NASA-CR-203494

Final Report

DEVELOPMENT OF SOFTWARE TO MODEL AXAF-I IMAGE QUALITY

Contract No. NAS8-38609, D.O. 145
UAH Account No. 5-33865/6

Submitted to:

NASA/MSFC
Marshall Space Flight Center, AL 35812

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October 1996

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ABSTRACT

This draft final report describes the work performed under the delivery order number 145 from May 1995 through August 1996. The scope of work included a number of software development tasks for the performance modeling of AXAF-I. A number of new capabilities and functions have been added to the GT software, which is the command mode version of the GRAZTRACE software, originally developed by MSFC.

A structural data interface has been developed for the EAL (old SPAR) finite element analysis FEA program, which is being used by MSFC Structural Analysis group for the analysis of AXAF-I. This interface utility can read the structural deformation file from the EAL and other finite element analysis programs such as NASTRAN and COSMOS/M, and convert the data to a suitable format that can be used for the deformation ray-tracing to predict the image quality for a distorted mirror. There is a provision in this utility to expand the data from finite element models assuming 180 degrees symmetry. This utility has been used to predict image characteristics for the AXAF-I HRMA, when subjected to gravity effects in the horizontal x-ray ground test configuration.

The development of the metrology data processing interface software has also been completed. It can read the HDOS FITS format surface map files, manipulate and filter the metrology data, and produce a deformation file, which can be used by GT for ray tracing for the mirror surface figure errors. This utility has been used to determine the optimum alignment (axial spacing and clocking) for the four pairs of AXAF-I mirrors. Based on this optimized alignment, the geometric images and effective focal lengths for the as built mirrors were predicted to cross check the results obtained by Kodak.

The multishell imaging capability has been added to the GT program, and the size of its ray storage area has been increased. The multishell imaging feature has been implemented only for the random ray distribution trace for now. Basically, the existing raytrace code was placed in a loop such that the ray data from more that one mirror shell could be traced and accumulated. It was necessary to add several new variables to the source code, alter some existing commands peripherally related to the multishell ray trace (e.g. RES), add a new command to activate and query the status of the multishell imaging feature (MSH), and add or make changes to some of the existing source code which prepares GT for, and actually performs, the ray trace (e.g. WSP command). The storage area for ray intercept and other ray data was increased from 200k to 400k rays. An analysis of the program was also performed to determine what interactions, if any, existed between the ray storage arrays and other parts of the source code.

The new software, called "psdgenc," is being developed to convert HDOS mirror roughness data files into PSD files readable by the EEGRAZ program used to predict the performance degradation due to scattering. Software called "psdgen_dfm" was already in existence to generate PSDs from surface micro-roughness data, but it was only capable of operating interactively which means that the user has to enter the name of the file to be processed and select the desired processing options for each file. When completed, the new software, called "psdgenc," will have the ability to function in batch mode as well as interactive mode. In interactive mode, "psdgenc" will "look and feel" very similar to "psdgen_dfm." In batch mode, processing options will be set

on the command line and "psdgenc" will read a list of file names to be processed from a single ASCII file. Processing options not set on the command line will revert to the default values.

In addition to the "psdgenc" software, two other software tools have been developed to help with sorting through the large number of HDOS data files: 1. "vfits" - allows FITS (Flexible Image Transport System format) and FITS-like files (e.g. the HDOS micro-roughness data files) to be viewed and saved in ASCII format; "prevw" - extracts the header information from a list of HDOS surface micro-roughness data files and writes it to an ASCII file which can then be browsed.

As the GT program was used and tested during the year, a number of changes were made to debug and upgrade its existing features. This is, of course, an on-going task. A number of commands have been added, deleted or modified. For example, a command called RMM was added to GT which allows the user to set the minimum and maximum radii of the optical system annulus (or aperture) independent of the minimum and maximum values of the mirror itself. For ease of maintenance, the source code was divided up into separate files such that there is a single subprogram in each source code file. These files were placed under SCCS (Source Code Control System) control in order to track the changes made from one version to the next.

The GT on-line help has been revised and updated according to the changes made in the commands. Some of the wording and content of the on-line help document have been modified. The description of the new RMM command, which allows the user to temporarily set the maximum and minimum radii of the system (only from the WSP, WS2, GRI, and GR2 prompts), was added. The command menu was neatly arranged. Revisions were made to reflect the changes in command syntax and function (e.g. with the modification to RES with respect to the multishell imaging).

A new software utility has been developed for processing of the WYKO data. This software is intended to streamline the process of obtaining surface micro-roughness data for the modeling effort. The WYKO used at Marshall is controlled by a computer/operating system which is not suitable for connection to a network and its floppy disks are in a format unreadable by the Sun workstations used by the Optical Analysis Branch. The method previously used to transfer data files from the WYKO to the Sun was to write the files to a specially-formatted high density (HD) floppy disk on the WYKO, transfer the floppy disk to a PC, copy the files to the PC's hard disk drive (HDD), and then transfer the files to a Sun workstation using file transfer protocol (ftp) over the network. To address these problems, a two part solution has been implemented. Part one of the solution is to establish a serial data transfer link between the WYKO and a nearby network-capable HP-UX (Hewlett-Packard UNIX) workstation. A FORTRAN subroutine has been developed to enable the processing software to read WYKO TOPO2D data files in their native form. A user manual has also been compiled to explain this file transfer procedure.

The IRAF/PROS/STSDAS system of image processing software has also been installed on the Sun computer used by the MSFC optical analysis branch. IRAF is a package for general scientific data analysis and data reduction, and also providing the image processing and data reduction tools. PROS (Post-Reduction Off-line Software) is an x-ray analysis software package, which takes into account the parts of image data peculiar to x-ray images, such as photon energy and

arrival time. STSDAS (the Space Telescope Science Data Analysis System), is used to calibrate and analyze data from the HST (Hubble Space Telescope). The correct versions (for the Sun/Solaris hardware/software platform) of the software were obtained from the anonymous ftp sites and were installed on ZEUS. In order to interface GT program with IRAF, a software utility called "g2i" has been developed. The g2i utility allows a user to translate GT PSF output files (in ".gtray" format) into an "intensity" distribution in the FITS (the Flexible Image Transport System) format which is recognized by IRAF.

A technical paper describing the modeling software developed under this contract was presented at the SPIE's Annual conference held at Denver, CO in August 1996. A copy of this paper is included with this report as appendix 5.

1. INTRODUCTION

The AXAF-I HRMA consists of four concentric paraboloid-hyperboloid mirror pairs. A diagram representing a side view of one mirror pair is shown in Fig. 1. The mirrors are made of Zerodur and the optical surfaces are coated with iridium. Each mirror is approximately cylindrical in shape and slightly cone shaped. The x-ray reflectivity is enhanced by the shallow grazing angles of the rays with respect to the mirror surfaces. The entrance aperture of each mirror pair is highly annular. The image intensities of the four mirror pairs add to increase the collecting area of the system as a whole. The diameters of the mirror pairs range from about 0.6 to about 1.2 meters; the length of each mirror is 0.8382 meters; and the effective focal length is 10.066 meters. The grazing angles range from about 0.85 degrees for the largest mirror pair to 0.45 degrees for the smallest mirror pair. The total on-axis geometric collecting area is about 1030 cm^2 allowing for vignetting by support structure. At lower x-ray energies down toward 0.1 keV the image of the largest shell predominates because it has the largest entrance aperture. At high x-ray energies up toward 10 keV, the image of the smallest shell predominates because it has the smallest grazing angle and thus relatively high reflectivity at high energy. The required resolution of the net image of the four mirror pairs is about 0.5 arc seconds for rays entering the system along the direction of the optical axis.

In-house optical performance modeling is being done at Marshall Space Flight Center (MSFC) in support of the development, fabrication, and testing of the Advanced X-ray Astrophysics Facility - Imaging (AXAF-I). Specialized software for modeling grazing-incidence x-ray telescopes is being developed by MSFC with assistance from the University of Alabama in Huntsville (UAH). This report explains the work performed by UAH, such as the software interfaces between the optical model and the mirror surface metrology data. These mirror surface measurements were provided by the mirror manufacturer, HDOS. A structural model of the AXAF-I High Resolution Mirror Assembly (HRMA) has been developed at MSFC. UAH has also developed an interface between the optical modeling software and finite-element modeling codes. These modeling tools have been used to the optimize the alignment of the as-built mirrors, and for the prediction of the x-ray image effects during the x-ray ground test configuration.

2. EAL CONVERSION UTILITY

The structural/thermal figure errors for the mirrors must be prepared for input to the GT program by reformatting the output files of Finite Element Analysis (FEA) models. There are currently provisions for reformatting the output of NASTRAN, EAL, and COSMOS/M programs. In processing the FEA data, filtering out small scale errors is not necessary since the structural/ thermal surface effects are generally relatively large scale deformations that can be used in the ray trace. During this year, the EAL data conversion utility has been completed. This FEA to GT data conversion program now consists of the following utilities:

drinfea.f	main interactive conversion program
spa.f	SPAR data extraction

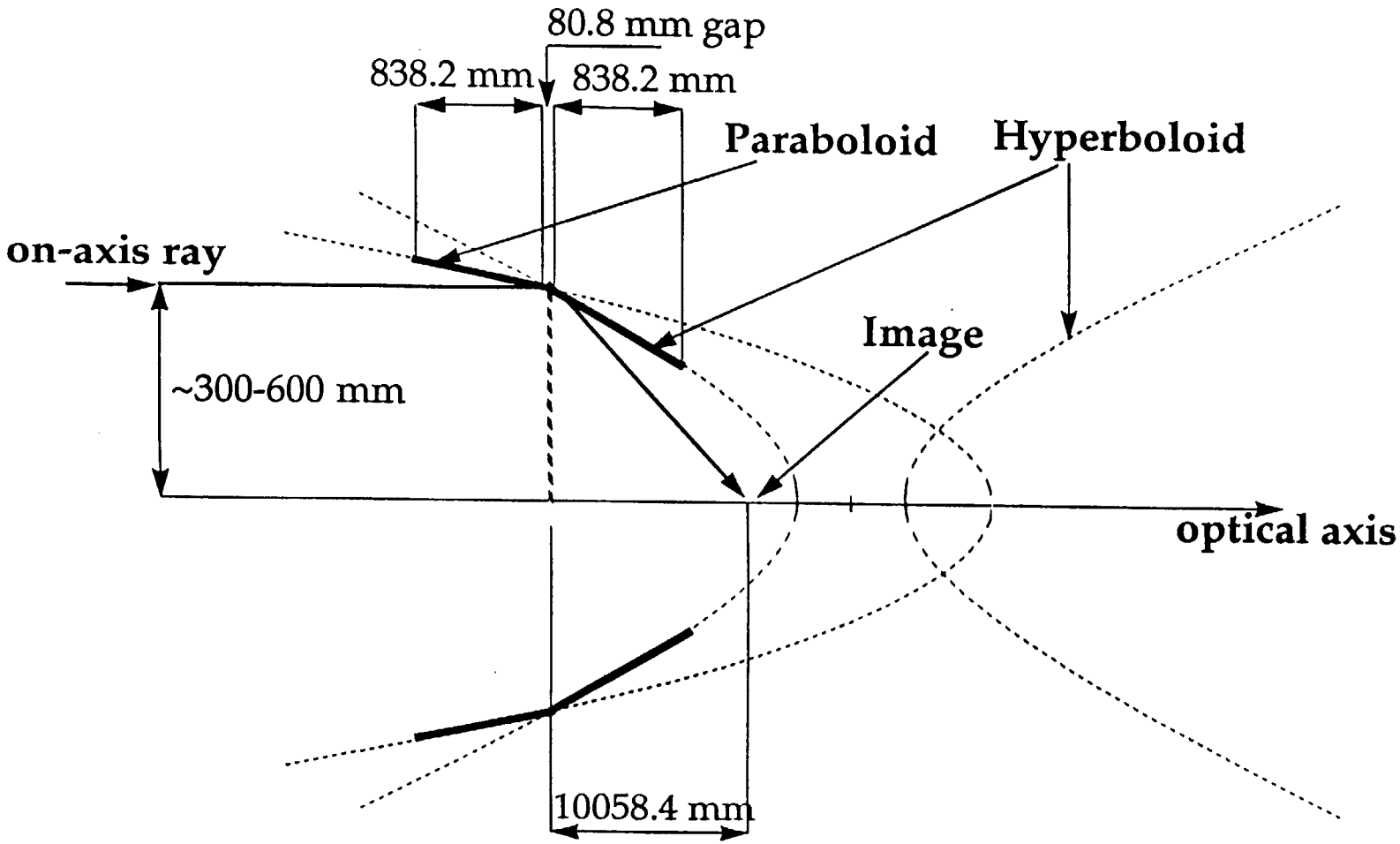


Fig. 1. A sectional side view of a typical mirror pair showing geometrical relationships.

rnas.f	NASTRAN data extraction
rcos.f	COSMOS/M data extraction
extend.f	extend data 30 degrees
modify.f	modify data by shifting the coordinates and scaling

Currently, all these files and executable code are in the directory /export/home/chen /stru/spar/drinfea on ZEUS. The new *spa.f* utility allows reading of the data without any header restrictions (i.e. the header lines do not need to be identified by $ and * symbols). Up to 20 lines of header information are echoed on the screen for the user information.

The data extraction, conversion and interpolation are processed in one program. The input data files for this utility are the EAL output files consisting of the node location file and the node deformation file, or one single file with both the node locations and deformations (for NASTRAN and COSMOS). The output file is the *.dfm for input to the GT. The header of the *.dfm file can be keyed in by the user.

The symmetric data is automatically checked and mirrored to generate complete data if the input file consists of half of the data. The output file can be for the parabola only, hyperbola only, or the combination of parabola and hyperbola. The mirror shell center, shell length, intersection location, and scale can be defined by the user. The default length of the shell is 100% of length used in the input data file.

A file existence check has also been added for the output file to allow the user to overwrite the output file, if desired. The headers of both the node location file and the deformation file are echoed to inform the user about the files being processed. The automatic mirroring of the data was modified and tested. Currently, the program can accept 180 degree data and 360 degree data with any starting position, such as from -90 degree to +90 degree positions.

The structural deformation files for P1, H1 of AXAF-I HRMA and XRCF test mirror were used to test the conversion utility as well as the GT analysis routines. Spot diagrams and point spread functions were generated for the distorted mirror in both cases. The deformation processing subroutines were modified by MSFC to fix some problems. The affected routines are dfm02, prtdfm, rdfm, strco2, and utrc02. The updated routines are in file deform.4.f. The routines in deform.4.f were modified to comply with the output device assignment in GT. The modified routines have been saved as deform.5.f.

3. HDOS METROLOGY DATA PROCESSING SOFTWARE

Several steps are needed in order to prepare the mirror surface measurement data for use in ray tracing. Units and coordinate systems must be converted. The smaller scale surface errors along the direction of the optical axis must be filtered out since their effects on the image must be included as a scattering distribution. The value of the highest spatial frequency allowable for geometrical analysis depends on the grazing angle, x-ray energy, and the magnitude of the surface errors. (An axial surface error of a given spatial frequency can be included in the ray trace

if the result doesn't differ from its physical optics effect as a diffraction grating by more than the required accuracy.) There is also an option in the software to remove low order polynomial terms of the axial surface errors during the process of filtering the data. The data must be interpolated onto an equally spaced output grid for a surface deformation file which the ray trace program uses. Currently, bilinear interpolation is used.

As a first step HDOS metrology software was modified and recompiled on ZEUS. The surface map data analysis program *mapanal* was modified to work on ZEUS. The analysis software can read FITS surface map files and some of the processing functions, such as the Fourier-Legendre polynomial fit and subtraction, are now working.

HDOS processing software *mapanal* consists of more than 100 routines in VAX FORTRAN. To make it run on ZEUS, the following modifications were made.

a. The including file path has been changed such as fmr.common. Some system library calls have been eliminated because these are not available.

b. Filenames such as the including files in the routines have been changed to all lowercase because the UNIX operating system is case sensitive.

c. The output device numbers have been changed to terminal output only.

d. The file descriptor routines have been simplified.

e. Record length in open statement in *opnafile.for* has been changed from RECL=720 to RECL 2880 because the buffer character *80 fmrd_current_record(36). 720 was an error.

f. The maximum number of points per meridian has been increased to 42000 because the data file consists of 41932 points per meridian. (PARAMETER max_npts = 4000 has been changed to 42000)

g. The SECND and DATE calls have been eliminated because these are not available.

h. Eliminated some other functions. The modified source files are in /export/home/chen/fits/

The Makefile and makerules have been prepared to compile the program. More than 50 files have been recompiled and linked. The executable MAPANAL is now working in a command mode.
The AXAF_I HRMA shell #4 surface map file was used to test MAPANAL. The following functions were tested:

RECALL ..... read FITS data file
SETPOLY ..... set polynomial type
SET ..... set order of polynomials
FIT ..... fit polynomials to the map data
DISPLAY ..... display current set of fitted coefficients

SUBTRACT ..... subtract the specified polynomials
STOP ..... terminate the program

A data processing program has also been developed to process the metrology data from HDOS in the FITS format. The data is then converted to the *.dfm* format for the GT program. The progarm has been tested and modified. It has been refined, tested, and used by NASA personnel to verify the telescope alignment. Some of the major tasks completed are as follows:

1. The FITS format HDOS metrology data reading routine has been rewritten. The new routine "rfits.f" to read in the surface map in the FITS format has the same calling sequence as the existing routine "rsmp.f" to read the surface map in ASCII format.

2. A 3-D PV-WAVE plot routine has been implemented to plot the surface data at each stage of processing.

3. A 2-D PV-WAVE plot routine has built to plot the data average and standard deviation along the axial direction.

4. An *axial cut* option has been furnished to select the data range before processing.

5. A Legendre polynomial fit routine has been programmed to fit the surface data up to the 20th order in a recursion formula.

6. A Hanning window routine has been developed to process the axial data before performing the FFT.

7. A "data thinning" process has been added to reduce the number of data points to a more manageable number before performing the interpolation.

