (I,J) are calculated. Because this point corresponds to the first order fringe maximum, d for this point is arbitrarily set equal to Δh in the matrix. This forces a fringe to be plotted about this point in the contour simulation. The remaining matrix data points are re-normalized by setting $d_{ij} \rightarrow d_{ij} - (d_{I,J} - \Delta h)$. The theoretical fringe pattern is then generated using the algorithm previously described except that now the first fringe corresponds to $\Delta h - D \leq d \leq \Delta h + D$ rather than $0 \leq d \leq D$.

SIMULATED THEORETICAL MIRROR CONTOUR PATTERNS

The method for the assignment of the dispersion halfwidth is illustrated in Figure 19. The dispersion halfwidth was taken as the darkened fractional part of the experimental contour interval or

$$D = \frac{1}{2} (\Delta h) \left(\frac{S}{\ell} \right) \quad (42)$$

A full set of theoretical contours for mirror facets distributed from the collector center to its outer edge appears in Figure 20. The FORTRAN IV program, MOIRE, used to generate these contours appears in the appendix. The contour interval and dispersion halfwidths were 0.0733 mm and 0.018 mm respectively.

COMPARISON OF MODELING RESULTS AND EXPERIMENTAL CONTOURS

To quantify the quality of the mirror facets, an algorithm which calculates actual mirror figure deviations from a theoretical surface was developed. Facet #3 was chosen for detailed analysis. While fringe symmetry is not a requisite for the procedure to be discussed, it does facilitate matching of the experimental fringe pattern with a model generated pattern thereby allowing approximate location of the facet on the paraboloidal surface (if this

FIGURE 18. Phase Matching Procedure for Theoretical Contour Generation Algorithm

$$\text{DISPERSION HALFWIDTH} \equiv D = \frac{1}{2} \frac{S}{l} (\Delta h)$$

FIGURE 19. Determination of Dispersion Halfwidth Parameter

A. Theoretical Facet #1

B. Theoretical Facet #5

C. Theoretical Facet #10

D. Theoretical Facet #15

E. Theoretical Facet #20

F. Theoretical Facet #25

G. Theoretical Facet #30

H. Theoretical Facet #31

FIGURE 20. Modeled Surface Contours for Theoretical Facets

information is not known a priori). Recall that in this case the proper location of the parabolic facets in the dish collector is unknown. As Figure 20 illustrates, the differences between the theoretical contours for the particular collector studied are small, especially toward the rim of the dish. This fact does not detract from the utility of the technique as discussed below.

Data collection begins by dissecting the facet surface into five equal intervals with six horizontal lines. This procedure is depicted in Figure 21. For future reference, these lines are referred to as S1-S6. The fringe order is then noted for all fringes with fringe number one being the centermost fringe (or partial fringe). The horizontal lines (S1-S6) are subdivided into 100 increments to allow digitization of the points of intersection with the fringe maxima. The digitized intersection coordinates are recorded along with the corresponding fringe order on a line by line basis. The points are used to generate regression coefficients for a second degree polynomial fitting

FIGURE 21. Geometry for Quantitative Figure Error Analysis by the Moiré Method

function by the method of least squares. Plots of the smoothing function and the corresponding data points for lines S1-S6 appear in Figures 22A-22F. The nominal error in reading the data is represented by the size of the symbol used to designate the data point.

Note that if the smoothing function is of the form $y = A + BX + CX^2$ then its slope is obtained from the first derivative, $y' = B + 2CX$. This slope relation may be used to generate an error parameter for the sample facet. Average slope values for discrete, adjacent points on the mirror surface may be calculated from the fringe coordinate data displayed in Figure 22. These discrete average slopes versus the midpoint of the two points used to determine them are plotted in Figures 23A-23F along with the first derivative of the smoothing function for all the lines.

