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Optical Analysis of Thermal Induced Structural Distortions

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ABSTRACT

This paper will outline the techniques utilized to analyze optical components, such as scanning mirrors and telescope optics. The methodology utilized in the analysis of the GOES scan mirror will be reviewed along with representative results. The technique along with some of the possible pitfalls will be outlined.

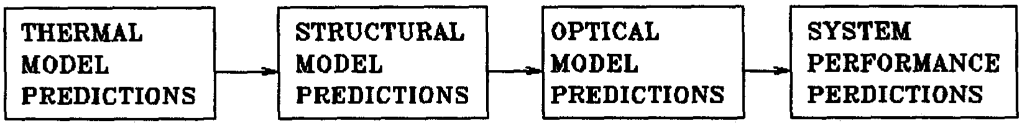
1.0 INTRODUCTION

ITT is developing the next generation spaceborne meteorological radiometers for a geosynchronous orbit (GEO). The primary mission of the Geostationary Operational Environmental Satellite (GOES) is to collect data that will be utilized for making global and local weather predictions. The Imager and Sounder instruments are designed and manufactured by ITT, these instruments are the primary payload for the GOES system. The instruments scan the earth and detect various wavelengths of visible and infrared radiation being emitted by the earth. The instruments are required to operate 24 hours a day in a very harsh thermal environment. The GOES system operates on a three axis stabilized platform positioned in a Geostationary orbit which is 23,500 miles above the earth. During a single diurnal period the optics are exposed to the direct view of the sun for approximately 4 hours during the day and deep space during the remaining periods. Even with highly reflective optical sufaces, the mirrors still experience large temperature excursions with complex gradient conditions present during the heating and cooling periods. Making predictions of mirror distortions requires detailed modeling.

To meet the system performance requirements, the optical elements cannot distort when exposed to the transient thermal environment. The need for developing an efficient end to end analysis technique to evaluate the thermal induced distortions into optical system degradations is required. The ability to create extremely detailed simulations have been tremendously enhanced by advances in computer technology. On projects such as the development of the GOES instruments, the performance and design evaluations are performed using computer analysis techniques. The general analysis flow for evaluating the thermal induced distortions of the GOES optical system can be seen in FIGURE 1. The sequence involves generating a thermal, structural and optical models of the system. The analytical predictions from the thermal model is used as inputs into the structural model which in turn produces a distorted shape of the optical element. The distorted shape is then inputed into the system optical model, from this system performance predictions can be made. The remaining portion of the paper will be dedicated to outlining the analysis methodology that was utilized in evaluating impact on performance of the thermal induced distortions of the GOES scanning mirror.

ANALYSIS METHODOLOGY

FIGURE 1



2.0 THERMAL ANALYSIS

The first step in the detailed analysis begins with the creation of a detailed thermal model that will accurately predict the temperature environment that the optic experiences. Since the GOES instrument operates in a space environment the modes of energy transfer are radiation and conduction. The thermal model must be of sufficient detail such that excessive averaging of temperature gradients do not occur. It is always good practice to begin with a course model of the optic and system for a first order analysis. The detail of the thermal model should be increased until effects on the structural model output are negligible. It is critical that the conductive paths and the surface emissive and absorbtivity properties are modeled accurately. Even small conductive paths that are normally neglected in most thermal analysis can have significant influences. After the thermal model has been created and debugged it is now time to input the results into the structural model of the optic. For the GOES system the transient diurnal temperature predictions were made for several seasonal periods. A representative set of thermal predictions for the GOES scan mirror can be seen in FIGURE 2 and FIGURE 3. In FIGURE 2 the average temperature prediction for the scan mirror for several orbital positions. In FIGURE 3 a Isotherm of the scan mirror can be seen for the orbital hours of 12 midnight and 6 am. It can be seen from figures 2 and 3 that the GOES scan mirror not only experiences large temperature excursions, but that complex gradients are produced during the heating and cooling periods. The system performance impact of these gradients cannot be accessed at this time. The temperature profile must be inputed into a structural model to determine distortions.