8. The metrology processing program "drinfsmp.f" is working now. This program includes the following steps:

   a) Read in the surface map in HDOS/FITS format.

   b) Plot the raw surface data.

   c) Plot the axial distribution of the average and the standard deviation.

   d) An optional *axial cut* to define the range of the data to be processed.

   e) Fit the Legendre polynomials to the axial data at each azimuthal position per the user defined order.

   f) Remove the Legendre terms up to the user selected order from the axial data at each azimuth.

g) Plot the surface again.

h) Apply a Hanning window, if desired, to the axial data at each azimuth.

i) Filter the lowpass data. Fourier transform the data and cut the high frequency at the user defined point. Fourier transform back the data.

j) Add back the Legendre terms that were removed earlier.

k) Plot the final surface data.

l) Thin the data to reduce the number of data points while maintaining the low frequency information.

m) Interpolate the data to a rectangular grid of the points and write to a result file in the *.dfm* format for Graztrace.

A sample copy of various types of plots is shown in figure 2. These plots show the results of various steps implemented to process the metrology data.

4. THE MULTISHELL IMAGING

The multishell imaging capability has been added to the GT program and the size of its ray storage area has been increased. For the time being, the multishell imaging feature has been added only to the random ray distribution trace. Basically, existing raytrace code was placed in a loop such that the ray data from more that one mirror shell could be traced and accumulated. Of course the actual implementation of this change was not so simplistic. It was necessary to add several new variables to the source code, alter some existing commands peripherally related to the multishell ray trace (e.g. RES), add a new command to activate and query the status of the multishell imaging feature (MSH), and add or make changes to some of the existing source code which prepares GT for, and actually performs, the ray trace (e.g. WSP command).

New Variables

emsh (logical) - TRUE if RES detects multiple prescriptions in a prescription file; FALSE otherwise.

umsh (logical) - TRUE if emsh is TRUE and the user elects to perform multishell imaging.

tmsh(4) (logical) - If a prescription has been restored and emsh is FALSE, only the first element of this array is set to TRUE indicating that the first (and only) mirror shell is to be traced. If a prescription is restored and emsh is TRUE, but umsh is FALSE, then only the element of tmsh() corresponding to the sequential number of the currently restored prescription in the prescription is set to TRUE. If a prescription is restored and emsh and umsh are TRUE, then only the

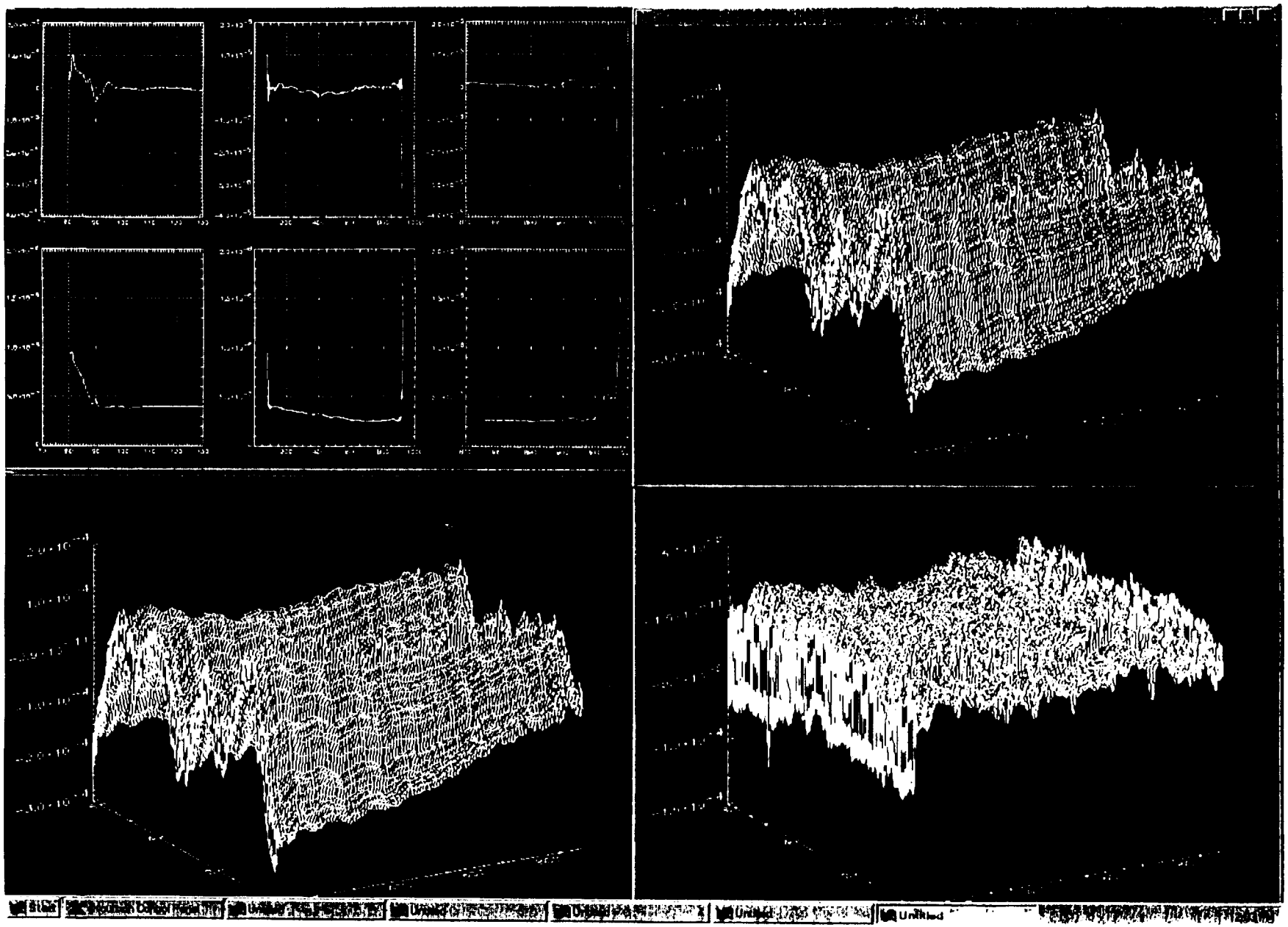


Figure 2: Sample plots for the metrology data processing.

elements of tmsh() specified by the user and corresponding to shells in the prescription are set to TRUE. If the user specifies no elements when activating the multishell imaging, all elements are set to TRUE.

itpre (integer) - the total number of prescriptions found by RES in a particular prescription file.

lpass, lerr, lvig (integer) - the number of rays which passed through the system to the focal plane, the number of rays for which an error occurred while being traced, and the number of rays which were vignetted, respectively. These variables are used to keep track of their respective figures for individual mirror shells and are subsequently added to their common block counterparts (npass, nerr, nvig) which are used to keep track of these figures overall.

nshells (integer) - the number of shells for which a raytrace is to be performed; nshells will always lie in the range 1 <= nshells <= itpre.

nstep (integer) - used by the entry subroutine wsvrst() (in source file wraysv.f) to increment an index to the ray weight array such that the index is set to the beginning of the group of ray weights for the current shell. (Before, the index would simply start at the beginning of the array, which was fine when only a single shell was being traced. However, with multiple shells, the ray information for the first shell is saved in, for example, indices 1-2000 of the various arrays while the ray information for the second shell will be saved in indices 2001-4000 of the various arrays.)

Altered Commands Peripherally Related to the Ray Trace:

When invoked with a valid prescription filename, RES now cycles through the entire file counting the number of prescription. RES then goes back either to restore the prescription which the user has specified or to restore the first prescription if none was specified. Example:

GTRACE> RES sample 3<ENTER>

would restore the third prescription from file "sample" if the file exists and contains at least three prescriptions. If the "3" were omitted from the command line above, the first prescription in "sample" would be restored. Finally, if "sample 3" were replaced with "?", RES would report the current prescription filename and the sequential number of the prescription which has been restored from that file.

The PRE, SAV, and LEN commands all work the same as before but are slightly altered to account for the new manner in which RES functions.

The New Multishell Command:

The new command added to GT to activate and query the status of the multishell imaging feature is MSH (MultiSHell). MSH is only accessible from the"WSP>" prompt. The MSH command is used to activate the multishell imaging capability for all or for a subset of the shells in a multiple prescription file and to inquire as to the status of the multishell imaging feature (i.e. whether or

not the multishell feature is active and, if so, which shells have been selected for tracing). Examples: Given that the current prescription file contains multiple prescriptions,

WSP> MSH ?<ENTER>

will cause GT to display to the user the current setting for the variable umsh and the status of each element in the tmsh() array which corresponds to a prescription in the current prescription file.

WSP> MSH<ENTER>

sets umsh and all elements of the tmsh() array which correspond to a prescription in the current prescription file to TRUE, and displays these values to the user. If MSH is entered followed by a sequence of integers separated by a space, then umsh is set to TRUE, the elements of tmsh() indexed by the integers and corresponding to a prescription in the current prescription file are set to TRUE, and these values are displayed to the user.

Modification to Random Ray Set-up Command (WSP):

The modifications to the WSP command were modest, consisting only of increasing the default number of rays to be traced to 4k (up from 1k) and resetting umsh and all elements of tmsh() to FALSE except the element of tmsh() corresponding to the currently restored prescription.

Modification to Random Ray Trace Subroutine:

The wspot1.f source code file was modified to receive the new formal parameters "lsv" and "nstp". The variable "lsv" keeps track of the total number of rays which have been traced and is passed to the subroutine wraysv(). The variable "nstp" indicates which shell is being traced and is used by wspot1() to indicate which shell has just been traced when writing out the ray trace results for individual shells. Also, "nstp" is passed to the entry subroutine wsvrst() located in the same file as wraysv().

Modification to Ray Information Storage Subroutine:

As each ray completes its travel through the optical system, the subroutine wraysv() increments "lsv" by one and stores the information concerning that ray in several arrays. Additionally, wraysv() uses "lsv" to set its local ray counting variable ("nsv") to the proper value for indexing those arrays when performing a multishell trace.

Modification to Ray Failure Compensation Subroutine

Entry subroutine wsvrst() recalculates the weight of each ray in the event that any rays fail to make it through the system. This subroutine was modified to receive two new parameters ("mspot" and "nstep") which are used to index the ray data stored in various arrays for a particular shell should any of the rays fail of those being traced through that shell.

Increasing of Ray Storage Area

Storage area for ray intercept and other ray data was increased from 200k to 400k rays. An analysis of the program was also performed to determine what interactions, if any, existed between the ray storage arrays and other parts of the source code. At the end of the analysis, it was determined that only two further changes were necessary: 1. The size of an array used as a work space was enlarged from 600k to handle 800k rays; 2. The x and y ray intercept coordinate arrays were realigned inside the work space array to account for the increased size of the ray storage area.

5. CONVERSION OF HDOS METROLOGY DATA TO PSD FILES

New software has been written to convert HDOS mirror roughness data files or WYKO TOPO2D data files into PSD files readable by EEGRAZ. This software also allows the user to plot the PSDs with Visual Numerics' PV-WAVE plotting package and to output those plots to the screen and/or to a PostScript file. The software is basically complete with the exception that its output has not yet been verified. There is also an intermittent problem with generating one of the PostScript plots, but it is suspected that this problem lies with PV-WAVE. (We are working with Visual Numerics to determine the nature of this problem and to resolve it.)

Software called "psdgen_dfm" was already in existence to generate PSDs from surface micro-roughness data. With some modification, "psdgen_dfm" could have been made to recognize the HDOS MPMI data files. However, "psdgen_dfm" was only capable of operating interactively which means that the user has to enter the name of the file to be processed and select the desired processing options for each file. Even though only a subset (17 percent) of the 22K HDOS surface micro-roughness data files have been selected for processing, that subset consists of 3,801 files! Needless to say, just typing 3,801 file names would be extremely time consuming. So, it was determined that new software was in order.

The new software, called "psdgenc," performs the same essential functions as "psdgen_dfm" but with significant differences. The new software has the ability to function in batch mode as well as interactive mode. In interactive mode, "psdgenc" "looks and feels" very similar to "psdgen_dfm." In batch mode, the processing options can be set on the command line and "psdgenc" reads a list of file names for processing from a single ASCII file. The processing options not set on the command line revert to default values. A fringe benefit of writing this new software is that it also satisfies the SOW item 9.

The "psdgenc" application functions by reading an input data file and allowing the user to subtract a 0-10 degree polynomial fit from the data and apply a Hanning window to the data. Afterwards, "psdgenc" performs a cosine FFT on the data to calculate the PSD. Plots of the data in various stages of processing, plots of the polynomial fit to the data, and plots of the window function may be displayed on screen and written to a PostScript file if the user so chooses. Otherwise the user can elect to have the plots either written to the screen only, or written to the PostScript file only, or not written at all.

In addition to the "psdgenc" software, two other software tools have been developed to help with sorting through the large number of HDOS data files: 1. "vfits" - allows FITS (Flexible Image Transport System format) and FITS-like files (e.g. the HDOS micro-roughness data files) to be viewed and saved in ASCII format; 2. "prevw" - extracts the header information from a list of HDOS surface micro-roughness data files and writes it to an ASCII file which can then be browsed.

An example "psdgenc" session and corresponding plots are included as Appendix 1.

6. DEBUG AND UPGRADING OF GT SOFTWARE

As the GT program was used and tested during the year, a number of changes were made to debug and upgrade the existing features of GT. This is, of course, an on-going task. This year the following upgrades and debugs were performed.

Any place where the user is allowed to alter elements of a data array from the command line, GT now checks to see that the given array ind(ex/icies) (is/are) within the proper range. If not, a summary on the use of the command in question is displayed to the user which includes the range of the array ind(ex/ices).

A command called RMM was added to GT which allows the user to set the minimum and maximum radii of the optical system annulus (or aperture) independent of the minimum and maximum values of the mirror itself. This is useful in order to adjust the size of the aperture to compensate for finite and/or off-axis sources (i.e. a source condition in which incident rays are not parallel).

For ease of maintenance, the source code was divided up into separate files such that there is a single subprogram in each source code file. These files were placed under SCCS (Source Code Control System) control in order to track the changes made from one version to the next.

The coding for mirror surface types grzcon01, grzcon02, grzcon03 was deleted from source files ssrt.f and utrc02.f. The name of the named common workspace was changed from "worksp" to "zwrkspc" in the source code files encirc.f, focus.f, spdiag.f, and wstat.f

The default value for the "iener" variable has been set to 1 (one) everywhere in GT.

The processing for the WST command was fixed to correctly compute the apparent focal length in the following manner: All elements of the "xref(15)" and "yref(15)" arrays are initialized to 0 (zero) at program start-up and in LEN, RES, and PRE. After the call to the subroutine "wstat()" from WST, the "xref()" and "yref()" values for the particular energy in question are set to "xav" and "yav" only if the value of "elev" is 0 (zero). This allows the focal length to be calculated from the sensitivity of the image centroid position to the field angle.

At the program start-up the value of "pi" is set; the subroutine "czero()" is called which now, among other things, also sets the defaults for "itype(50)" and "imode(50)" to `flat' and `thru' respectively, for all surfaces; the defaults for "kmax" and "delta" are set to 50 and 1.d-7, respectively; the defaults for "zrange," "azim," and "elev" are set to 1.d50, 0 (zero), and 0 (zero) respectively; the default for "foclen" is set to 1 (one); the default for "nnrg" set to 1 (one); the default for "irstr" is set to 0 (zero) for no restore. Also, in LEN, RES, and PRE the subroutine "setcom()" is called. Additionally, the subroutine "czero()" is called in LEN.

The SOU command calculations were incorrect. This command has been deleted for the time being. The MAT command, which changes the values of the "rmat(3,3,50)" array, has also been removed since the "rmat(50)" values are computed from tilt and itilt values in the subroutine "setcom()."

In WSP, WS2, GRI, and GR2, the user is now able to temporarily set the radial limits independently of the radial limits on surface 1 (one) or simply check the radial limits by using the new command RMM (Radial Minimum and Maximum). The default limits, however, are the radial limits on surface 1 (one).

7. REVISION OF ON-LINE HELP

As changes, revisions and updates are made to the GT, the on-line help, user's manuals and related documentation must be revised and updated on an on-going basis. David Zissa (MSFC) had refined some of the wording and content of the on-line help document. At his request, his revised version of the help document was copied for use with GT.

The description of the new RMM command, which allows the user to temporarily set the maximum and minimum radii of the system (only from the WSP, WS2, GRI, and GR2 prompts), was added. The command menu was neatly arranged. Revisions were made to reflect changes in command syntax and function (e.g. with the modification to RES as detailed in the report on item 1). An example page from the revised on-line help is included as Appendix 2.

8. SOFTWARE TO PROCESS WYKO DATA

A new method has been developed to streamline the process of obtaining surface micro-roughness data for the modeling effort. The device used at MSFC to obtain the micro-roughness data is a WYKO TOPO2D non-contact surface profilometer. The WYKO is controlled by a computer/operating system which is not suitable for connection to a network and its floppy disks are in a format unreadable by the Sun workstations used by the Optical Analysis Group.

The method previously used to transfer data files from the WYKO to the Sun was to write the files to a specially-formatted high density (HD) floppy disk on the WYKO, transfer the floppy disk to a PC, copy the files to the PC's hard disk drive (HDD), and then transfer the files to a Sun workstation using file transfer protocol (ftp) over the network.

There are a few snags in this process. First, the specially formatted floppy disk cannot be read like a regular MS-DOS disk. Software called "WCOPY" (sold separately by WYKO) is needed to copy the files from the specially-formatted floppy disk to the PC's HDD. Second, there are significant limitations as to the number of files which can be transferred on a single floppy disk. These limitations are imposed by the size of the floppy disk itself and by the number of files which WCOPY can recognize on a single disk. Finally, once the data files were on the Sun workstation, the data contained in the files had to be extracted and written to a separate file in a format recognized by the processing software. Only then could processing and analysis begin.