The distribution of absolute slope errors is depicted in Figure 24 where the fraction of mirror points exhibiting an absolute beam deflection error ($2 \times$ absolute slope error) less than or equal to a given value is plotted versus absolute angular deflection error. If the absolute differences are computed between the average slope values and the corresponding values predicted by the derivative of the smoothing function, an average value for the slope error may be computed. The use of absolute differences is justified because the sign of the errors is irrelevant when computing a mirror introduced beam deflection. The averages of the absolute error values for lines S1-S6 appear in Table 2. The average of the absolute slope errors computed for the entire mirror surface is 0.0462 degrees (0.807 milliradians). Note that a slope error, $\Delta\phi$, introduces a beam deflection of $2\Delta\phi$ so that the average of the mirror deflection error is 0.0924 degrees (1.61 milliradians).

A justification for the above error analysis procedure is obtained from analysis of the computer generated moiré contours. To obtain a valid comparison, a modeled contour closely resembling the experimental pattern of Facet #3 was chosen. This pattern was reasonably approximated by Facet #25 of the theoretical paraboloid (see Table 1 and Figure 20F). Raw data in the form of reference plane-paraboloid separation distances were generated for six equal interval horizontal lines (R1-R6) across the surface of the theoretical facet.

FIGURE 22A. Z-Profile Across Line S1 (R1) for Facet #3 (Theoretical Facet #25)

FIGURE 22B. Z-Profile Across Line S2 (R2) for Facet #3 (Theoretical Facet #25)

FIGURE 22C. Z-Profile Across Line S3 (R3) for Facet #3 (Theoretical Facet #25)

FIGURE 22D. Z-Profile Across Line S4 (R4) for Facet #3 (Theoretical Facet #25)

FIGURE 22E. Z-Profile Across Line S5 (R5) for Facet #3 (Theoretical Facet #25)

FIGURE 22F. Z-Profile Across Line S6 (R6) for Facet #3 (Theoretical Facet #25)

FIGURE 23A. Slope Distribution Across Line S1 (R1) for Facet #3 (Theoretical Facet #25)

FIGURE 23B. Slope Distribution Across Line S2 (R2) for Facet #3 (Theoretical Facet #25)

FIGURE 23C. Slope Distribution Across Line S3 (R3) for Facet #3 (Theoretical Facet #25)

FIGURE 23D. Slope Distribution Across Line S4 (R4) for Facet #3 (Theoretical Facet #25)

FIGURE 23E. Slope Distribution Across Line S5 (R5) for Facet #3 (Theoretical Facet #25)

FIGURE 23F. Slope Distribution Across Line S6 (R6) for Facet #3 (Theoretical Facet #25)

FIGURE 24. Distribution of Absolute Beam Deflection Errors for Facet #3

TABLE 2. Average Absolute Slope Errors for Sample Facet (Facet #3)

<u>Sample Line</u>	<u>Average Absolute Slope Error $\Delta\alpha$ (milliradians)</u>	<u>$\sigma_{ \Delta\alpha }$ (milliradians)</u>
S_1	0.944	0.553
S_2	0.937	0.665
S_3	0.745	0.415
S_4	0.722	0.569
S_5	0.865	0.662
S_6	0.646	0.497
All Lines (all data points)	0.807	0.547

The separation values were then tabulated for seven equally spaced points across lines R1-R6 and once again the data points (within a horizontal line) were fitted to a second degree polynomial smoothing function. Plots of these polynomials and the corresponding data points for lines R1-R6 appear in Figures 22A-22F. Note the excellent agreement between the fitting polynomial and the discrete data points confirming the legitimacy of the smoothing operation in the experimental case. Once again the derivative of the smoothing function may be calculated and its value can be compared to the average slope obtained from the discrete data at corresponding points. Average absolute slope errors of 0.0032, 0.0026, and 0.0023 milliradians were obtained for horizontal data lines at the top, center, and bottom respectively of Facet #25. The average absolute slope error for all three lines is 0.00272 milliradians. Note that these values are roughly two orders of magnitude below those generated for the experimental facet and may be taken as the limiting accuracy of the technique.