3.0 STRUCTURAL ANALYSIS

The structural model of the scan mirror was a NASTRAN finite element model that contains 1126 grids. The structural model was very similar in detail to the thermal model. The structural model can be seen in FIGURE 4. The structural model was correlated to actual mirror with the use of modal analysis on the scan mirror. By correlating the structural model a higher degree of confidence can be given to the model predictions. Complicated models such as the scan mirror should be correlated by testing hardware whenever possible. After the structural model is validated the temperature distribution is then mapped on to the structural model. The thermal induced structural distortions are then solved for. Typical surface distortions for the 12 midnight and 6 am temperature conditions are shown in FIGURE 5. Once the distortions of the optical surface are found, it is converted into a form that can be utilized by the optical programs.

4.0 OPTICAL ANALYSIS UTILIZING ZERNIKE COEFICIENTS

Until fairly recently(the late 1970's or the early 1980's) it was difficult if not impossible for optical designers to properly analyze optical systems that incorporate distorted optical surfaces. Often superficial, simplistic simulations were performed, such as defocus or astigmatism (by two different orthogal values of curvatures). However, with the recently widespread use of Zernike polynomials to simulate optical surfaces, there now exists a tool to study optical performance under the condition of imperfect optical surfaces. For our purpose the Zernike coefficients are used as the interface between the mechanical distortion outputs and the optical surface inputs to ACCOS V or CODE V lens design programs. Born and Wolf (Pergammon Press, 6th Edition, pg 464, Section 9.2.1) state that the geometric aberration function can be expanded in terms of Zernike polynomials which is the only set of polynomials that are both orthoganal and are invariant. "The circle polynomials are distinguished from the other sets by certain simple invariance properties." One such invariant is "with respect to rotation of axes about the origin".

Why were the Zernike polynomials used by us?

1) The first and foremost reason is that they are the single set of polynomials that are accepted by ACCOS V and CODE V as a method of representing an imperfect surface. The polynomials are far easier to implement than more cumbersome methods such as spline functions.

2) The Zernikes produce very accurate representations of the surface. This has been proven by comparing CODE V or ACCOS V surface data to the original distorted surface sags.

3) Zernike polynomials have very helpful mathematical properties. They are orthogonal, and they are independent (i.e. a change in one Zernike term does not affect the other Zernike terms).

4) The Zernike terms have meaning in that they are directly related to optical aberrations. As an example the "r^2 cos 2A" term is 3rd order, 0 degree, astigmatism. Likewise the "r^3 cos A" is 3rd order Xcoma.

From theory and from empirical usage there are certain useful facts about the Zernikes:

1) There are 45 Zernike polynomials, which indeed are various forms of length times either the sine or cosine of an angle. Through a series of empirical studies conducted by several companies it was concluded that the first 28 Zernike coefficients sufficed to produce excellent simulation of every attempted surface.

2) There are several commonly accepted methods of ordering these Zernike polynomials. Thus the user must be extraordinarily careful in the use of these terms. For instance the "r^2 cos A" term is the 5th term in ACCOS, and the 4th term in CODE V and NASTRAN.

3) The distortions of an optical surface can be related to the Zernikes by using a least square fit to the Zernike polynomial. The only trick is to do the scaling properly; namely to scale all the distortions by the same factor.

4) It should be noted that for the past 5 or 10 years, methods have been developed by Interferometer companies (e.g. WYKO and ZYGO) and by interferometry consultants (e.g. BSC) which convert the interferograms of actual components into Zernike coefficients.

5.0 OPTICAL SYSTEM PERFORMANCE EVALUATION

The application of the Zernike coefficients to an optical surface is the only major difference from the typical evaluation of an optical system. Because of the time variation of thermal effects, multiple evaluations are performed on the optical systems i.e. the optical analyses are done for each hour of a 24 hour day, with a different Zernike set of coefficients applied at each hour. In addition if the thermal effects are radiative, a day is chosen for each of about 5 different seasons. Thus for each type of analyses, such as MTF or FOV, there are 120 computer runs required. With such a large volume of optical analyses, it has been mandatory that the inputs of the Zernikes be automated.