To address these problems, a two part solution was implemented. Part one of the solution was to establish a serial data transfer link between the WYKO and a nearby, network-capable HP-UX (Hewlett-Packard UNIX) workstation. WYKO TOPO2D software incorporates XMODEM software for serial data transfers over an RS232 ("null modem") cable. To make the link work, XMODEM software was also needed for the HP-UX workstation. The appropriate software was obtained (via the Internet from a site in Japan using Mosaic on a Sun and a WWW search engine, downloaded, written to an MS-DOS HD floppy, copied from the floppy to the HP-UX workstation (not on the network at that time)) and installed on the HP-UX workstation. Also, the RS232 port on the HP-UX workstation was activated and configured to match the settings in the WYKO TOPO2D XMODEM software. While there is no batch mode for transferring files over the serial line, the user is limited only by the space on the HDD of the HP-UX workstation as to how many files can be transferred from the WYKO in one sitting. With the transfer rate set to 19200 baud (the upper limit of the WYKO), TOPO2D files (4608 bytes long) transfer in about 15 seconds. Once on the HP-UX workstation, the files are transferred, using ftp, to the Sun workstation where the modeling is being performed. The ftp software does allow batch transfers of virtually any number of files.

Part two of the solution was to enable the processing software ("psdgen_dfm") to read WYKO TOPO2D data files in their native format. (Previously, data contained in TOPO2D files had to be extracted and re-written to another file in a different format by a software utility called "2dfmat.")

The "psdgen_dfm" software can read in data sets which are to be used as either surface or reference surface data. There were initially two subroutines to read in surface data (rd_serr1.f and rd_topo2d_1_ref.f) and a single subroutine to read in surface reference data (get2d_ref.f). In order to use data from native TOPO2D files as surface data, software was modified in existing subroutines (e.g. main_dfm.f and readin_ref.f) to recognize the native TOPO2D files, and a subroutine was added (rd_topo2dn.f) to read the native TOPO2D files.

In order to use data from native TOPO2D files as reference surface data, the subroutine which reads in reference data (get2d_ref.f) was modified (and renamed get2dn_ref.f) to recognize and read in native TOPO2D data files.

The version of "psdgen_dfm" that has been modified in this manner can be found in zorro:/home/lhawkins/gpsd.

A user's guide was prepared which tells how to perform the serial data transfer, and how to understand the format and content of the TOPO2D (and TOPO3D) binary data files as transferred. Even though the RS232 link has already been set up, the process was quite involved. Therefore, a section has been included in the guide which details how to set up the link. The user guide explaining this serial data transfer procedure is attached as Appendix 3.

9. IRAF/PROS/STSDAS SOFTWARE

The delivery order also required the UAH to install the IRAF/PROS/STSDAS system of image processing software on the Sun computer used by the MSFC optical analysis branch. Also, interfaces were to be developed between the IRAF/PROS/STSDAS system and data involved with AXAF-I image quality analysis (GT).

The first step was to obtain the software from the various authors over the Internet. IRAF (the Image Reduction and Analysis Facility) is produced by NOAO (the National Optical Astronomy Observatories). IRAF is a package for general scientific data analysis and data reduction providing image processing and data reduction tools. The IRAF "environment" is a command driven shell, similar in appearance to the MS-DOS command prompt. PROS (Post-Reduction Off-line Software) is an x-ray analysis software package meant to be run from the IRAF environment. PROS, produced by SAO (the Smithsonian Astrophysical Observatory), provides tools which take into account the parts of image data peculiar to x-ray images, such as photon energy and arrival time. STSDAS (the Space Telescope Science Data Analysis System), produced by STScI (the Space Telescope Science Institute) is a used to calibrate and analyze data from the HST (Hubble Space Telescope). Like PROS, STSDAS is intended to be run from the IRAF environment. TABLES, also produced by STScI, must be installed in order for STSDAS to run. TABLES provides a means of working with tabular data as well as performing several other functions.

Correct versions (for the Sun/Solaris hardware/software platform) of the software were obtained from the anonymous ftp sites maintained by each entity. James Carter (MSFC), the system administrator for the Sun computers used by the optical analysis group, installed the software. IRAF & STSDAS/TABLES worked, but PROS would not. We found out from SAO that the version of PROS we had, 2.3, would not work with our SOLARIS operating system. SAO said we would have to wait for PROS 2.4 which would run under Solaris. PROS 2.4 was subsequently obtained, along with upgrades for IRAF, STSDAS, and TABLES, and all were installed by James Carter.

In order to interface the AXAF-I image quality analysis data with IRAF, software called "g2i" (gtray to intensity; g2i.c, 1556 lines) was developed. The g2i application allows a user to translate GT PSF output files (in ".gtray" format) into an "intensity" distribution in the FITS (the Flexible Image Transport System) format which is recognized by IRAF.

Appendix 1: Sample session of "psdgenc" and plots

An Example "psdgenc" Session

```
Script started on Fri Sep 27 18:22:42 1996
{zeus}:Lamar > psdgenc -ib

psdgenc: Plots on screen and to P.S. file.

Enter name of file to be processed
or enter 'stop' to end this session...t2d.test

avg            = 1.813048e-01 um
rms (about avg) = 2.363419e-02 um
rms (about 0)   = 1.828387e-01 um

Remove a polynomial fit from the data (y or n)?...y

Remove a polynomial of what degree (0-10)?...2

Press <RETURN> to display fitted data...

avg            = -1.620167e-16 um
rms (about avg) = 2.860366e-04 um
rms (about 0)   = 2.860366e-04 um

Apply a windowing function to the data (y or n)?...y

Apply what window (H1)?...H1

Press <RETURN> to display windowed data...

avg            = -7.271278e-06 um
rms (about avg) = 3.190401e-04 um
rms (about 0)   = 3.191229e-04 um

Press <RETURN> to display PSD data...

PSD rms = 3.187824e-04 um


Default Output File Name: t2d.psd.fits

Enter output file name or
<RETURN> to accept the default:
```

GT ".gtray" files contain information regarding the number of rays traced to produce the PSF and the number of x-ray energies at which the trace was performed. GT ".gtray" files also contain the following information for each of the ray intercepts recorded therein: x and y coordinates, slope w.r.t. the x and y planes, a "weight" for each x-ray energy level traced. Additionally, more than one PSF may be contained in a single ".gtray" file.

With g2i, the user is able to read a summary of information about each PSF in a ".gtray" file and elect either to bypass or process that PSF. The user then selects the energy levels for which a single "intensity" distribution will be produced. Next, the user has the opportunity to specify the size of the grid, and the size of the constituent pixels used to sample the PSF. Finally, the user is shown the percent of the rays and the percent of the effective area which are included in the "intensity" distribution. If desired, the user can adjust either the grid size, the pixel size, or both and resample the PSF.

A sample session of "g2i" software, and the plots obtained are included as Appendix 4.

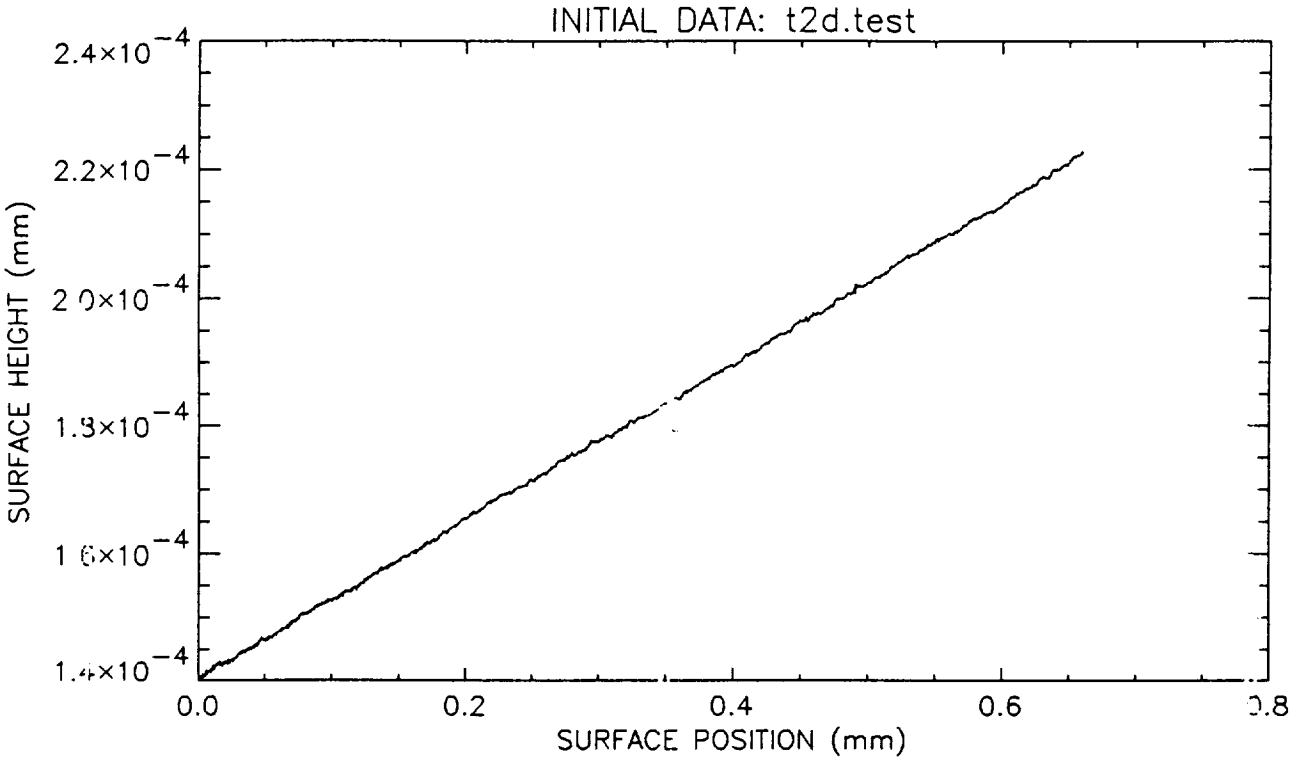
10. SUMMARY AND RECOMMENDATIONS

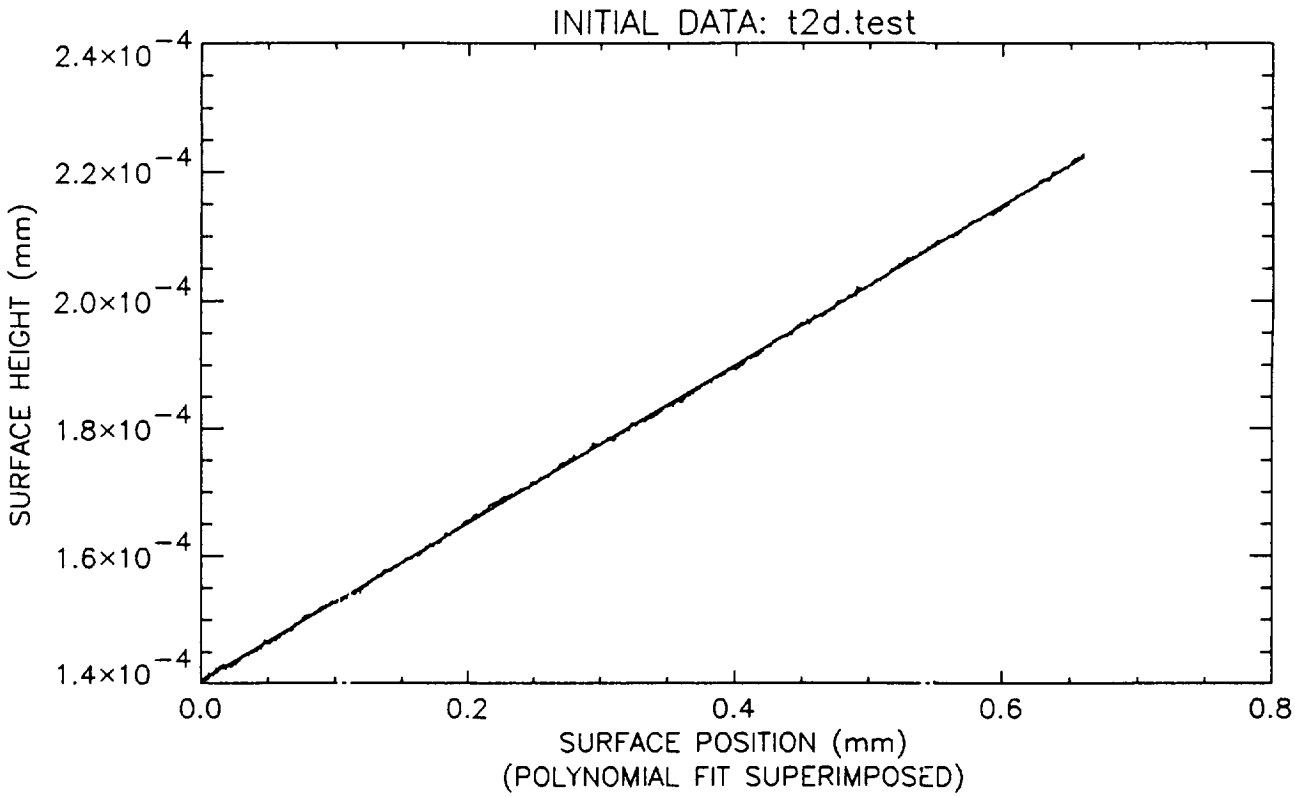
A number of significant analysis and modeling features have been added to the GT software such as processing of the HDOS mirror surface maps for raytracing and scattering predictions, and multishell imaging. The GT software has been debugged and upgraded to correct the errors that were discovered during use, and to reflect the new functions that were added. The online help has also been revised and updated to improve its wording and content, and by adding the description of new commands. A new method has been developed for the serial data transfer from WYKO to a network capable HP UNIX workstation. A number of software utilities have also been modified and developed to enable the processing software to read the native WYKO files. The latest version of IRAF/PROS/STSDAS system of image processing software was obtained, and was installed on ZEUS. An interface software utility has also been developed to translate the GT output files into FITS format, which can be read by IRAF.

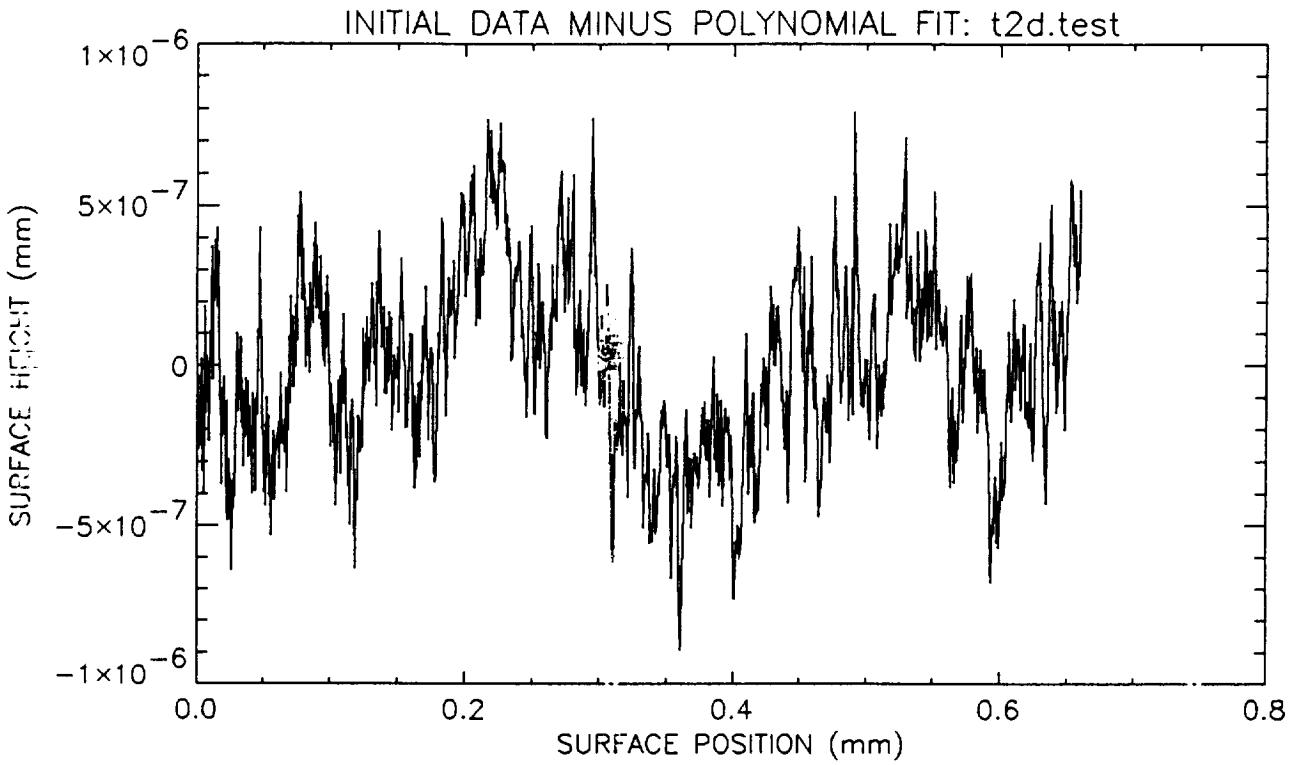
A number of new capabilities must be added to the GT program to enhance its modeling capabilities, and to include the features that are needed for image prediction in support of the AXAF-I HRMA x-ray testing. This includes developing the software and programs to compute the axial PSD's from HDOS mirror surface maps, and for plotting these surface maps and axial surface errors from "Big 8" scans. The PSD's from multiple mirror surface measurements must be organized and combined for input to the EEGRAZ program, which must also be modified to read in the FITS format PSD files.