If the exact spatial location of the experimental facets in the dish is unknown, the slope of the smoothing polynomial may be of use in determining whether the correct parameters have been used to generate the theoretical fringe pattern. For example, after the smoothing polynomials have been generated for data lines S1-S6 and R1-R6 of the sample and model respectively, the slopes of these lines as a function of spatial position may be compared. Note that a tilt error in the sample will introduce a bias level in the slope function. For a valid comparison, then the two slope functions should first be normalized at some point. The normalized model slope functions along with the previously generated sample slope functions are plotted in Figures 23A-23F. The close agreement between these two curves indicates that the sample facets were probably from the outer rim region near model Facet #25. With an additional effort the sample slope curves could probably be used to pinpoint the exact parameters for the model facet.

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VI. COMMENTS ON THE MOIRÉ TECHNIQUE

ACCURACY OF THE MOIRÉ METHOD

A quantitative error analysis of the moiré method is most easily performed by individually considering the effect of each factor in the contour relation (Eq. 7). The contour interval relation for collimated illumination and observer at infinity is given by

$$\Delta z = \frac{S}{(\tan \theta + \tan \phi)} \quad (43)$$

for $N = 1$. Note that Δz is linearly dependent upon S . Consequently an error in the line ruling spacing will be manifested as an equal error in the contour interval. Since the ruling spacing will certainly vary over the grating dimensions, this error will be different for different spatial areas of the mirror under test. Perhaps the easiest way to determine and quantify ruling errors is to observe a reference surface (typically an optical flat) utilizing a "perfectly" collimated beam. Nonparallelism and/or unequal spacing of the observed fringes is indicative of ruling errors. Note that grating substrate inhomogeneity may also be manifested as ruling periodicity error since refractive index discontinuities will perturb the line projection angle (i.e., the illumination incidence angle).

Probably the more significant contributors to contour error are illumination beam divergence, and the finite viewing angle resulting from fringe observation at a finite distance. Assuming a viewing direction normal to the grating, the contour interval becomes

$$\Delta z = \frac{S}{\tan \theta} \quad (44)$$

and

$$\left| (d\Delta z) \right| = \frac{S}{\sin^2 \theta} \left| d\theta \right| \quad (45)$$

Note that for a given θ , the variation in Δz is proportional to the angular divergence of the illumination beam. This anomaly may also be ascertained by observing a diffusely reflecting reference flat behind a grating of well-characterized periodicity. The effect of a nonzero observation angle span is

to produce an analogous variation in the contour interval across the object surface. This situation is minimized by observing the fringes from an extended distance. In this manner the angle subtended by the mirror surface at the observation plane (film plane) is minimized.

For high accuracy surface topography measurements, the photographic record of a fringe pattern should be electronically analyzed (e.g., with a densitometer). While this scenario requires a knowledge of additional experimental parameters (e.g., film γ , optimum exposure, etc.), it does allow a continuous mapping of surface topography rather than the generation of discrete contour lines. The price for such an intimate knowledge of the mirror morphology is excessive data reduction time.

RESOLUTION LIMITS OF THE MOIRÉ METHOD

Three factors affect the spatial resolution capability of the moiré technique when used in discrete contour (as opposed to continuous) mode. These factors are the spatial grating frequency and the illumination incidence and observation angles.

For fixed illumination and observation angles the highest practical grating frequency is determined by the onset of appreciable diffraction effects. Diffraction at the grating surface results in a lowering of the contrast of the projected grid and causes a degradation of fringe visibility. Since this effect is predominant for grating frequencies exceeding 1000 lines/in. it is a minor consideration for gratings of use in solar mirror figure evaluation. The large size requirements on gratings for solar reflector analysis dictate the necessity of lower spatial frequencies (≤ 200 lines/in.) in order that the method remains financially viable. In addition, a cursory discussion with grating manufacturers indicates a lack of instrumentation for production of large gratings ($>2' \times 2'$) with spatial frequencies exceeding 200 lines/in.

Clearly an increase in contour interval resolution can also be acquired by simply increasing the illumination and observation angles for more oblique incidence. While this is certainly an option, there are limits imposed by the quality of the resultant fringes and the deconvolution operation necessary to

obtain the true surface topography. Consider the case of oblique illumination and normal incidence viewing. Beyond some optimum range of illumination incidence angles, insufficient light is scattered by the test surface in the viewing direction to form fringes of sufficient contrast and intensity. In the reported investigation the maximum acceptable incidence angle was 60° (for normal incidence viewing). With only a moderate research effort, other more diffusely reflecting coatings could probably be implemented that would allow an increase in illumination incidence angle.