In most tasks the evaluated parameters have been MTF (both for visible and infrared channels), FOV as captured by a given field stop dimension, and encircled energy at a given field stop. FIGURE 6 and FIGURE 7 show the point spread function for the GOES optical system with Ideal scan mirror and with a slightly distorted scan mirror respectively. It can be seen that the point spread function is disrupted by the thermal induced distortion. The analysis methodology was utilized on the GOES program to verify that the thermally induced distortions were at acceptable levels. With this technique improved mechanical designs were analyzed and then implemented, such that the GOES scan mirror performance is successful.

6.0 CONCLUSIONS

The purpose of this paper has been to present a technique that allows an accurate representation of performance of an optical system whose capability is affected by thermal induced structural distortions. The use of Zernike coefficients has allowed an accurate, effective and simple linkage between thermal/mechanical effects and the optical design. In addition, because the latest models of interferometers generate Zernike coefficients, there is now a very powerful tool to compare reality and theory for the testing of mechanically and thermally stressed components.

7.0 ACKNOWLEDGMENTS

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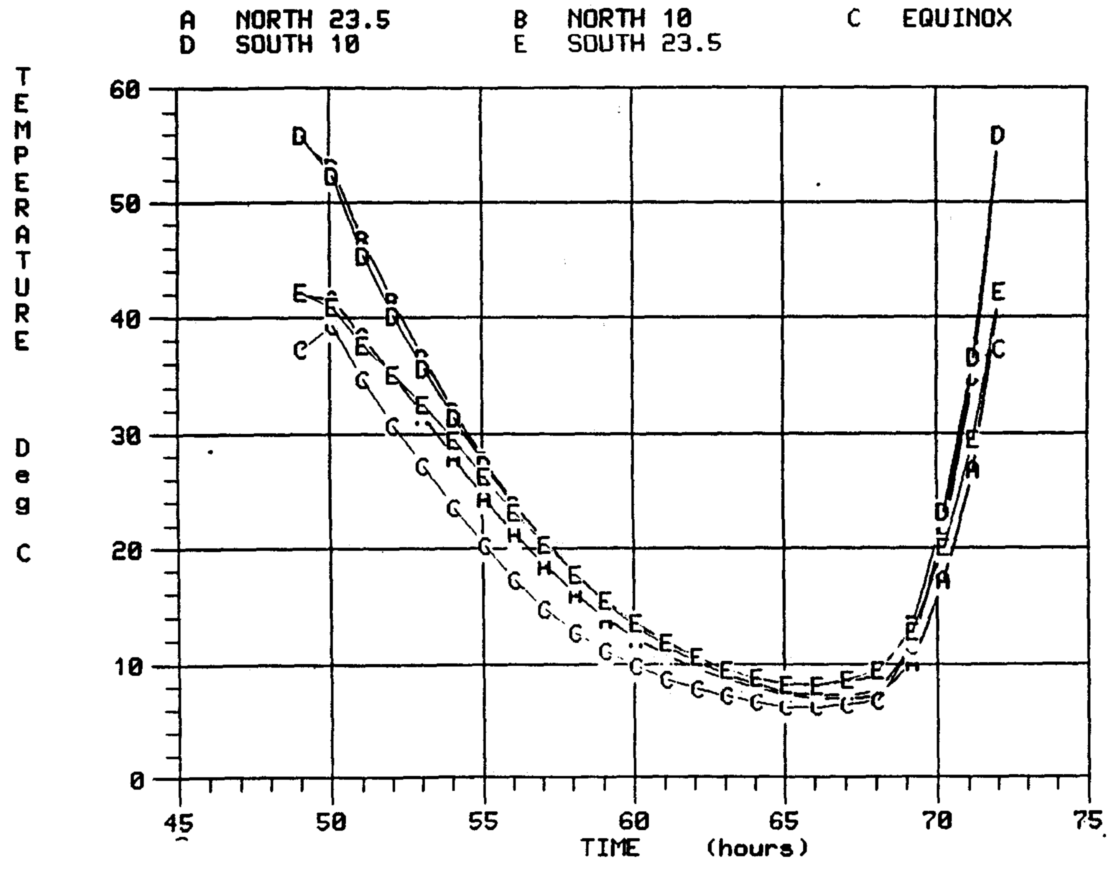
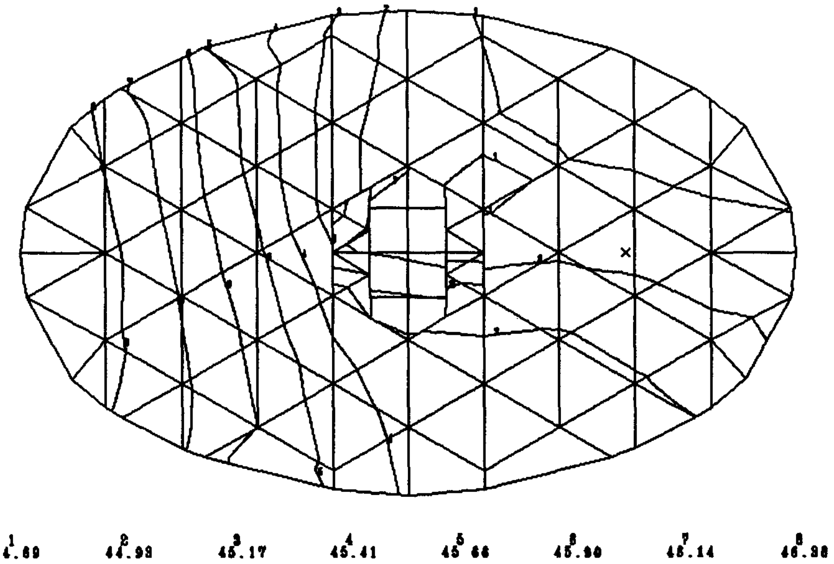
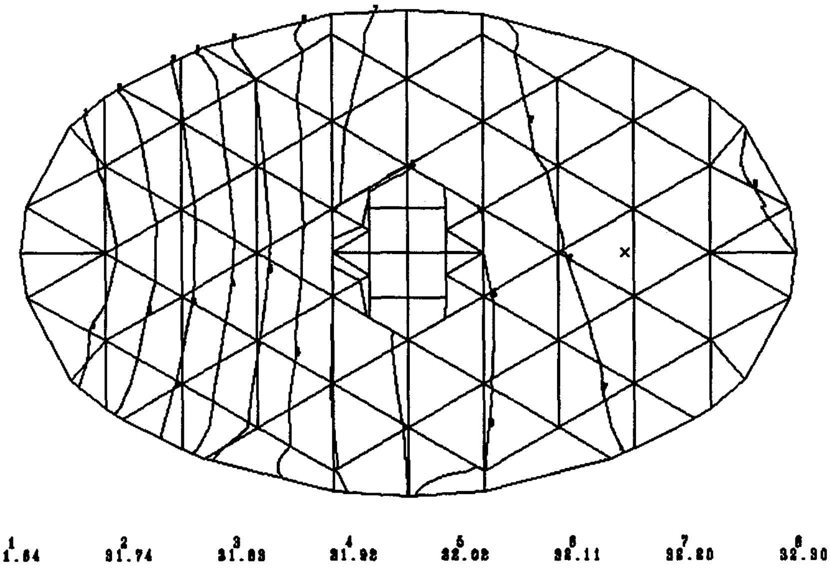