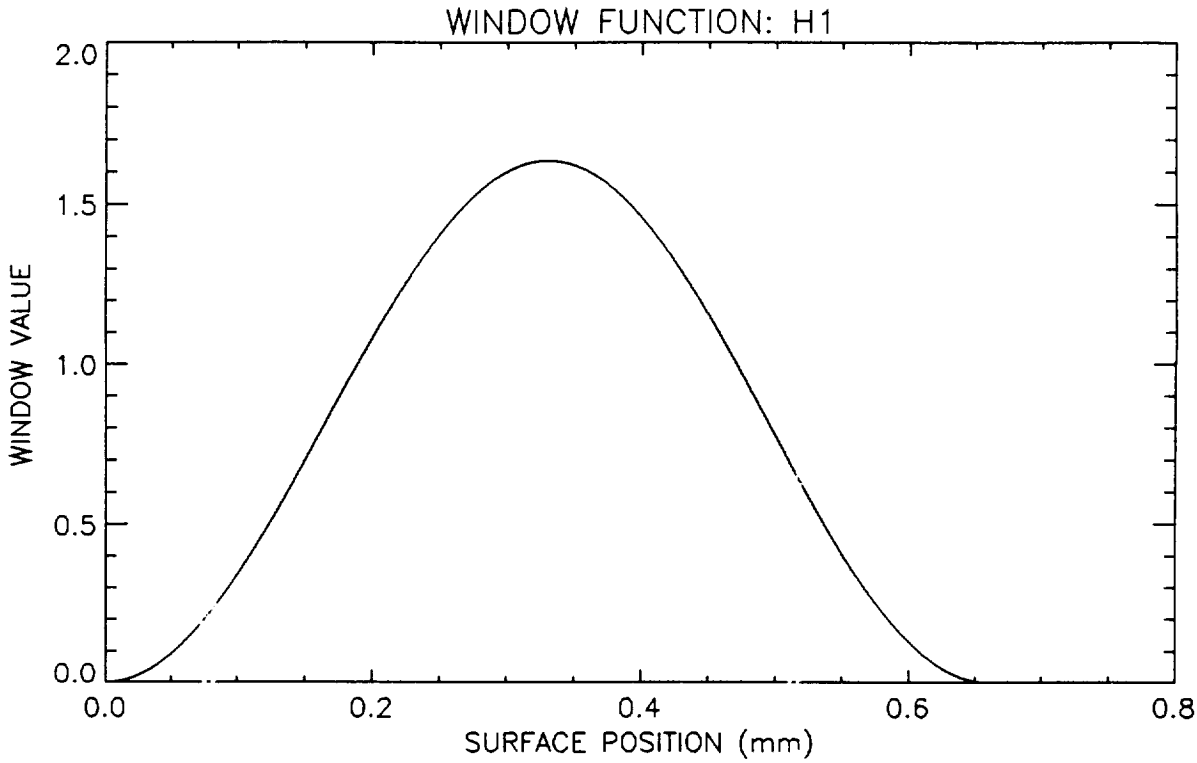
The existing features of the GT program must also be tested, debugged and upgraded, and some new function must be added to enhance the functionality and user-friendliness of the program. These may include optical system prescription insertion via spreadsheet; visual layout of the optical system in a meridional plane; visual display of the ray-trace overlaid on layout; encircled energy plots; and convolution of scattering distributions with spot diagrams.

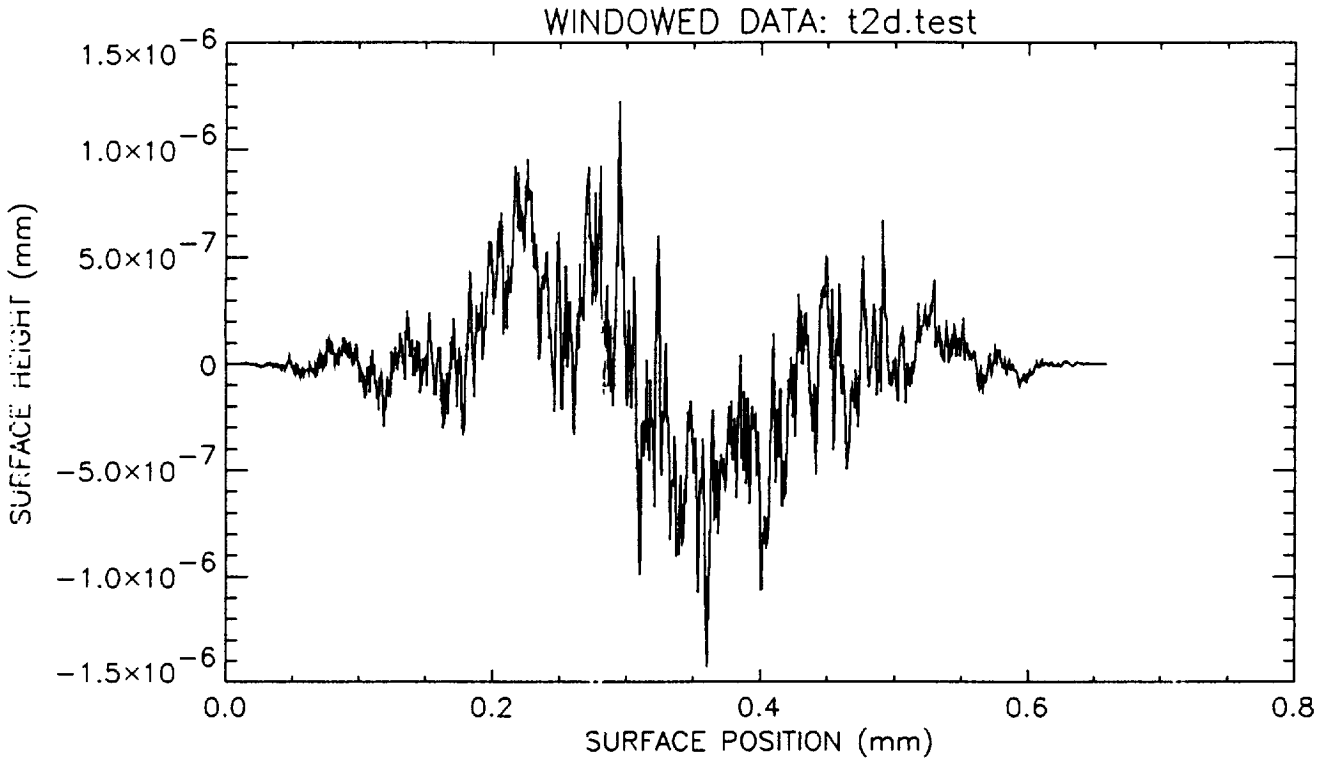
```
Do you want to enter comment lines (y or n)?...n


PSD data successfully written to file t2d.psd.fits


Enter name of file to be processed
or enter 'stop' to end this session...stop


psdgenc: done!

{zeus}:Lamar > exit
{zeus}:Lamar >

script done on Fri Sep 27 18:24:05 1996
```

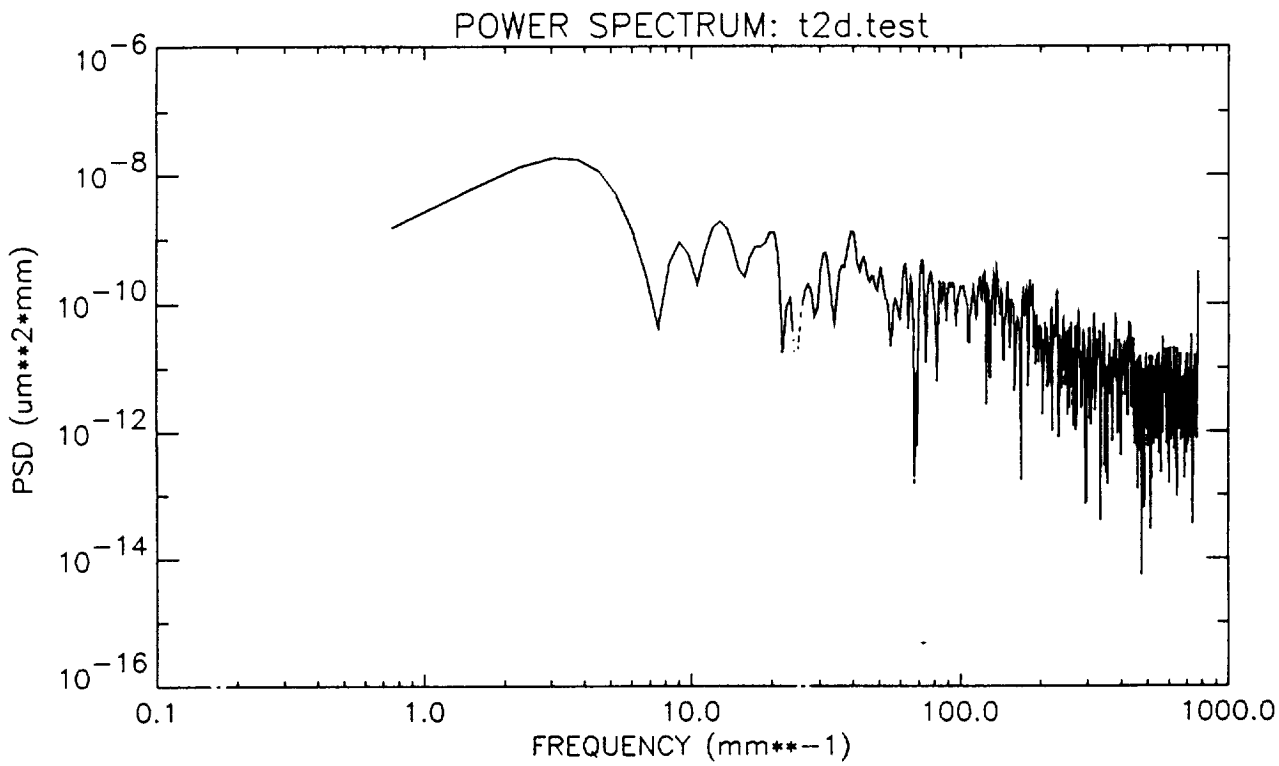

INITIAL DATA: t2d.test
SURFACE HEIGHT (mm)
2.4×10^-4
2.2×10^-4
2.0×10^-4
1.8×10^-4
1.6×10^-4
1.4×10^-4
0.0
0.2
0.4
0.6
0.8
SURFACE POSITION (mm)

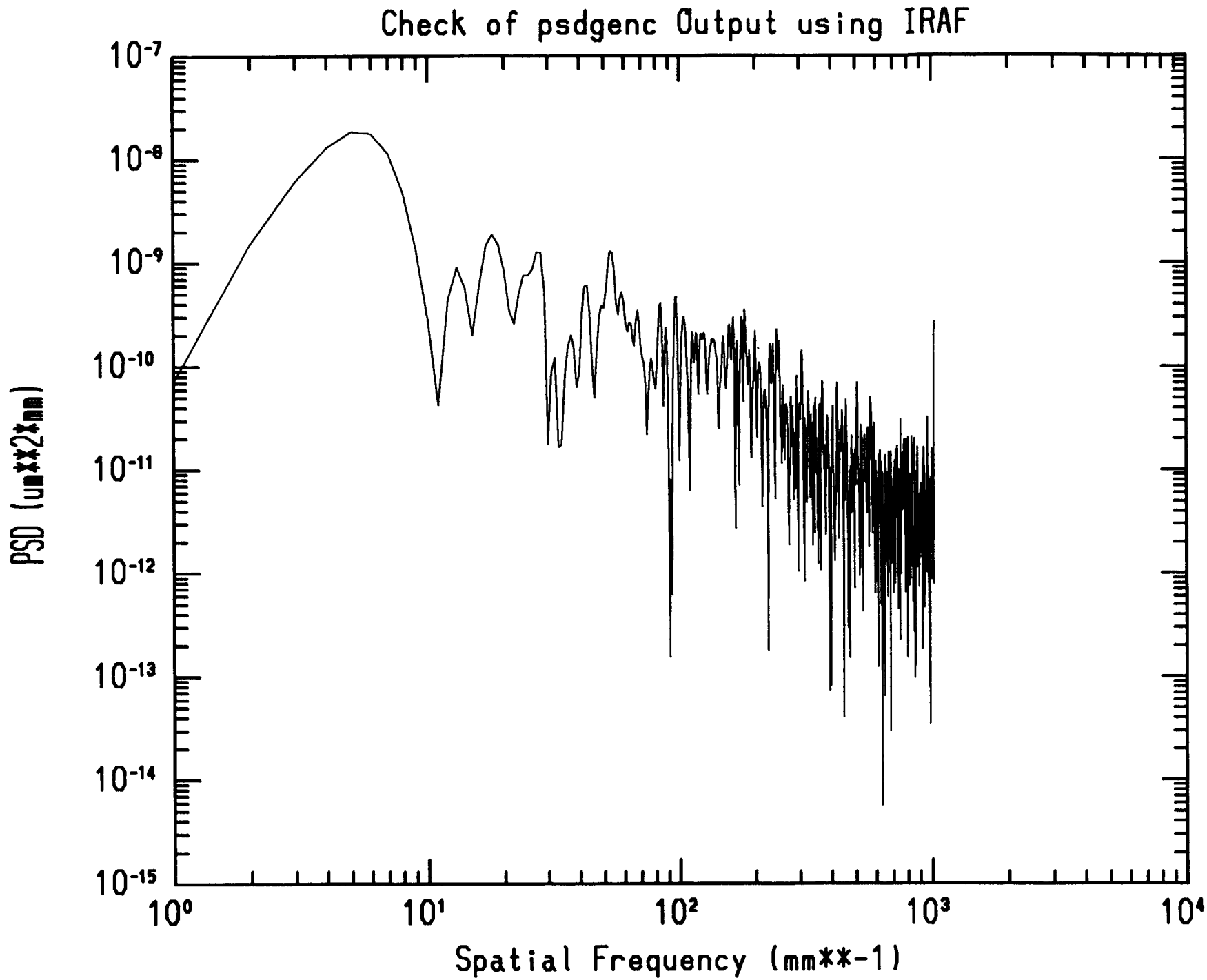

INITIAL DATA: t2d.test
2.4×10^-4
2.2×10^-4
2.0×10^-4
1.8×10^-4
1.6×10^-4
1.4×10^-4
SURFACE HEIGHT (mm)
0.0
0.2
0.4
0.6
0.8
SURFACE POSITION (mm)
(POLYNOMIAL FIT SUPERIMPOSED)


INITIAL DATA MINUS POLYNOMIAL FIT: t2d.test
1×10^−6
5×10^−7
0
−5×10^−7
−1×10^−6
SURFACE HEIGHT (mm)
0.0
0.2
0.4
0.6
0.8
SURFACE POSITION (mm)


WINDOW FUNCTION: H1
WINDOW VALUE
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
SURFACE POSITION (mm)


WINDOWED DATA: t2d.test
1.5×10^−6
1.0×10^−6
5.0×10^−7
0
−5.0×10^−7
−1.0×10^−6
−1.5×10^−6
SURFACE HEIGHT (mm)
0.0
0.2
0.4
0.6
0.8
SURFACE POSITION (mm)


POWER SPECTRUM: t2d.test
PSD (um**2*mm)
10^-6
10^-8
10^-10
10^-12
10^-14
10^-16
0.1
1.0
10.0
100.0
1000.0
FREQUENCY (mm**-1)


Check of psdgenc Output using IRAF
PSD (um**2*mm)
Spatial Frequency (mm**-1)
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^0
10^1
10^2
10^3
10^4

Appendix 2: Example of GT On-line Help

```
Script started on Tue Aug 27 17:09:41 1996
[1] 25351
{zeus}:Lamar > gt2
```

```
                    ****************************
                    *                          *
                    *         GrazTrace        *
                    *                          *
                    ****************************
```

```
GTRACE>hel res

     RES filspec [pre_num]

          Restore system from first prescription in
          a prescription file (by omitting pre_num) or
          restore specified prescription from
          prescription file.

          filspec - file name [80 char]
          pre_num - prescription number to be restored [int]

     See also: PRE, SAV, LIS.

GTRACE>hel msh

     MSH [shell1 [shell2...]]

          Activate multishell mode.
          (only at WSP random ray distribution prompt)
          To turn off multishell mode, leave the WSP
          option with CAN command.

          [The total number (NRA) of rays to be traced
           are equally divided among shells traced.]

          shell1,shell2 - integers denoting specific
          mirror prescriptions within a multishell
          prescription file which are to be traced.
          The shells are completely described by the
          contents of the file.
          (A multishell prescription file is a
           concatenation of single shell prescriptions.)

          MSH with no arguments activates multishell
          imaging and specifies that ALL shells in the
          current prescription file are to be traced.

     See also WSP.
```

```
GTRACE>exi
EXITING THE PROGRAM ? (Y/N)y
[1]  + Done                 perfmeter zeus
{zeus}:Lamar > exit
{zeus}:Lamar >
script done on Tue Aug 27 17:10:29 1996
```

Appendix 3: WYKO Data Transfer User Manual

WYKO DATA TRANSFER METHODS

Transferring Data Between TOPO2D V4.611 or TOPO3D V4.953 and HP-UX 9.0

Last Modification: 28 Aug 1996

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Section 5: Important Notes about the Transferred Files.

APPENDIX A (Copying Between the HP-UX HDD and MS-DOS HD Floppy Disk)

APPENDIX B (TOPO2/3D Binary Data File Formats)

INTRODUCTION

The purpose of this document is to detail several methods of transferring WYKO TOPO2D and TOPO3D data files to and from another computer. The main focus is a serial communication link which allows the transfer of WYKO data to another computer without the use of floppy disks. However, a method (other than WCOPY) of transferring WYKO data to another computer using a WYKO-formatted floppy disk is also covered.

SCOPE

This document specifically covers the transfer of WYKO TOPO2D V4.611 and TOPO3D V4.953 files to and from an HP9000 Controller 382 computer running HP-UX (Hewlett-Packard UNIX) version 9.0 August 1992. The procedures contained herein are only guaranteed to work for the versions of TOPO2D, TOPO3D, and HP-UX mentioned. Furthermore, some of the instructions given are specific to the WYKO-to-HP-UX serial communication link as implemented in the Optics and Radio Frequency Division at NASA/Marshall Space Flight Center.

HOW TO USE THIS GUIDE

Be sure that you understand the definitions on the following page. If the serial communication link between the WYKO and the HP9000/382 HP-UX 9.0 computer is already set up, skip to Section 2 for TOPO2/3D data transfer instructions. If the serial link is not set up, read Section 1 to find out how to establish the link or look in Section 5 to learn how to transfer files using a WYKO-formatted floppy disk. Both processes will be much easier if you read through all the instructions before attempting either form of data transfer.