The measurements reported herein were performed using a viewing angle normal to the grating surface. This configuration was utilized for two reasons. First, a normal incidence viewing angle is easily achieved using retroreflection methods. A laser beam may be directed onto the grating surface center and the laser orientation adjusted until the reflected beam returns incident onto the exit aperture. This beam then defines the grating normal and the camera may be positioned so that its optical axis coincides with the grating normal. The second reason for choosing normal observation is that the object plane may be observed within a narrow depth of field. This is especially important if the fringes are being recorded using a moderate telephoto lens of low aperture. In cases where the illumination level is fixed and the fringe intensity is low, photography at full aperture may be a necessity to allow reasonable exposure times. Consequently, the shallower the required depth of field, the better the chances of obtaining acceptable contour fringe photographs.

Another incentive for choosing normal viewing is found by noting that the resulting photograph is a true projection of the mirror surface contours. By appropriately scaling the photographic print, a one-to-one correspondence may be established between points on the photograph and the normally viewed test surface. Consequently the mirror surface topography is easily intuitively envisioned without the need for fringe digitization and subsequent isometric plotting. Such is not the case for oblique viewing angles.

If the above optical constraints are deemed insignificant, a substantial increase in z-axis resolution capability may be realized by oblique observation. The observation angle should be chosen in order to optimize fringe visibility and maximize z-axis resolution. The best value will probably be

near the specular reflection angle for the given illumination beam incidence angle. At observation angles near the specular reflection value, advantage may be taken of the relatively high intensity forward scattered diffuse component of the illuminating light. Care must be taken to avoid the specularly reflected beam from the grating surface as this is usually of appreciable intensity and will degrade the observed fringe quality.

A cursory value of the maximum practical resolution capability of the moiré contour method as applied to solar mirror figure analysis may be calculated based on the above discussion. For an illumination incidence angle of 60° and an equal observation angle, a 200-line/in. grating will produce z contours spaced 0.0366 mm apart.

VII. CONCLUSIONS AND RECOMMENDATIONS

The moiré method has been shown to be an effective technique for the figure analysis of solar mirrors. Its practical implementation into quality assurance procedures will require an additional research and development effort in order to automate and thereby speed up the analysis algorithm.

The method is constrained by the practical size limitations on the Ronchi ruling (grating) and the auxiliary collimation/illumination system. The former difficulty may be alleviated by mapping the mirror figure (and slope) in a piecewise manner and the latter constraint may be overcome by using noncollimated illumination techniques.

Using the suggested data reduction algorithm the mirror quality parameter takes the form of a surface averaged absolute slope error. For the parabolic facet investigated, this average absolute slope error was 0.0462 degrees or 0.807 milliradians. Since a slope error $\Delta\phi$ introduces a beam deflection error $2\Delta\phi$ the mirror introduced beam deflection for the investigated facet is 0.0924 degrees or 1.61 milliradians. The technique may also be used to generate an average absolute figure error with minor changes in the analysis algorithms. While this parameter is of less value to the collector designer than mirror introduced beam deflection, it may be of use in evaluating molds and dies used in the facet fabrication procedure.

Suggested refinements to the experimental method include:

1. Use of CCD arrays and peripheral hardware/software for digitizing and recording fringe coordinates.
2. Development of data deconvolution algorithms that would permit the implementation of noncollimated illumination and finite viewing angle methods. Note that a research effort in this area may facilitate field implementation since solar radiation could be utilized as the illumination source.
3. Development of improved techniques for the application of the diffuse mirror overcoat.

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APPENDIX

FORTRAN IV Programs for Calculation of Theoretical Facet Contours

ZBND5

This FORTRAN IV program calculates the upper and lower Z boundaries for facets comprising a parabolic collector. The required input parameters are:

1. Focal length (FOCAL) of the parabolic collector
2. Lower Z boundary (ZINIT) for lowest facet
3. Maximum height (ZMAX) of collector (along Z-axis)
4. Facet face height (FFH) of component facets. All facets are assumed to have the same face height.
5. Iterative error bound (DELZ) for convergent Z boundary values.