SCANNING MIRROR DAILY TEMPERATURE VARIATIONS

FIGURE 2

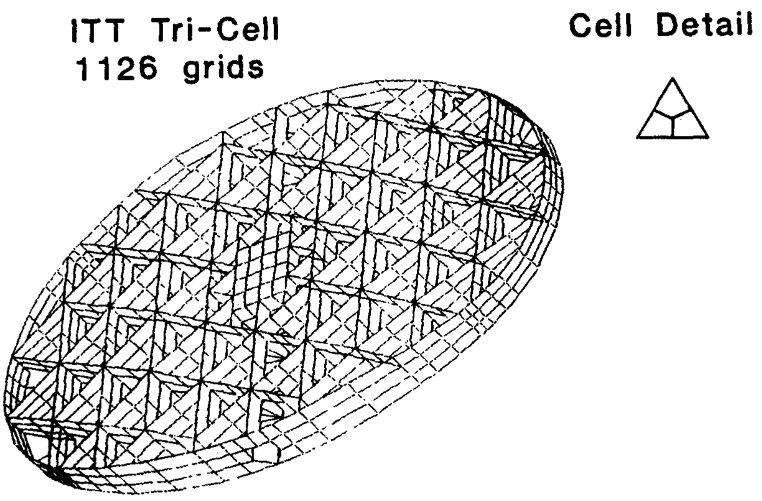


MIDNIGHT

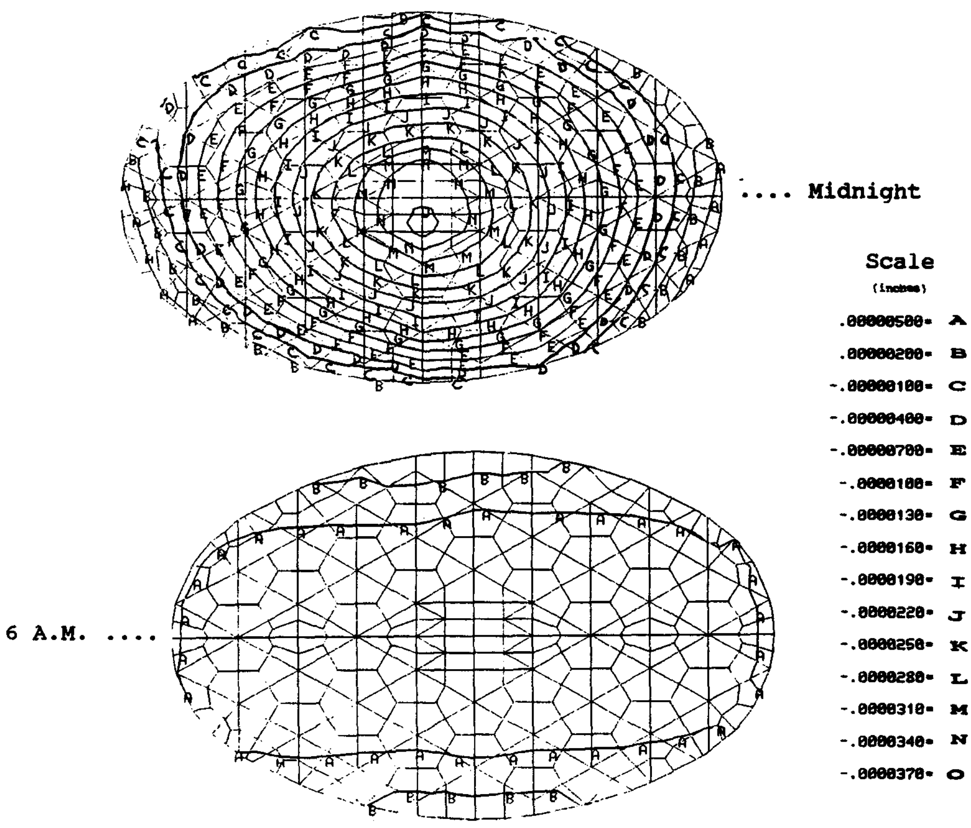


6 AM

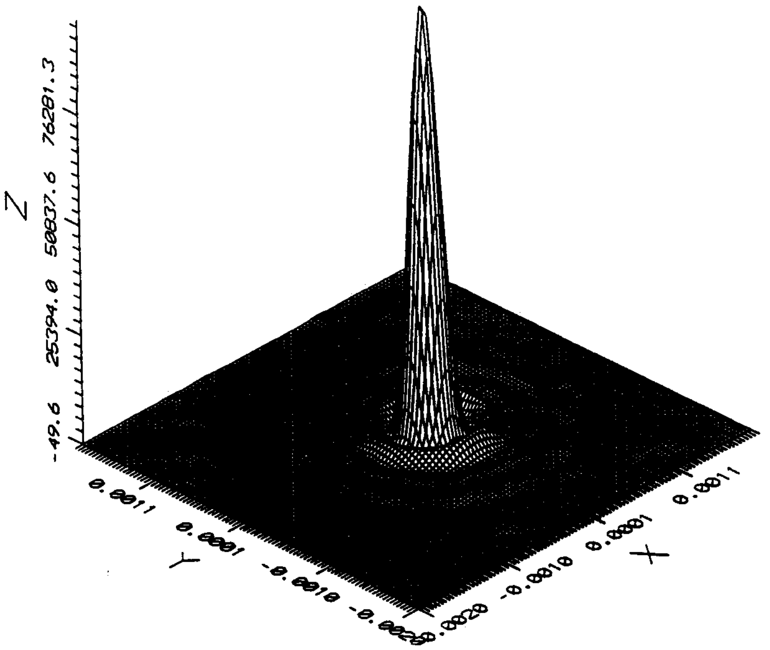
SCAN MIRROR TEMPERATURE ISOTHERMS FOR MIDNIGHT AND 6 AM
FIGURE 3