DISCLAIMER

Some of the information contained herein has been copied verbatim from WYKO and Hewlett-Packard user manuals. This document is not intended for publication, but is simply a compilation and organization of information necessary to perform the specific task indicated in the introduction. Full acknowledgment is given to the respective authors for their work.

DEFINITIONS

The phrase "TOPO2D file" always refers to a full-size binary TOPO2D data file which is composed of a 400-byte header (160 8-bit character values + 20 64-bit double precision values + 20 32-bit (long) integers) and a 4096-byte data array (1024 x 32-bit (long) integer) for a total file size of 4496 bytes.

The phrase "TOPO3D file" always refers to a full-size binary TOPO3D data file which is composed of a 400-byte header (160 8-bit character values + 20 64-bit double precision values + 20 32-bit long integers) and a 118544-byte data matrix (248 x 239 x 16-bit (short) integer) for a total file size of 118944 bytes.

The expression "TOPO2/3D" means "either TOPO2D or TOPO3D."

stty </dev/ser0

Your results should be identical to those shown below.

speed 19200 baud; -parity hupcl
start = ^Q; stop = ^S; swtch = ^@
-inpck -istrip -ixon -opost
-isig -icanon -iexten -echo -echoe -echok

1.2: Obtain & Install the XMODEM Software on the HP-UX Machine

An xmodem software package that is ready for compilation on an HP-UX 9.0 system may be obtained using NCSA Mosaic or an equivalent World Wide Web browser. Set the browser up to download a binary file and tell it to open the following URL:

http://avalon.phys.hokudai.ac.jp/pub/hpux/Users/xmodem-3.9/xmodem-3.9-ss-8.07.tar.gz

The xmodem software is compressed using GNU gzip (hence the "gz" extension) which can be obtained from the anonymous ftp site prep.ai.mit.edu in the file /pub/gnu/gzip-1.2.4.tar

Once the file has been received, uncompress it by entering

gzip -d xmodem-3.9-ss-8.07.tar.gz

The compressed file will be replaced with the (uncompressed) file: xmodem-3.9-ss-8.07.tar.

Next, extract the archived files by entering

tar xvf xmodem-3.9-ss-8.07.tar

The tar process will create a directory named xmodem-3.9 in your current directory and place the rest of the extracted files there. Next, change to the xmodem-3.9 directory and enter the following command

make

This will "make" the executable (assuming that you have a cc compiler on your system). On my system, I received a warning that the compiler did not support one of the compiler options, -O (capital oh), but the software compiled just fine anyway. The -O option is probably just for optimization of the code.

Section 2: Transferring TOPO2/3D Data Files via RS232

When the WYKO is first booted up, it will automatically load the TOPO2D software. If you want to transfer TOPO3D files, wait until you see the TOPO2D main menu and type X to exit TOPO2D followed by Y to confirm the exit. You should now be in the Pascal operating system and the following line will appear at the top of the screen

Command: Compiler Editor Filer Initialize Librarian Run eXecute Version ?

This is the Pascal operating system command line. To run TOPO3D type X and then enter *:TOPO3D. The TOPO3D software should begin to run immediately and the main menu will appear within a few seconds.

If you are in TOPO3D but wish to transfer TOPO2D files, then go to the TOPO3D main menu and type X to exit TOPO3D followed by Y to confirm the exit. You will again be at the Pascal operating system command line. To run TOPO2D, type X and then enter *:TOPO2D. The TOPO2D software should begin to run immediately and the main menu will appear within a few seconds.

Next, locate the Digital Equipment Corp. LQPX2-SW switch box (a small, silver-colored metal box) to the left of the WYKO and set the switch to position B. The switch box allows the WYKO's RS232 port to be used both for controlling the WYKO's auto stage driver, when set to position A, and for transferring data, when set to position B. (IMPORTANT: Remember to set the switch back to position A when you are done transferring files!)

If you are transferring a TOPO2D file, continue reading with the following section. If you are transferring a TOPO3D file, skip to Section 2.3.

2.2: Setting up TOPO2D to Transfer Data Files via RS232

From the main TOPO2D menu, type N to go to the next menu and then type R to enter the RS232 communications menu. The TOPO2D RS232 communications menu is illustrated below. Select the settings as shown.

H: Header lines (sent)
C: separating Chars (0, 0, 0, 0, 0)
D: Data type (binary)
U: transfer or receive (data file)

Format:

B: Baud rate: (19200)
S: Stop bits (1 stop) L: character Length (8-bits)
Y: paritY (none) O: sOftware protocol (xmodem)

R: Ready to (transmit)

If you are going to receive a TOPO2D file, then type R to toggle the "Ready to (----)" item from "transmit" to "receive." Next, press E to begin the transfer and one of the following will occur. If you are transmitting a file, you will be given a listing of stored data files available for transfer. Select a TOPO2D file to transfer with the arrow keys and press <RETURN> which will cause the WYKO to write "Press Any Key To Begin Transfer" to the screen. DO NOT PRESS A KEY YET! If you are receiving a TOPO2D file, you will be prompted to enter a file name for the incoming data. Enter the file name and the WYKO will write "Press Any Key To Begin Transfer" to the screen. Here again, DO NOT PRESS A KEY YET! Now, skip to Section 3.

2.3: Setting up TOPO3D to Transmit Data Files via RS232

From the main TOPO3D menu, type N to go to the next menu and then type R to enter the RS232 communications menu. The TOPO3D RS232 communications menu is illustrated below. Select the settings as shown.

N: Numeric data set (all data)
H: Header lines (sent)
C: separating Chars (0, 0, 0, 0, 0)
D: Data type (binary)
U: transfer or receive (data file)

Format:

B: Baud rate: (19200)
S: Stop bits (1 stop) L: character Length (8-bits)
Y: paritY (none) O: sOftware protocol (xmodem)

R: Ready to (transmit)

If you are going to receive a TOPO3D file, then type R to toggle the "Ready to (----)" item from "transmit" to "receive." Next, press E to begin the transfer and one of the following will occur. If you are transmitting a file, you will be given a listing of stored data files available for transfer. Select a TOPO3D file to transfer with the arrow keys and press <RETURN> which will cause the WYKO to write "Press Any Key To Begin Transfer" to the screen. DO NOT PRESS A KEY YET! If you are receiving a TOPO3D file, you will be prompted to enter a file name for the incoming data. Enter the file name and the WYKO will write "Press Any Key To Begin Transfer" to the screen. Here again, DO NOT PRESS A KEY YET! Now, go on to Section 3.

Section 3: Setting Up the HP-UX Computer to Receive a TOPO2/3D Data File

Log in (as user wyko) on the HP-UX computer. Upon logging in, you will be placed in your home directory (/users/wyko) Since your home directory may vary, we will use $HOME to refer to it. If you are going to transfer TOPO2D files, change to the directory $HOME/t2data. If you are going to transfer TOPO3D files, change to $HOME/t3data.

If you are **receiving** a TOPO2/3D file from the WYKO, type the command shown below at the command line on the HP-UX computer, replacing "file" with the name of the file in which you want the received data to be stored.

rx file

If you are **transmitting** a TOPO2/3D file to the WYKO, type the command shown below at the command line on the HP-UX computer, replacing "file" with the name of the file that you want to send.

sx file

Once you've typed one of the above commands, press <RETURN> on the HP-UX computer, then walk immediately over to the WYKO and press any key there to begin the transfer. A counter will appear on the WYKO screen indicating the number of 128 byte data blocks which have been transmitted or received. For a TOPO2D file the number of blocks will range from 0 to 35 and the transfer will take only a few seconds. For a TOPO3D file, the number of blocks will range from 0 to 929 and the transfer will take about one minute and fifteen seconds. When the transfer is successfully completed, the WYKO will display a message to that effect and the command prompt will return on the HP-UX computer.

Now, take a moment to read Section 5 for some important notes about the transferred files.

Section 4: Transferring TOPO2/3D Files Using a WYKO-formatted Floppy

The intent of this section is to provide the uninitiated user with enough information to be able to carry out the following tasks without having to refer to any other source of documentation. To this end, procedures that can also be found in the WYKO TOPO2/3D manuals are detailed here. The disk to be used should be a standard 3.5 inch, double-sided HD (High Density) floppy disk. **NOTE**: Please be aware that the WYKO TOPO2/3D software is run under the Pascal operating system. The Pascal operating system references disk drives and files in a manner that is very different from both the MS-DOS and the UNIX operating systems. So, it will take time before you feel comfortable looking for and copying files under Pascal.

4.1: Formatting the WYKO Floppy

Insert the floppy disk into the WYKO's 3.5 inch floppy disk drive. From the main menu of either TOPO2D or TOPO3D type N to select "Next menu." Then type CTRL U to select "system Utilities," and from this menu, type M to choose Mediainit. At the prompt "Volume ID ?," enter the floppy drive volume number preceded by # (e.g. #3). Press <RETURN> again to confirm the initialization. When prompted to enter the format option, select the default format option, 0 (zero). When prompted to enter the interleave factor, select the default interleave factor, 2. The disk initialization process will begin and should be finished in about two minutes.

4.2: Listing TOPO2/3D Files on the WYKO HDD

To list the contents of a directory on the WYKO HDD (hard disk drive), first enter the system utilities menu as described in Section 4.1 above, but this time type F to select Filer. Next, type L to select List Dirs. You will be prompted "List what directory ?" at which point you should enter the full file descriptor (file path) of the directory to be listed. For example,

VOL:PATH

where VOL is the name of the HDD volume (or HDD partition) and PATH is the full file descriptor for the directory. The contents of the directory will be displayed to you one screenfull at a time. Type Q to quit Filer.

4.3: Copying TOPO2/3D Files From the WYKO HDD to a WYKO Floppy Disk

To copy a single file from the WYKO HDD (hard disk drive) to a WYKO-formatted floppy disk, first enter the system utilities menu as described in Section 4.1 above, but this time type F to select Filer. Next, type F to select Filecopy. You will be prompted "Filecopy what file ?" at which point you should enter the full file descriptor (file path) of the file to be copied. A file descriptor consists of a volume name, followed by a colon, followed by a path. For example,

VOL:PATH

where VOL is the name of the HDD volume (or HDD partition) and PATH is the full path to the file, including the file name. If you are copying a file from the current working volume, VOL can be eliminated from the file descriptor. If you are also copying from the current working directory, all of PATH can be eliminated except for the file name itself.

Next, you will be prompted "Filecopy to what ?" at which point you should enter the full file descriptor to which the file will be copied. For example, assuming your floppy disk's volume name is V3

V3:PATH

or, to copy the file under its original file name, simply type

V3:$

If you want to copy many, but not all, files from the HDD to the floppy disk, first type F to select Filecopy. You will be prompted "Filecopy what file ?" at which point you should enter the volume name, a colon, the PATH, and a question mark, like this

VOL:PATH/?

Next, you will be prompted "Filecopy to what ?" at which point you should enter the floppy disk volume name, a colon, and a dollar sign. For example, assuming that your floppy disk's volume name is V3, you would enter

V3:$

Now you will be prompted, one by one, with the names of all the files in VOL and asked if you want each particular file copied. Respond to each prompt by typing either a Y or N. Finally, when you have responded to all the file names, you will be asked if you want to proceed with copying the files. Respond with either a Y or N. All the files which you selected will be copied to the floppy disk under their original names.

If you want to copy all the files from a particular volume and path then, when you are prompted "Filecopy what file ?"enter

VOL:PATH/=

and when prompted "Filecopy to what ?" enter

V3:$

Now, all the files on volume VOL in directory PATH will be copied to the floppy disk under their original names. When you are done copying files, type Q to quit Filer.

4.4: Listing Files on a WYKO Floppy under HP-UX

Under HP-UX 9.0, floppy disks which have been formatted for use with HP's Pascal operating system (the system used by the WYKO) can be read from, and written to, using LIF (Logical Interchange Format) utilities.

To list the contents of a WYKO floppy disk, first insert the disk into the HP-UX's 3.5 inch floppy drive. Then enter

lifls -l /dev/fdd0:

and a detailed listing of all the files on the floppy disk will be displayed.

4.5: Copying TOPO2/3D Files From a WYKO Floppy Disk to HP-UX HDD

To copy a TOPO2/3D file from a WYKO floppy disk to the HP-UX computer in your current working directory, insert the WYKO floppy disk into HP-UX's 3.5 inch drive and enter

lifcp /dev/fdd0:SRCFIL ./DESTFIL

where /dev/fdd0 is the device file for the HP-UX's 3.5 inch floppy drive. Of course, you should replace "SRCFIL" with the name of the file on the WYKO floppy disk that you want to copy, and replace "DESTFIL" with the name you want the file to have on the HP-UX computer.

Now, take a moment to read Section 5 for some important notes about the transferred files.

4.6: Copying TOPO2/3D Files From HP-UX HDD to a WYKO Floppy Disk

To copy a TOPO2/3D file from the HP-UX computer to a WYKO floppy, insert the WYKO floppy disk into the HP-UX's 3.5 inch drive and enter one of the following

For TOPO2D files:
lifcp -r -T -5622 -i 0x1190 SRCFIL /dev/fdd0:DESTFIL

For TOPO3D files:
lifcp -r -T -5622 -i 0x1d0a0 SRCFIL /dev/fdd0:DESTFIL

this time replacing "SRCFIL" with the name of the file on the HP-UX computer that you want to copy to the WYKO floppy disk, and replacing "DESTFIL" with the name you want the file to have on the WYKO floppy disk. You must use the lifcp options shown above, otherwiseTOPO2/3D won't be able to recognize the file. These options are explained below.

-r Forces RAW mode copying.

-T Forces the file type of the LIF directory entry to be set to the argument given. (For TOPO2/3D files, the type is -5622)

-i Sets the implementation field of the LIF directory entry to the argument given. (For TOPO2D files, the implementation value is 0x1190... for TOPO3D files, the implementation value is 0x1d0a0)

Section 5: Important Notes about the Transferred Files.

A TOPO2D file resident on either the WYKO HDD or a WYKO floppy disk, has a file size of 4496 bytes. However, when the file is transferred to the HP-UX computer, either by xmodem over the RS232 cable or using a WYKO floppy disk and lifcp, the file is padded at its end such that its size in bytes is an integer multiple of 128. This results in a file length on the HP-UX HDD of 4496 + 112 = 4608 bytes. When the transfer is done via xmodem, the 112 padding bytes are decimal 26 (SUB) characters. If you use the WYKO floppy disk and lifcp for the transfer, the padding bytes are decimal 64 (@) characters.

A TOPO3D file resident on either the WYKO HDD or a WYKO floppy disk, has a file size of 118944 bytes. However, when the file is transferred to the HP-UX, either by xmodem over the RS232 cable or using a WYKO floppy disk and lifcp, it is also padded such that its size in bytes is an integer multiple of 128. This results in a file length on the HP-UX HDD of 118944 + 96 = 119040 bytes. The 96 padding bytes are, here again, decimal 26 (SUB) characters if the transfer is done via xmodem, and decimal 64 (@) characters if you use the WYKO floppy disk and lifcp.

Once you have transferred your TOPO2/3D files to the HP-UX computer, either by xmodem over the RS232 cable or using a WYKO floppy disk and lifcp, you can then use ftp to bulk transfer all of them to any computer connected to the Internet to which you have access. Please do transfer your TOPO2/3D files to the computer of your choice, and then remove the copies from the HP-UX HDD. This will keep the HP-UX HDD clean and make it easier for others to use this data transfer capability.

APPENDIX A

Copying Between the HP-UX HDD and MS-DOS HD Floppy Disk

One final note: the HP-UX computer can also read from and write to MS-DOS-formatted 3.5 inch HD floppy disks. This capability provides a way to transfer data from the HP-UX HDD to another UNIX machine which uses IEEE format numeric data and can read MS-DOS floppy disks. However, if you want to use the data on a PC, the bytes of the data will have to be reversed.

To list the contents of an MS-DOS disk, insert the disk into the HP-UX's 3.5 inch drive and enter the following

```
dosls -l /dev/fdd0:
```

A detailed listing of the contents of the disk will be displayed.

To copy files **from** the MS-DOS disk **to** the HP-UX HDD enter

```
doscp /dev/fdd0:/SRC ./DEST
```

replacing SRC with the path to the file(s) on the MS-DOS disk that you want to copy, and replacing DEST with the file name(s) or directory to which you want the file(s) to be written on the HP-UX HDD.

To copy files **to** the MS-DOS disk **from** the HP-UX HDD enter

```
doscp SRC /dev/fdd0:/DEST
```

this time replacing SRC with the path to the file(s) on the HP-UX computer that you want to copy and replacing DEST with the file name(s) or directory to which you want the file(s) to be written on the MS-DOS disk.

APPENDIX B

TOPO2/3D BINARY DATA FILE FORMATS

TOPO2/3D binary data files are composed of two parts: 1) a 400-byte header and 2) a data array (TOPO2D) or a data matrix (TOPO3D). The formats are detailed below. For a detailed explanation of what each of the values represents, see either the TOPO2D manual (Appendices F and G) or the TOPO3D manual (Chapter11).

TOPO2D Binary Data File

The TOPO2D 400-byte header is composed of 160 bytes of ASCII values, 160 bytes of 64-bit real values (i.e. 20 double precision numbers), and 80 bytes of 32-bit integer values (i.e. 20 long integers). What follows is a specific description of these values.

Byte Number	Contents
1-20	Title
21-25	Observation Time (hh:mm, in 24-hour mode)
26-33	Observation Date (mm/dd/yy)
34-113	Comment
114-153	UNUSED
154-159	Type of File (i.e TOPO2D)
160	Version number (a single ASCII character)

Real Number (Bytes 161-320)	Variable
1	Wavelength (nm)
2	Magnification
3	UNUSED
4	Left tilt pixel
5	Right tilt pixel
6	Stage x coord
7	Stage y coord
8-20	UNUSED

Integer Number (Bytes 321-400)	Variable
1	Number of [data] arrays
2	Array_size
3	UNUSED
4	Current left pixel
5	Current right pixel
6-7	UNUSED

8	Flags Bit 1: User tilt on Bit 2: Leveling on Bit 3: Tilt on Bit 4: Curvature on Bit 5: UNUSED Bit 6: UNUSED Bit 7: Reference subtracted Bit 8: UNUSED
9	Multiplier
10	Modulation Threshold
11	Number of measurements averaged
12-20	UNUSED

The TOPO2D data array immediately follows and is composed of Array_size 32-bit integers (1024 maximum). These integers may be converted to a surface height in nanometers by multiplying by (Wavelength/(2*Multiplier)).