In addition to calculating the Z bounds for the component facets, ZBND5 also calculates the deviation angle of the normal for the best fit reference plane for all facets. Finally as a final check on the iterative Z boundary solutions, the facet face height is calculated from the Z-ordinate values. Agreement between entered and calculated facet face height values confirms the accuracy of the mathematical algorithm.

Sample input parameters and the corresponding output follow the program listing.

```

0001  FTN4.L
0002  PROGRAM ZBND(S),J.W.GRIFFIN 2/25/80
0003  DIMENSION ZOLD(50),ZNEW(50),Z(50),X(50),IP(5)
0004  REAL ZOLD,ZNEW,Z,FOCAL,ZMAX,FFH,ZINIT,DELZ,SLOPE,ANGLE,X
0005  INTEGER N,I,J
0006  CALL RMPAR(IP)
0007  LU=MAX(1,IP(1))
0008  1 FORMAT("ENTER FOCAL LENGTH OF COLLECTOR (M)")
0009  2 FORMAT("ENTER MAXIMUM Z VALUE OF DISH (CM)")
0010  3 FORMAT("ENTER FACET FACE HEIGHT (CM)")
0011  4 FORMAT("ENTER INITIAL Z VALUE (CM),VALUE MUST BE NONZERO")
0012  5 FORMAT("ENTER ERROR VALUE (CM)")
0013  6 FORMAT("THE Z BOUNDS FOR ALL FACETS APPEAR BELOW")
0014  7 FORMAT("ZSUB",I3,"=",F6.3,"CM")
0015  8 FORMAT("ITERATIVE SOLUTION COMPLETED"/"ALPHA VALUES FOR BEST FIT
0016  1 REFERENCE PLANES APPEAR BELOW")
0017  9 FORMAT("FACET NO.",I3,"ALPHA=",F6.3)
0018  10 FORMAT("FACET BOUNDARY AND SLOPE CALCULATIONS COMPLETED")
0019  11 FORMAT("COMMENCE FACET FACE HEIGHT CHECK")
0020  12 FORMAT("FACET NO.",I3,"HYPOT=",F6.3)
0021  WRITE(LU,1)
0022  READ(LU,*)FOCAL
0023  FOCAL=FOCAL*100.
0024  WRITE(LU,2)
0025  READ(LU,*)ZMAX
0026  WRITE(LU,3)
0027  READ(LU,*)FFH
0028  WRITE(LU,4)
0029  READ(LU,*)ZINIT
0030  WRITE(LU,5)
0031  READ(LU,*)DELZ
0032  Z(1)=ZINIT
0033  N=1
0034  WRITE(6,6)
0035  WRITE(6,7)N,Z(N)
0036  N=2
0037  20 ZOLD(N)=Z(N-1)
0038  30 ZNEW(N)=((FFH**2)-(ZOLD(N)**2)+(8.*FOCAL*SQRT(ZOLD(N)*Z(N-1)))-(4.
0039  1*FOCAL*Z(N-1))-(Z(N-1)**2))/((4.*FOCAL)-(2.*Z(N-1)))
0040  IF((ABS(ZNEW(N)-ZOLD(N))).LT.DELZ) GOTO 40
0041  ZOLD(N)=ZNEW(N)
0042  GO TO 30
0043  40 Z(N)=ZNEW(N)
0044  WRITE(6,7)N,Z(N)
0045  IF(Z(N).GT.ZMAX) GOTO 50
0046  N=N+1
0047  GO TO 20
0048  50 WRITE(6,8)
0049  DO 60 I=1,N
0050  60 X(I)=SQRT(4.*FOCAL*Z(I))
0051  DO 70 J=1,N-1
0052  SLOPE=(Z(J+1)-Z(J))/(X(J+1)-X(J))
0053  ANGLE=ATAN(SLOPE)
0054  ANGLE=ANGLE*57.296
0055  ANGLE=90.-ANGLE
0056  WRITE(6,9)J,ANGLE
0057  70 CONTINUE
0058  WRITE(6,10)
0059  WRITE(6,11)
0060  DO 80 I=1,N-1
0061  HYPOT=SQRT(((X(I+1)-X(I))**2)+((Z(I+1)-Z(I))**2))
0062  WRITE(6,12)I,HYPOT
0063  80 CONTINUE
0064  END