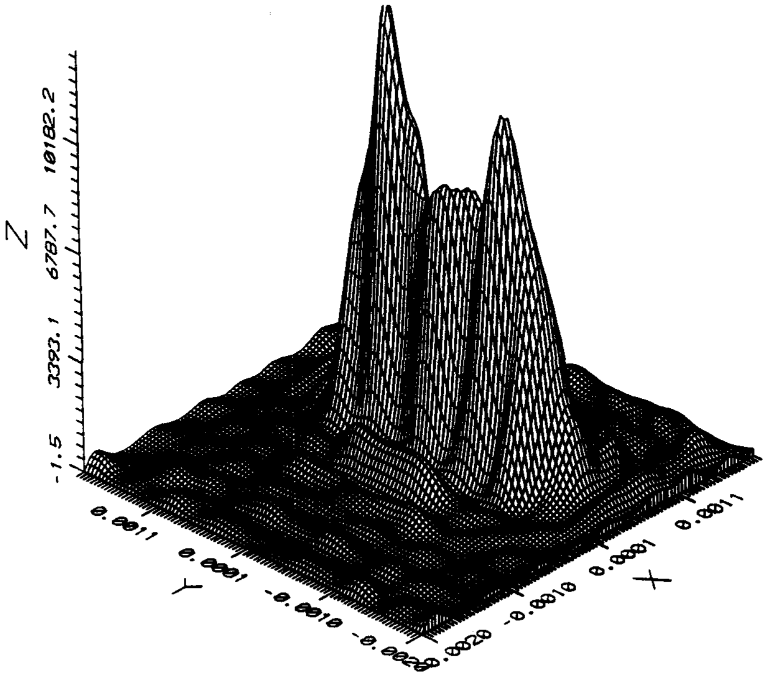
DETAILED STRUCTURAL MODEL
FIGURE 4



ON ORBIT DISTORTION PREDICTIONS 12 MIDNIGHT AND 6 AM
FIGURE 5



POINT SPREAD FUNCTION PERFECT SCANNING MIRROR
FIGURE 6



POINT SPREAD FUNCTION SCANNING MIRROR AT 6 AM
FIGURE 7