TOPO3D Binary Data File

The TOPO3D header, like the TOPO2D header, is composed of 160 bytes of ASCII values, 160 bytes of 64-bit real values (i.e. 20 double precision numbers), and 80 bytes of 32-bit integer values (i.e. 20 long integers). However, there are a few differences between the two headers. A detailed description of the TOPO3D header follows.

Byte Number	Contents
1-20	Title
21-25	Observation Time (hh:mm, in 24-hour mode)
26-33	Observation Date (mm/dd/yy)
34-113	Comment
114-153	UNUSED
154-159	Type of File (i.e TOPO3D)
160	Version number (a single ASCII character)

Real Number (Bytes 161-320)	Variable
1	Wavelength (nm)
2	Magnification
3	Zero level
4	X tilt
5	Y tilt
6	Stage x coord (um)
7	Stage y coord (um)
8	Pixel spacing (40 um)

9	Wedge (0.5)
10-20	UNUSED

Integer Number (Bytes 321-400) Variable

1	Number of [data] arrays
2	X-width of array
3	Y-width of array
4	X data start
5	X data finish
6	Y data start
7	Y data finish
8	Flags Bit 1: User fit Bit 2: UNUSED Bit 3: UNUSED Bit 4: UNUSED Bit 5: UNUSED Bit 6: UNUSED Bit 7: Reference subtracted Bit 8: Terms removed/data analyzed
9	Full Wave Value
10	Modulation Threshold (% * 100)
11	Number of measurements averaged
12-20	UNUSED

The TOPO3D data matrix immediately follows and is composed of X-width of array * Y-width of array 16-bit integers (248 * 239 = 59272 maximum). (The data matrix is stored in row major order.) The integers may be converted to a surface height in nanometers by multiplying by (Wavelength*Wedge/(Full Wave Value)).

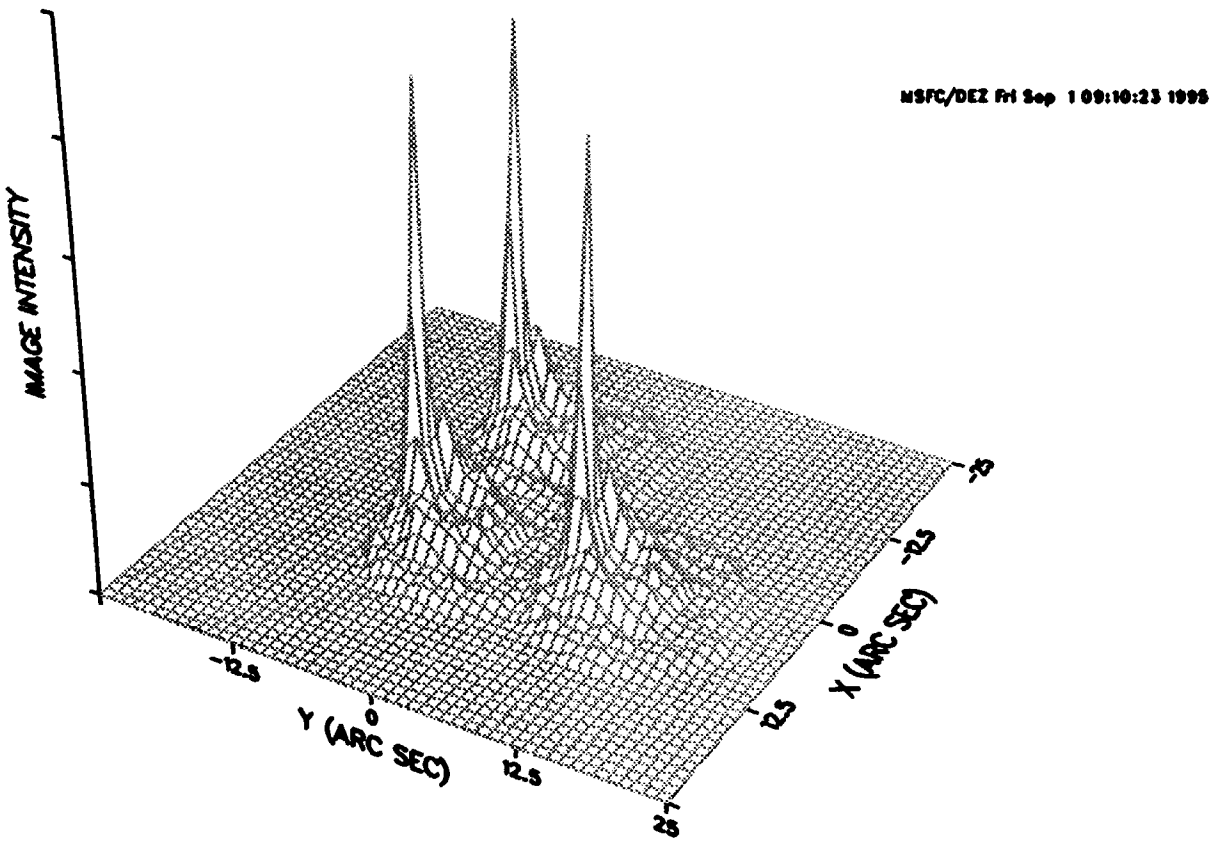
Appendix 4: Sample session and plots of "g2i"

```
Script started on Wed Aug 28 09:12:23 1996
[1] 27285
{zeus}:Lamar > g2i test.gtray


******************************
FILE: test.gtray
PSF #: 1

Number of rays:       30000
Number of energies:       1
The z-shift:         0.0000e+00
The focal length:    6.5738e+02
Number of comments:      20
******************************

Process this PSF (y or n)?...y

Select an(other) energy level at which to convert
the weighted PSF into an intensity distribution.
Enter 'a' to select all. Enter 'q' to quit.

----------------------------
Energy level  1: 1.4867e+00
----------------------------

Enter selection 1: 1


The following 1 energy levels were selected

----------------------------
Level  1: 1.4867e+00
----------------------------

Are these okay (y or n)?...y


**************************************************

FILE: test.gtray

ENERGY: 1.486700e+00 (keV)

The current bin dimensions are:

bin_xdim = 0.002000
bin_ydim = 0.002000

**************************************************

Change these values (y or n)?...n


**************************************************

FILE: test.gtray

ENERGY: 1.486700e+00 (keV)

The current grid dimensions are:

grid_xdim = 101
grid_ydim = 101

**************************************************
```

```
Change these values (y or n)?...y

Enter grid_xdim (integer value): 51

************************************************

FILE: test.gtray

ENERGY: 1.486700e+00 (keV)

The current grid dimensions are:

grid_xdim = 51
grid_ydim = 51

************************************************

Change these values (y or n)?...n

************************************************

Results of calculating the intensity distribution

FILE: test.gtray

ENERGY: 1.486700e+00 (keV)

bin_xdim: 0.002000
bin_ydim: 0.002000

grid_xdim: 51
grid_ydim: 51

Percent of rays included: 95.39

Percent effective area included: 95.81

************************************************

Are these results acceptable (y or n)?...n

************************************************

FILE: test.gtray

ENERGY: 1.486700e+00 (keV)

The current bin dimensions are:

bin_xdim = 0.002000
bin_ydim = 0.002000

************************************************

Change these values (y or n)?...n

************************************************

FILE: test.gtray

ENERGY: 1.486700e+00 (keV)
```

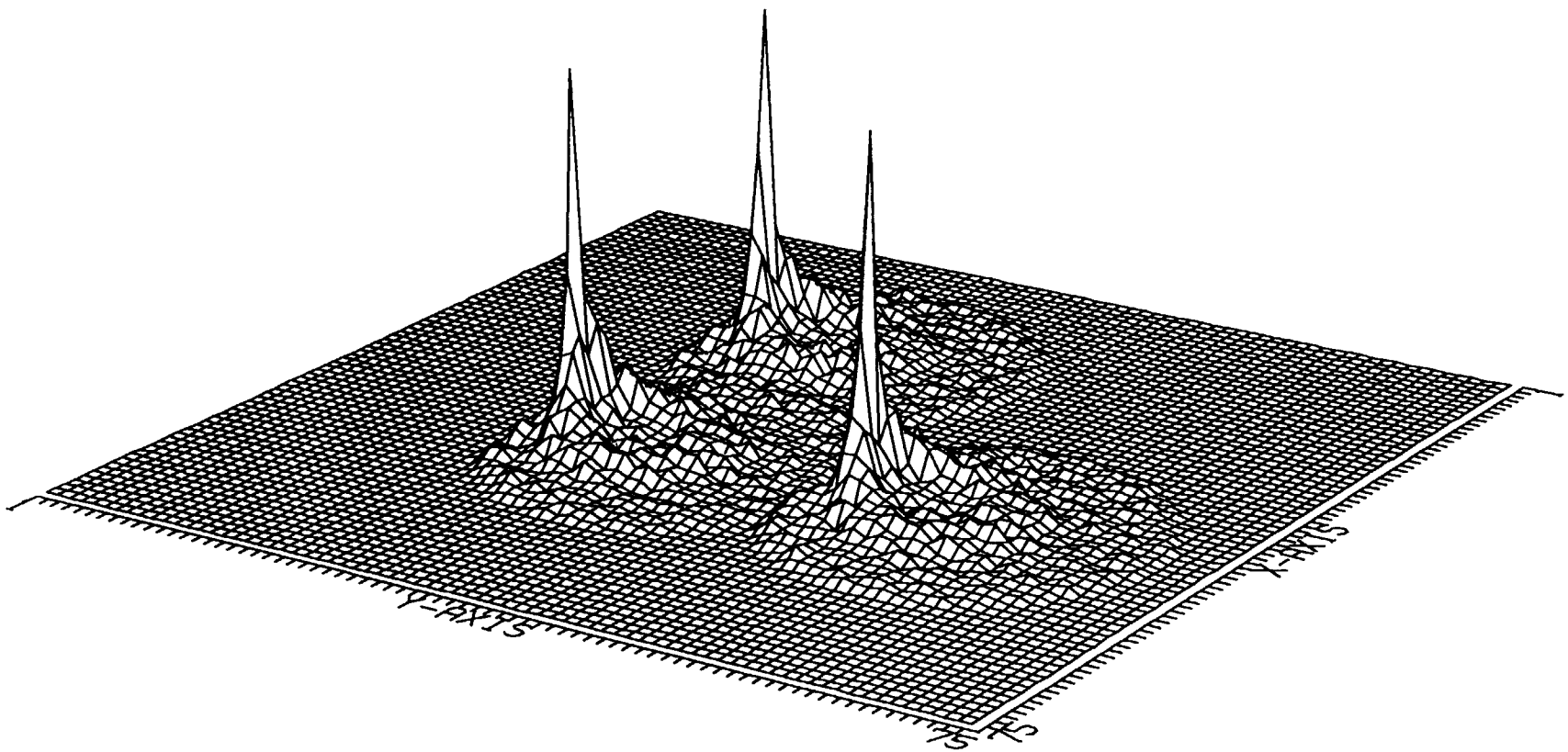
```
The current grid dimensions are:

grid_xdim = 51
grid_ydim = 51

************************************************

Change these values (y or n)?...y

Enter grid_xdim (integer value): 75


************************************************

FILE: test.gtray

ENERGY: 1.486700e+00 (keV)

The current grid dimensions are:

grid_xdim = 75
grid_ydim = 75

************************************************

Change these values (y or n)?...n


************************************************

Results of calculating the intensity distribution

FILE: test.gtray

ENERGY: 1.486700e+00 (keV)

bin_xdim: 0.002000
bin_ydim: 0.002000

grid_xdim: 75
grid_ydim: 75

Percent of rays included: 100.00

Percent effective area included: 100.00

************************************************

Are these results acceptable (y or n)?...y

EOF encountered while searching for PSF # 2: test.gtray

g2i: done!

[1]  + Done                    perfmeter zeus
{zeus}:Lamar > exit
{zeus}:Lamar >
script done on Wed Aug 28 09:13:43 1996
```

input file: sxi.mult.net.gtray



peak intensity= 812956.
effective focal length= 657.375 rays= 30000 energy= 1.48670 keV
image centroid (x,y)= -8.37038E-02 15.0763 (arc minutes)

GRAZTRACE-to-IRAF Example



Appendix 5: A Copy of the paper presented at the SPIE Annual Conference at Denver, CO, August 1996

Performance modeling of grazing-incidence optics with structural deformations and fabrication errors

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ABSTRACT

In-house optical performance modeling is being done at Marshall Space Flight Center (MSFC) in support of the development, fabrication, and testing of the Advanced X-ray Astrophysics Facility - Imaging (AXAF-I). Specialized software for modeling grazing-incidence x-ray telescopes is being developed by MSFC with assistance from the University of Alabama in Huntsville. Interfaces between the optical model and the mirror surface metrology and the predictions of structural/thermal deformation models have been developed. The mirror surface measurements were provided by the mirror manufacturer. A structural model of the AXAF-I High Resolution Mirror Assembly (HRMA) has been developed at MSFC. The AXAF-I system, optical modeling software, and the image effects of specific mirror figure errors are discussed. In particular, the optimization of the alignment of the as-built mirrors and prediction of the x-ray image effects of the x-ray ground test configuration are described.

Keywords: x-ray optics, grazing-incidence optics, optical analysis, fabrication errors, structural deformations, finite-element analysis, integrated system modeling, alignment, calibration, AXAF-I

1. INTRODUCTION

The Advanced X-ray Astrophysics Facility - Imaging (AXAF-I) is a large high resolution x-ray telescope system to be launched into earth orbit in the fall of 1998. It is required to have an image resolution of about 0.5 arc seconds. Marshall Space Flight Center (MSFC) is managing the project. This paper is a report on the in-house x-ray optical modeling at MSFC done as a cross check on the image modeling being done by the organizations involved in constructing the system. The prime contractor is TRW Space and Technology Group. The mirrors were manufactured by Hughes Danbury Optical Systems (HDOS). Eastman Kodak Company (EKC) is currently assembling the mirrors into the High Resolution Mirror Assembly (HRMA). The Smithsonian Astrophysical Observatory (SAO) is providing scientific and engineering support.

Although the image modeling process for grazing-incidence x-ray optics is similar to that of normal-incidence optics, it requires specialized software that is not commercially available. This is because of the short x-ray wavelengths and the unusual geometry of the nearly cylindrically shaped mirrors. The initial version of the software was written in 1991 for modeling the image of the x-ray ground test of the largest of the four concentric mirror pairs for AXAF-I. That test system was called the Verification Engineering Test Article-I (VETA-I). The VETA-I test is described in a report[1] by SAO which supplied the detectors. MSFC modeling of that system is described in a paper[2] on the ring-focus portion of the VETA-I test. Since that time MSFC has further developed[3] the optical model and has been assisted by the University of Alabama in Huntsville. In this report, the AXAF-I x-ray optical system, MSFC modeling software, and examples of using the software are discussed. The first example is the use of the HDOS mirror figure measurements in determining the optimal alignment of the as-built mirrors. The second example is the use of structural model results to predict the effects of the x-ray ground system test configuration on the image of the HRMA.

2. AXAF-I HIGH RESOLUTION MIRROR ASSEMBLY (HRMA)

The AXAF-I HRMA consists of four concentric paraboloid-hyperboloid mirror pairs. A diagram representing a side view of one mirror pair is shown in Fig. 1. The mirrors are made of Zerodur and the optical surfaces are coated with iridium. Each mirror is approximately cylindrical in shape and slightly cone shaped. The x-ray reflectivity is enhanced by the shallow grazing angles of the rays with respect to the mirror surfaces. The entrance aperture of each mirror pair is highly annular. The image intensities of the four mirror pairs add to increase the collecting area of the system as a whole. The diameters of the mirror pairs range from about 0.6 meters to about 1.2 meters; the length of each mirror is 0.8382 meters; and the effective focal length is 10.066 meters. The grazing angles range from about 0.85 degrees for the largest mirror pair to 0.45 degrees for the smallest mirror pair. The total on-axis geometric collecting area is about 1030 cm^2 allowing for vignetting by support structure. At lower x-ray energies down toward 0.1 keV the image of the largest shell predominates because it has the largest entrance aperture. At high x-ray energies up toward 10 keV, the image of the smallest shell predominates because it has the smallest grazing angle and thus relatively high reflectivity at high energy. The required resolution of the net image of the four mirror pairs is about 0.5 arc seconds for rays entering the system along the direction of the optical axis.

3. MODELING APPROACH

At x-ray wavelengths, pupil aperture diffraction effects are neglected. For the larger scale or figure errors the image effects are determined by tracing rays through the system to produce a geometric image. The figure errors are caused by surface fabrication errors and structural/thermal deformations.

The image effects of smaller scale surface errors and surface roughness are treated statistically with a scattering distribution. For grazing incidence, the scattering is mainly in the plane of reflection. The scattering is mainly caused by surface errors along the direction of the optical axis. The scattering distribution is computed by the EEGRAZ program[4] using the power spectral density of the small scale axial surface errors. This program is based on Beckmann-Spizzichino theory[5]. The power spectral density of the measured small scale surface errors is computed with software developed at MSFC.

Finally, the ray intercepts at the image plane are randomly perturbed according to the scattering distribution. Since the input rays to the system are also randomly distributed over the entrance aperture, this results in a Monte Carlo type model of the image. Typically, up to 200,000 rays are traced through a mirror pair.