```


SAMPLE OUTPUT FROM ZBND5

The input parameters were as follows:

FOCAL = 3.95 m

ZMAX = 60.0 cm

FFH = 9.843 cm

ZINIT = 0.000

DELZ = 1E-10

THE Z ROUNDS FOR ALL FACETS APPEAR BELOW

ZSUR 1= 0.000CM

ZSUB 2= .061CM

ZSUB 3= .245CM

ZSUB 4= .552CM

ZSUB 5= .980CM

ZSUB 6= 1.531CM

ZSUB 7= 2.203CM

ZSUB 8= 2.997CM

ZSUB 9= 3.912CM

ZSUB 10= 4.946CM

ZSUB 11= 6.101CM

ZSUB 12= 7.374CM

ZSUB 13= 8.765CM

ZSUB 14=10.274CM

ZSUB 15=11.899CM

ZSUB 16=13.640CM

ZSUB 17=15.496CM

ZSUB 18=17.465CM

ZSUB 19=19.546CM

ZSUB 20=21.739CM

ZSUB 21=24.042CM

ZSUB 22=26.453CM

ZSUB 23=28.973CM

ZSUB 24=31.599CM

ZSUB 25=34.330CM

ZSUB 26=37.165CM

ZSUB 27=40.102CM

ZSUB 28=43.141CM

ZSUB 29=46.279CM

ZSUB 30=49.515CM

ZSUB 31=52.848CM

ZSUB 32=56.277CM

ZSUB 33=59.799CM

ZSUB 34=63.414CM

ITERATIVE SOLUTION COMPLETED

ALPHA VALUES FOR BEST FIT REFERENCE PLANES APPEAR BELOW

FACET NO. 1 ALPHA=89.643

FACET NO. 2 ALPHA=88.929

FACET NO. 3 ALPHA=88.216

FACET NO. 4 ALPHA=87.504

FACET NO. 5 ALPHA=86.793

FACET NO. 6 ALPHA=86.083

FACET NO. 7 ALPHA=85.375

FACET NO. 8 ALPHA=84.669

FACET NO. 9 ALPHA=83.966

FACET NO. 10 ALPHA=83.265

FACET NO. 11 ALPHA=82.562

FACET NO. 12 ALPHA=81.873

FACET NO. 13 ALPHA=81.182

FACET NO. 14 ALPHA=80.496

FACET NO. 15 ALPHA=79.813

FACET NO. 16 ALPHA=79.134

FACET NO. 17 ALPHA=78.461

FACET NO. 18 ALPHA=77.792

FACET NO. 19 ALPHA=77.128

FACET NO. 20 ALPHA=76.469

FACET NO. 21 ALPHA=75.816

FACET NO. 22 ALPHA=75.168

FACET NO. 23 ALPHA=74.526

FACET NO. 24 ALPHA=73.890

FACET NO. 25 ALPHA=73.260

FACET NO. 26 ALPHA=72.636

FACET NO. 27 ALPHA=72.019

FACET NO. 28 ALPHA=71.408

FACET NO. 29 ALPHA=70.803

FACET NO. 30 ALPHA=70.205

FACET NO. 31 ALPHA=69.614

FACET NO. 32 ALPHA=69.030

FACET NO. 33 ALPHA=68.452

FACET BOUNDARY AND SLOPE CALCULATIONS COMPLETED
COMMENCE FACET FACE HEIGHT CHECK

FACET NO. 1HYPOT= 9.843
FACET NO. 2HYPOT= 9.843
FACET NO. 3HYPOT= 9.843
FACET NO. 4HYPOT= 9.843
FACET NO. 5HYPOT= 9.843
FACET NO. 6HYPOT= 9.843
FACET NO. 7HYPOT= 9.843
FACET NO. 8HYPOT= 9.843
FACET NO. 9HYPOT= 9.843
FACET NO. 10HYPOT= 9.843
FACET NO. 11HYPOT= 9.843
FACET NO. 12HYPOT= 9.843
FACET NO. 13HYPOT= 9.843
FACET NO. 14HYPOT= 9.843
FACET NO. 15HYPOT= 9.843
FACET NO. 16HYPOT= 9.843
FACET NO. 17HYPOT= 9.843
FACET NO. 18HYPOT= 9.842
FACET NO. 19HYPOT= 9.843
FACET NO. 20HYPOT= 9.842
FACET NO. 21HYPOT= 9.842
FACET NO. 22HYPOT= 9.843
FACET NO. 23HYPOT= 9.843
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FACET NO. 28HYPOT= 9.843
FACET NO. 29HYPOT= 9.842
FACET NO. 30HYPOT= 9.842
FACET NO. 31HYPOT= 9.842
FACET NO. 32HYPOT= 9.842
FACET NO. 33HYPOT= 9.842

MOIRE

This FORTRAN IV program generates a theoretical fringe contour pattern for any given component facet of a parabolic dish. Required parameter inputs are as follows:

1. Focal length (FOCLH) of parabolic collector
2. Upper (ZMAX) and lower (ZMIN) facet boundaries
3. Contour interval (DELH)
4. Fringe dispersion halfwidth (DHW)
5. Reference plane normal orientation (ALPHA, BETA)

If fringe phase matching is desired, two additional parameters are required:

1. Matrix coordinates of spatial match point (U, V)
2. Grating/mirror interseparation distance (FMDIS) at the match point

&MOIRE T=00004 IS ON CR00011 USING 00015 BLKS R=0120

```
0001  FINAL
0002  PROGRAM MOIRE(),J.W.GRIFFIN 2/25/80
0003  DIMENSION NDIST(50,50),IP(5)
0004  DIMENSION IG(192)
0005  REAL FOCLH,ZMIN,ZMAX,ZINC,DELH,DHW,ALPHA,BETA,FMDIS,ZCUR
0006  REAL LSPAN,LINC,LCUR,X,Y,Z,NDIST,MIN,MAX,DELTA,STDIS,RCUR
0007  INTEGER RES,U,V,I,J
0008  1 FORMAT("ENTER MIRROR FOCAL LENGTH (M)")
0009  2 FORMAT("ENTER LOWER Z BOUNDARY FOR FACET (CM)")
0010  3 FORMAT("ENTER UPPER Z BOUNDARY FOR FACET (CM)")
0011  4 FORMAT("ENTER CONTOUR INTERVAL (MM)")
0012  5 FORMAT("ENTER DISPERSION HALFWIDTH (MM)")
0013  6 FORMAT("ENTER GRATING NORMAL PARAMETERS,ALPHA=ELEVATION,BETA=AZIMU
0014  1TH(DEGREES)")
0015  7 FORMAT("IS FRINGE PHASE MATCHING DESIRED ?,1=YES,0=NO")
0016  8 FORMAT("ENTER FRINGE COORDINATE (U,V) AND NDIST VALUE (MM)")
0017  9 FORMAT("CALCULATION OF SPATIAL POINTS COMPLETED"/"COMMENCE SEARCH
0018  1FOR MINIMUM AND MAXIMUM")
0019  10 FORMAT("MINIMUM AND MAXIMUM DETERMINED, COMMENCE NORMALIZATION")
0020  11 FORMAT("NORMALIZATION COMPLETE, COMMENCE CONTOUR GENERATION"/
0021  1"LOWEST ORDER FRINGE IS PLOTTED FIRST")
0022  12 FORMAT("CONTOUR SIMULATION COMPLETE")
0023  13 FORMAT("*")
0024  CALL RMPAR(IP)
0025  LU=MAX0(1,IP(1))
0026  CALL PLOTR(IG,2,1,20)
0027  CALL VIEWP(IG,63.,108.,40.,70.)
0028  CALL WINDW(IG,0.,4.5,0.,3.00)
0029  CALL PEN(IG,1)
0030  CALL PENUP(IG)
0031  CALL FRAME(IG)
0032  CALL PENUP(IG)
0033  CALL PEN(IG,0)
0034  WRITE(LU,1)
0035  READ(LU,*)FOCLH
0036  WRITE(LU,2)
0037  READ(LU,*)ZMIN
0038  ZMIN=ZMIN/100.
0039  WRITE(LU,3)
0040  READ(LU,*)ZMAX
0041  ZMAX=ZMAX/100.
0042  ZINC=(ZMAX-ZMIN)/49.
0043  WRITE(LU,4)
0044  READ(LU,*)DELH
0045  DELH=DELH/1000.
0046  WRITE(LU,5)
0047  READ(LU,*)DHW
0048  DHW=DHW/1000.
0049  WRITE(LU,6)
0050  READ(LU,*)ALPHA,BETA
0051  ALPHA=ALPHA/57.296
0052  BETA=BETA/57.296
0053  WRITE(LU,7)
0054  READ(LU,*)RES
0055  IF(RES.EQ.0) GOTO 40
0056  WRITE(LU,8)