4. APPLYING MIRROR FIGURE ERRORS TO RAY TRACE

The design prescription for the conic surface gives the radial distance R from the optical axis to the nearly cylindrical shaped inner surface of a mirror[3] as shown in Fig. 2. The conic surface equation is written in the form:

$$R = \sqrt{R_0^{\,2} + 2Sz - kz^2}\ . \qquad [1]$$

The position on the surface is given by the azimuthal angle θ and axial position z. R_0 is the radius at z=0; S is the subnormal at z=0; and $k=1-e^2$ where e is the eccentricity. The radii of the large scale or figure errors are added to the design radii. An iterative process is used to find the intersection of a ray with the surface. The figure errors are represented by a grid of radius errors. The figure errors are bilinearly interpolated during the ray trace. The grid can be made dense enough to adequately represent the mirror figure errors.

4.1 Preparation of mirror surface measurements for use in ray tracing

Several steps are taken in order to prepare the mirror surface measurement data for use in ray tracing. Units and coordinate systems must be converted. The smaller scale surface errors along the direction of the optical axis must be filtered out since their effects on the image must be included as a scattering distribution. The value of the highest spatial frequency allowable for geometrical analysis depends on the grazing angle, x-ray energy, and the magnitude of the surface errors. (An axial surface

error of a given spatial frequency can be included in the ray trace if the result doesn't differ from its physical optics effect as a diffraction grating by more than the required accuracy.) There is also an option in the software to remove low order polynomial terms of the axial surface errors during the process of filtering the data. The data must be interpolated onto an equally spaced output grid for a surface deformation file which the ray trace program uses. Currently, bilinear interpolation is used.

4.2 Preparation of structural deformation model output for use in ray tracing

The structural/thermal figure errors are prepared by reformatting the output files of Finite Element Analysis (FEA) models. There are currently provisions for reformatting the output of NASTRAN, EAL, and COSMOS/M programs. The processing is similar to that of the mirror measurement data. However, filtering out small scale errors is not necessary since structural/thermal surface effects are generally relatively large scale deformations that can be used in the ray trace. There is a provision in this software to expand data from models assuming 180 degree symmetry.

5. GRAZTRACE RAY-TRACE PROGRAM

The ray-trace program GRAZTRACE first reads in the system prescription and surface deformation files. The average radius, average axial slope, and axial depth of curvature can be included as terms added to the conic formula. The x-ray source position is defined. Surfaces can be tilted, rotated, and displaced. Up to 200,000 rays can be traced in a random or wheel-spoke pattern on the entrance annulus. Also, individual rays can be traced. Ray weights represent the entrance aperture area and surface reflectivity. The effective collection area of the system is the sum of the ray weights. The image can be focused for minimum RMS diameter. Effective focal length can be calculated from the image centroid displacement caused by a small change in field angle. Image RMS and encircled energy diameters are computed. Images can be plotted and the ray intercepts, slopes, and weights can be saved for further processing.

6. CONVOLVE PROGRAM

This program can convolve traced rays with a scattering distribution or an x-ray source size. Multiple rays can be generated by adding randomly from the scattering distribution. In addition, various artificially generated distributions such as gaussian and disc distributions can be convolved with the image. The program can also simulate detector output for circular and rectangular detector apertures. Image size parameters can be computed.

The AXAF-I mirrors are rougher near the ends of the mirrors. Therefore, there are plans to allow scattering to differ in regions on a mirror by perturbing ray directions within the ray trace program. The convolve program will still be useful for x-ray source size effects, simulating detector output, and convolving the image with various shaped distributions. Other effects that could be convolved with the traced rays are spacecraft pointing errors and aspect determination system errors.

7. OPTIMIZING AXAF-I HRMA ALIGNMENT (WITH AS-BUILT MIRROR SURFACES)

The idea here is to find the optimum paraboloid-hyperboloid alignment for each mirror pair of the AXAF-I HRMA which minimizes the image size with the measured as-built shape of the mirrors. The mirror figure errors were processed as described above from the mirror manufacturer's (HDOS) mirror surface error maps. For the alignment, axial regions near the ends of the mirrors were not used where the surface errors are relatively large. Also, axial surface errors with spatial periods shorter than 100 mm were removed from the surface maps. Reflectivity of the surface was taken as 100% for this analysis.

A diagram of the alignment geometry is shown in Fig. 3. First, the axial spacing was adjusted for minimum image RMS by using a function minimization program with the ray trace program. (The optimal axial spacing was not much affected by the relative rotation or clocking angle of the hyperboloid with respect to the paraboloid.) Then the system was ray-traced with the hyperboloid rotated or clocked at 1 degree increments. The clocking angle which gave the minimum RMS image size was chosen.

After the optimal axial spacings and hyperboloid clocking angles were chosen, the mirror pairs were ray-traced using the surface errors over the full axial lengths of the mirrors with spacial periods down to 33.528 mm in length. (The image plane locations were determined by refocusing with only the central 2/3 of the entrance aperture since that is the way in which they are going to be focused in the actual alignment process.) Fig. 4 shows a sample 3D plot of the radial errors over the inner surface of a cylindrical mirror from one of the mirror pairs. Here, the surface errors are shown in terms of azimuthal angle in radians and axial position in millimeters. Fig. 5 shows the corresponding geometric image of the mirror pair. Here, the image intensity is plotted vs. image plane location in arc seconds. This is not a full image prediction. This only includes the effect of fabrication errors with axial periods down to 33.528 mm over the full axial lengths of the mirrors. However, the relative merit of different alignments are compared below with the use of the surface errors processed in this manner.

The geometric images were predicted in the above manner for the MSFC optimized axial spacings and clocking angles and also for the somewhat different values that EKC is using to bond the mirrors in place. It turns out that the image quality is only moderately sensitive to the axial spacing between the paraboloid and hyperboloid. The image quality has very low sensitivity to the relative clocking angles of the mirrors. Although the EKC values are different from the MSFC optimized alignment values, the image quality is similar. Table 1 shows a comparison of the image RMS diameters for the different

TABLE 1. Geometric Image RMS Diameters (arc seconds) (MSFC modeling using surface errors with spatial periods down to 33.528 mm)

	SHELL 1	SHELL 3	SHELL 4	SHELL 6
KODAK	0.77	0.70	0.66	0.80
MSFC	0.75	0.72	0.54	0.75

alignments. The four mirror pairs are labeled shells 1,3,4, and 6 because there were six pairs in the original design of the system. The EKC alignment is judged to be acceptable although the MSFC alignment results are somewhat better for shell 4. Although the image is only moderately sensitive to axial spacing and rather insensitive to hyperboloid clocking, it is still critical to have the foci of the four mirror pairs at the same point.

In addition to the on-axis image size, the as-built effective focal length is of interest. The dependence of the displacement δ of the image centroid vs. field angle α in radians is determined by the effective focal length F_{eff} of a mirror pair as

$$\delta \cong F_{eff} \times \tan\alpha \ . \qquad [2]$$

This determines the off-axis alignment of the images of the four mirror pairs. Although for AXAF-I the primary consideration is on-axis image quality, the off-axis image quality is also important. Table 2 shows a comparison of the predicted as-built

TABLE 2. Effective Focal Lengths (mm) (MSFC modeling using surface errors with spatial periods down to 33.528 mm)

	SHELL 1	SHELL 3	SHELL 4	SHELL 6
KODAK	10077	10067	10065	10063
MSFC	10076	10066	10067	10062

effective focal lengths for the MSFC and EKC alignment values. The variation in the effective focal lengths is judged to be acceptable in either case since the resulting centroid shifts are small compared to the off-axis image sizes.

8. AXAF-I GROUND TEST (STRUCTURAL DEFORMATION EXAMPLE)

The MSFC structures group made up a model of the AXAF-I HRMA horizontal x-ray ground test configuration with the effects of gravity using the Finite Element Analysis program EAL. The gravity off-loading forces to be applied to the system

to reduce mirror displacements and deformations were included in the model. There were 7800 nodal points on a mirror surface. The output of the model was reformatted for input to the ray trace program. The optical model also included the finite distance of about 1731 feet from the x-ray source to the center of the mirror system. For this case, the reflectivity of the mirror surfaces was assumed to be 100%. Fig. 6 shows a plot of the radius errors over the interior surface of one of the mirrors. The largest magnitude radius error is caused by a rigid body displacement of the mirror. However, the image is particularly sensitive to slope errors along the direction of the optical axis. Fig. 7 shows a plot of the corresponding axial slope errors. The artifacts in the axial slope error plot near the center of the mirror at z=0 are related to the twelve mounting points of the mirror. A plot of the predicted net image of the four mirror pairs in the horizontal test configuration is shown in Fig. 8. This predicted image can be used in deconvolving the test effects for on-orbit image prediction. Table 3 gives the predicted fraction of image energy contained within selected image diameters.

TABLE 3. Encircled Energy Diameters (arc seconds) of Net Image due to X-ray Ground Test Configuration

10%	30%	50%	70%	90%
0.48	0.78	1.04	1.39	1.99

9. SUMMARY

MSFC is cross checking image modeling being done for the AXAF-I project. Examples of using the mirror figure errors have been given here. These two cases represent a check on the mirror alignment and interpretation of the x-ray ground test to be done this fall. This software also has applications to other x-ray systems. For example MSFC is fabricating and testing the Solar X-ray Imager (SXI) and is developing replicated x-ray mirror technology. Currently, the smaller scale and surface roughness data for the AXAF-I mirrors are being examined and the x-ray scattering software is being further developed. The predicted scattering will be convolved with the geometric image. An on-orbit thermal deformation model is being developed at MSFC. An interactive version of the x-ray image modeling software is also being developed by MSFC and the University of Alabama in Huntsville (UAH).

10. ACKNOWLEDGMENTS

We would like to thank the AXAF-I contractors TRW Space and Technology Group, HDOS, EKC, and SAO for data and for helpful discussions. We would also like to thank Larry Craig of MSFC for the structural model of the AXAF-I horizontal x-ray test configuration.

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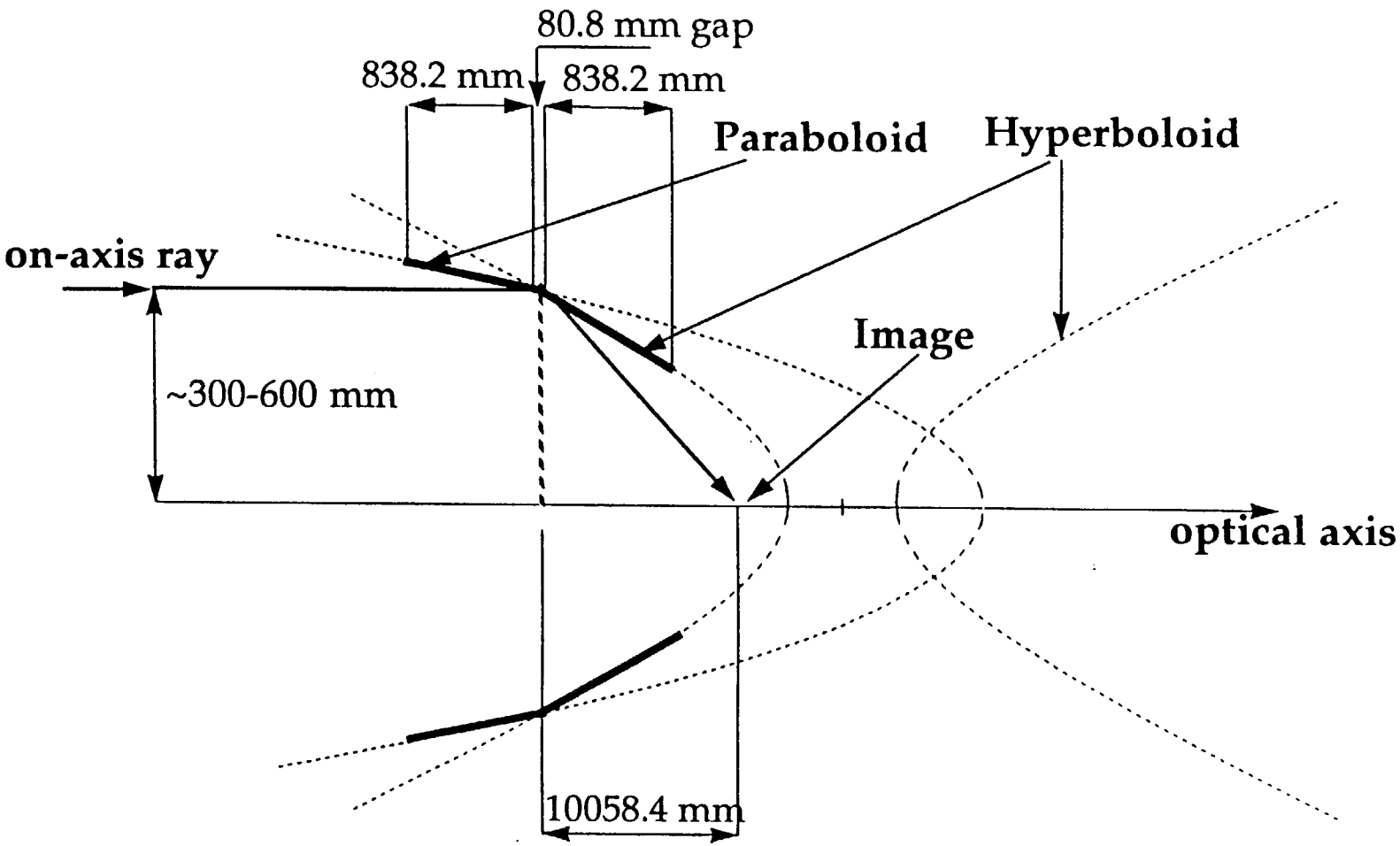

Fig. 1. A sectional side view of a typical mirror pair showing geometrical relationships.

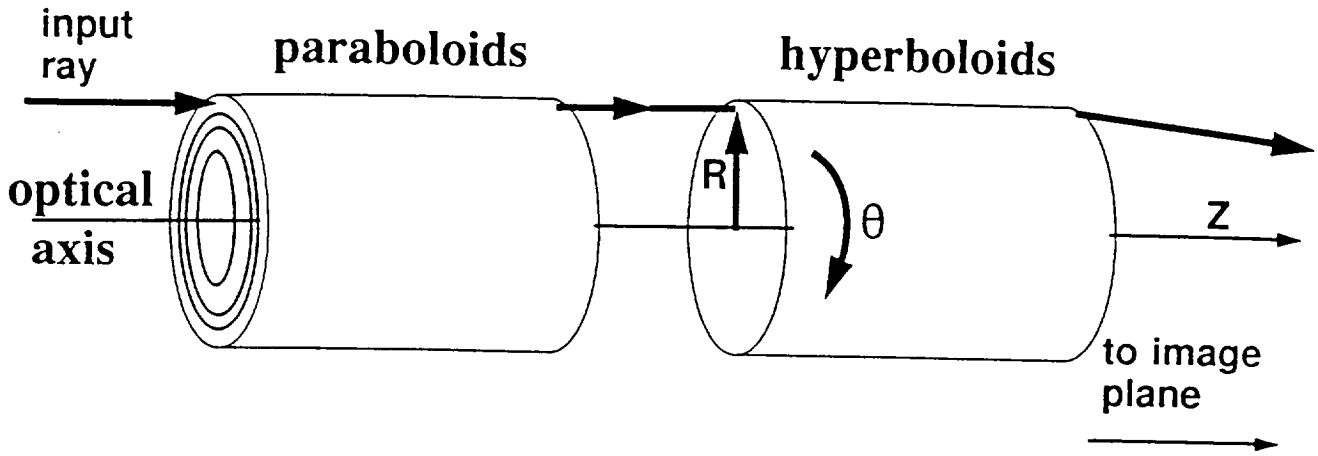

Fig. 2.The cylindrical coordinate systems employed for describing the optical design prescription.

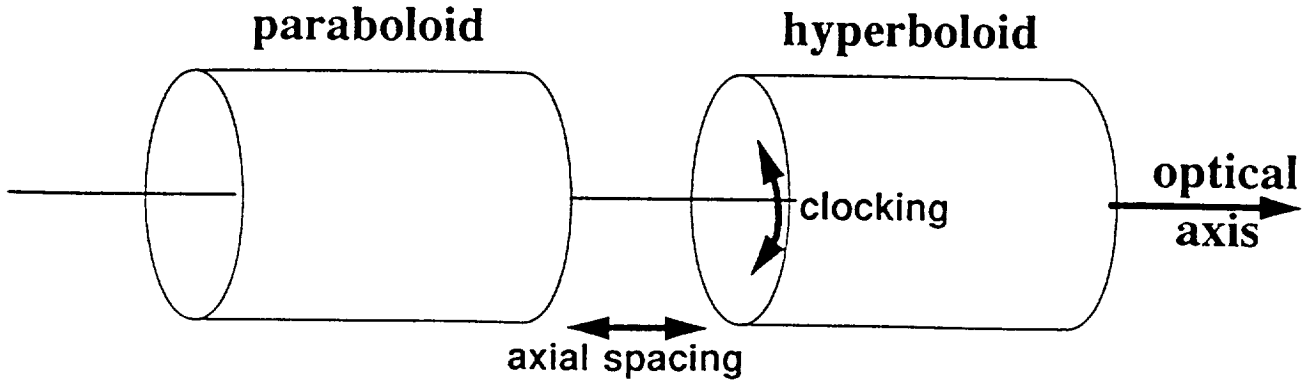

Fig. 3. The alignment geometry for a typical paraboloid-hyperboloid mirror pair.