0057  READ(LU,*)U,V,FMDIS
0058  FMDIS=FMDIS/1000.
```

```

0059      40 ZCUR=ZMAX
0060      DO 60I=1,50
0061      RCUR=SQRT(4.*FOCLH*ZCUR)
0062      LSPAN=.1524/RCUR
0063      LINC=LSPAN/49.
0064      LCUR=1.571+(LSPAN/2.)
0065      DO 50J=1,50
0066      X=-RCUR*SIN(LCUR)
0067      Y=RCUR*COS(LCUR)
0068      Z=ZCUR
0069      NDIST(I,J)=ABS((COS(ALPHA)*COS(BETA)*X)+(COS(ALPHA)*SIN(BETA)*Y)+
0070      1(SIN(ALPHA)*Z)-(.1*COS(ALPHA)*COS(BETA)))
0071      50 LCUR=LCUR-LINC
0072      60 ZCUR=ZCUR-ZINC
0073      WRITE(LU,9)
0074      MIN=NDIST(1,1)
0075      MXX=NDIST(1,1)
0076      DO 80I=1,50
0077      DO 70J=1,50
0078      IF(NDIST(I,J).GT.MXX) MXX=NDIST(I,J)
0079      IF(NDIST(I,J).LT.MIN) MIN=NDIST(I,J)
0080      70 CONTINUE
0081      80 CONTINUE
0082      WRITE(LU,10)
0083      DO 100I=1,50
0084      DO 90J=1,50
0085      NDIST(I,J)=NDIST(I,J)-MIN
0086      90 CONTINUE
0087      100 CONTINUE
0088      MXX=MXX-MIN
0089      WRITE(LU,11)
0090      IF(RES.EQ.0) GOTO 125
0091      DELTA=NDIST(U,V)-FMDIS
0092      DO 120I=1,50
0093      DO 110J=1,50
0094      NDIST(I,J)=NDIST(I,J)-DELTA
0095      110 CONTINUE
0096      120 CONTINUE
0097      STDIS=FMDIS
0098      MXX=MXX-DELTA
0099      125 IF(RES.EQ.0) STDIS=0.
0100      130 DO 150I=1,50
0101      DO 140J=1,50
0102      IF(NDIST(I,J).GT.(STDIS+DHW)) GOTO 140
0103      IF(NDIST(I,J).LT.(STDIS-DHW)) GOTO 140
0104      X=(J-1)*.09184
0105      Y=(3.000-((I-1)*.06122))
0106      CALL PEN(IG,1)
0107      CALL PLOT(IG,X,Y)
0108      CALL CPLOT(IG,-.3,-.24,-2)
0109      CALL LABEL(IG)
0110      WRITE(20,13)
0111      CALL CPLOT(IG,.3,.24,4)
0112      140 CONTINUE
0113      150 CONTINUE
0114      STDIS=STDIS+DELH
0115      IF((STDIS-DHW).GT.MXX) GOTO 160
0116      GO TO 130
0117      160 WRITE(LU,12)
0118      CALL PEN(IG,0)
0119      CALL PLOT(IG,.2,0)
0120      END

```

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