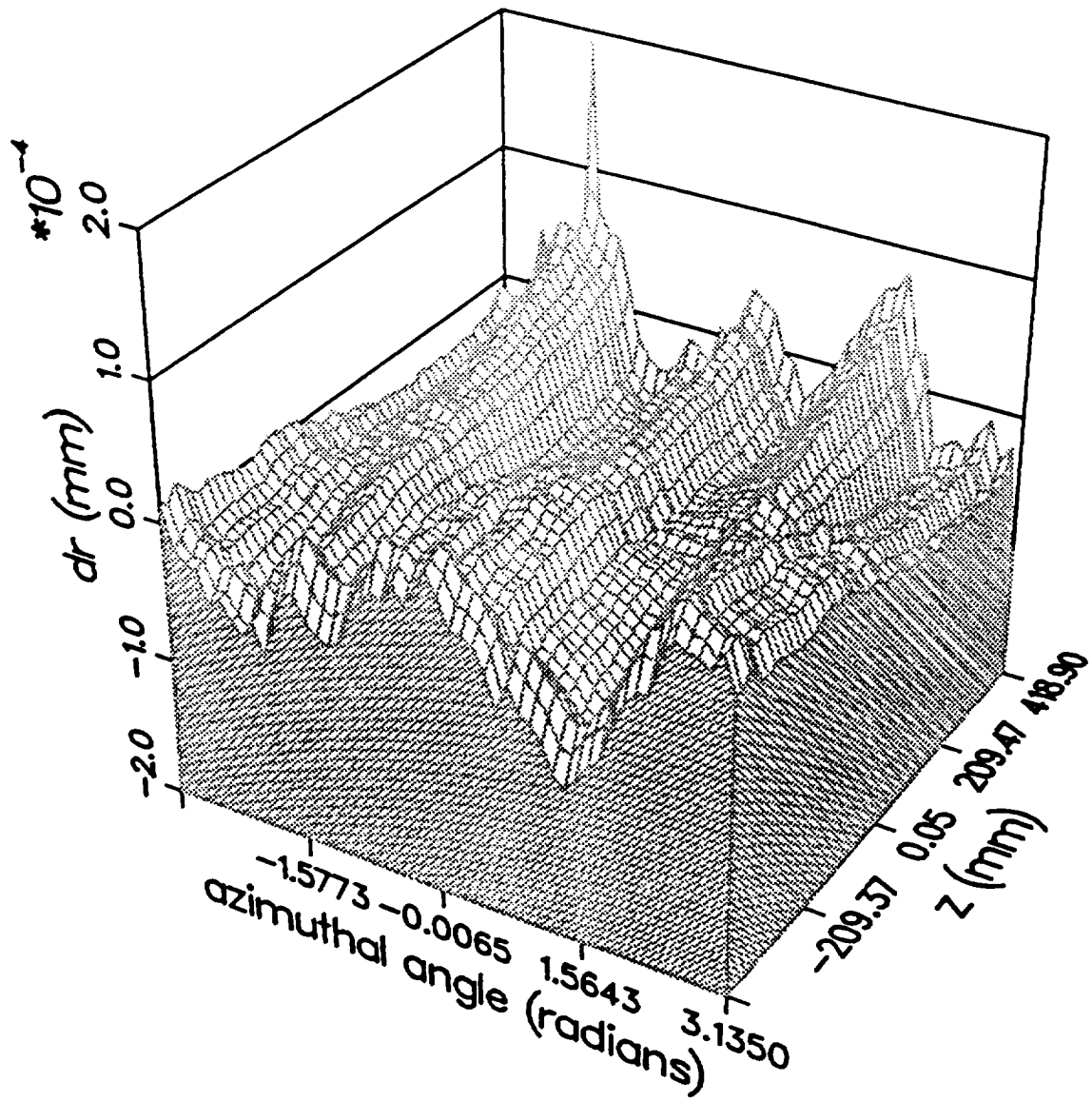

Fig. 4. A sample 3-D plot of radial deformations of a cylindrical mirror due to fabrication errors.

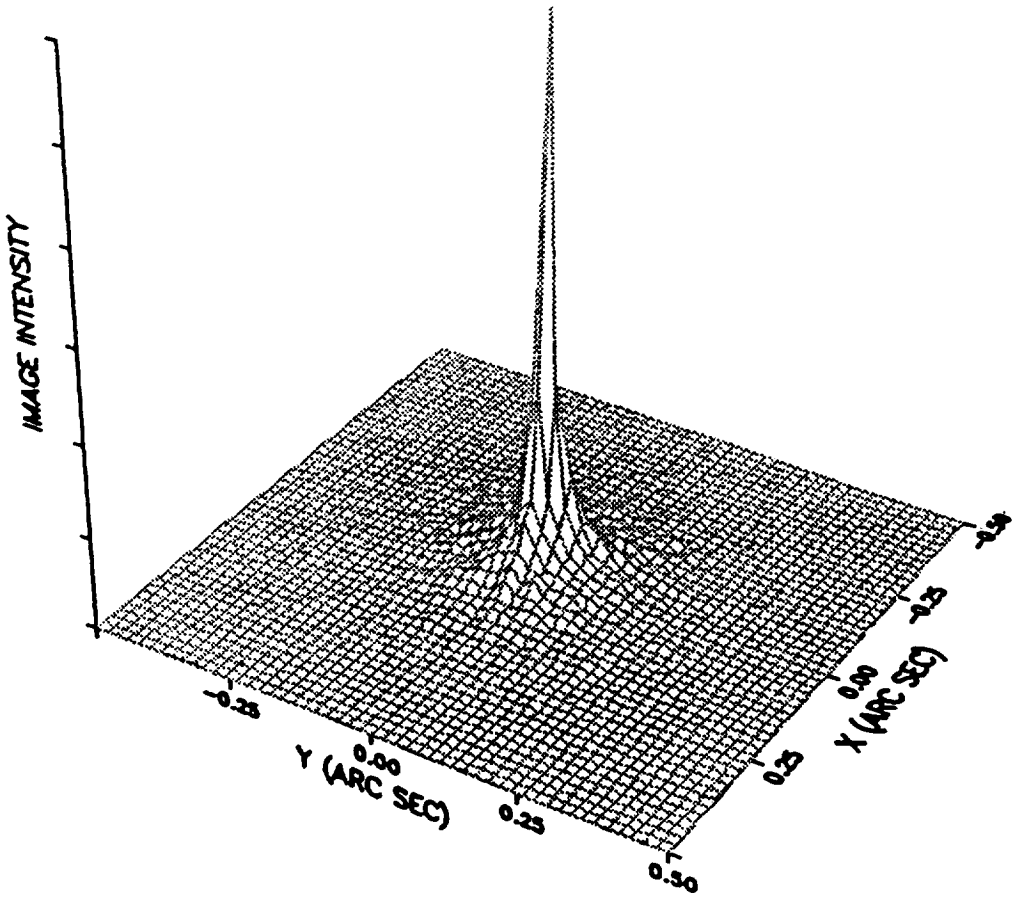

Fig. 5. A sample geometric image for a mirror pair due to fabrication errors.

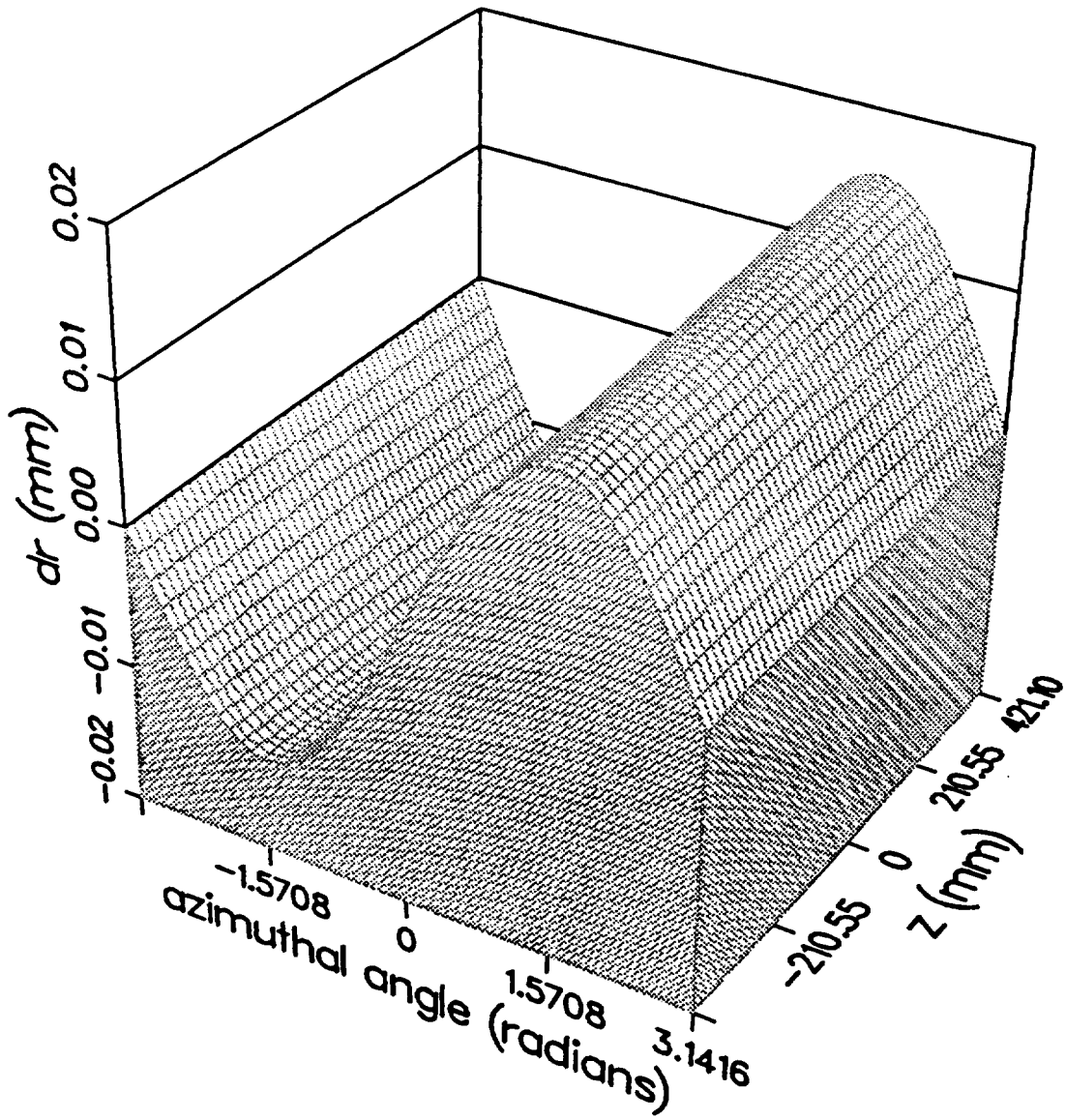

Fig. 6. Typical radial deformations predicted for a cylindrical mirror in the AXAF-I HRMA horizontal ground test configuration

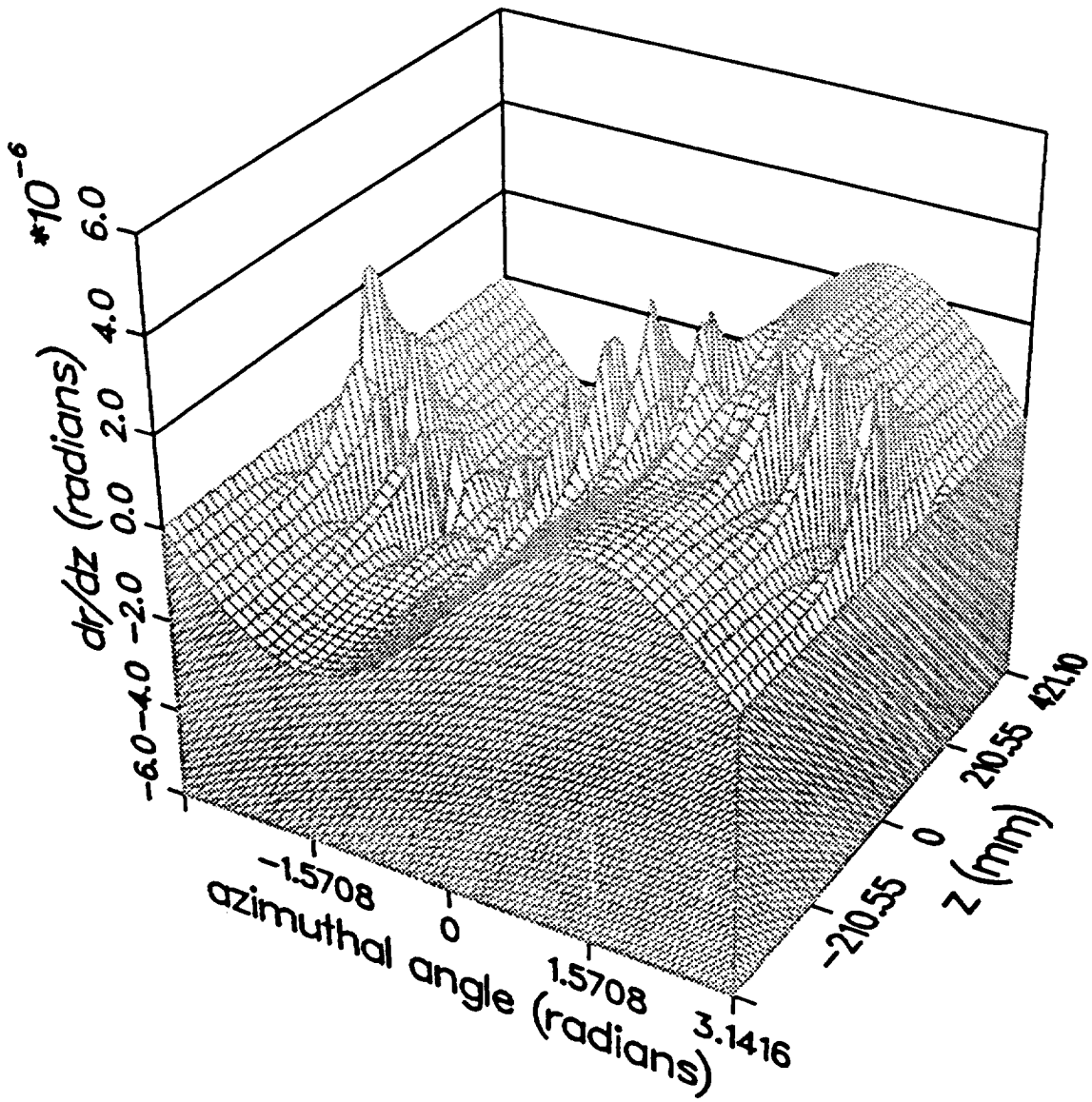

Fig. 7. Typical slope errors predicted for a cylindrical mirror in the AXAF-I HRMA horizontal ground test configuration.

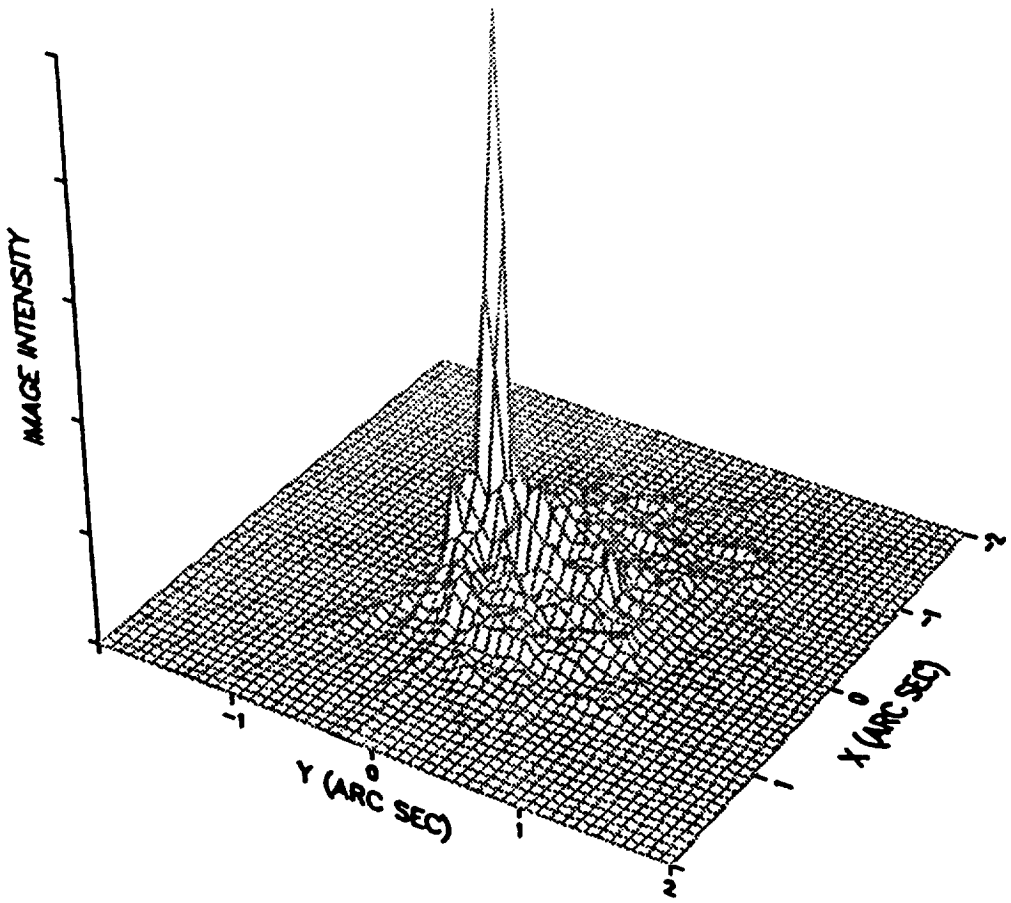

Fig. 8 The predicted net image of the four mirror pairs due to the horizontal ground test configuration.

Space Agency

Report Document Page

1. Report No. 6	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Development of Software to Model AXAF-I Image Quality		5. Report Due 10/4/96
		6. Performing Organization Code University of Alabama in Huntsville
7. Aurthor(s) Dr. Anees Ahmad and Lamar Hawkins		8. Performing Organization Report No. 6
		10. Work Unit No.
9. Performing Organization Name and Address University of Alabama in Huntsville Huntsville, Alabama 35899		11. Contract or Grant No. NAS8-38609, D.O. 145
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-001 Marshall Space Flight Center, AL 35812		13. Type of report and Period covered Final, 5/7/95-9/30/96
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

PLEASE SEE PAGE ONE OF THE REPORT.

17. Key Words (Suggested by Author(s)) X-ray telescopes, x-ray optics, grazing incidence optics, finite-element analysis metrology surface maps, ray tracing, multishell imaging, metrology data processing, WYKO data transfer, post-analysis image processing	18. Distribution Statement

19. Security Class. (of this report)	20. Security Class. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	64	

NASA FORM 1626 OCT 86