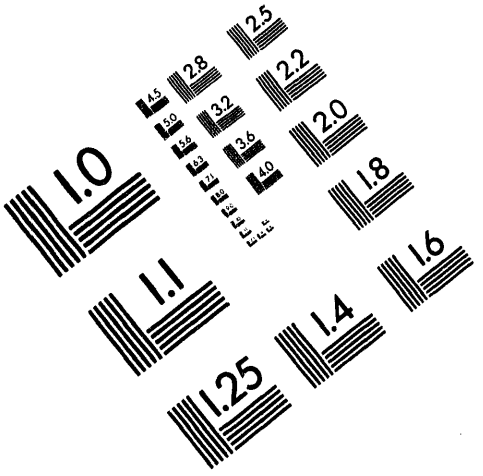

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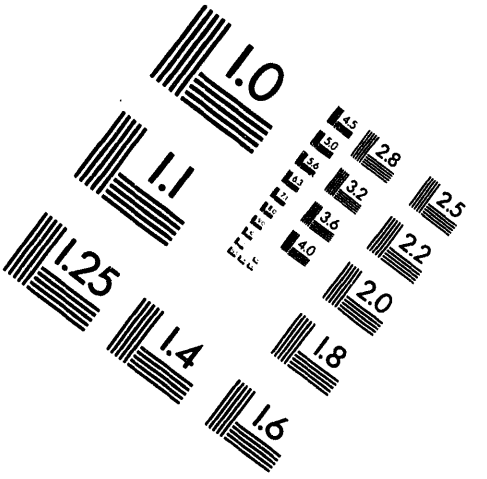

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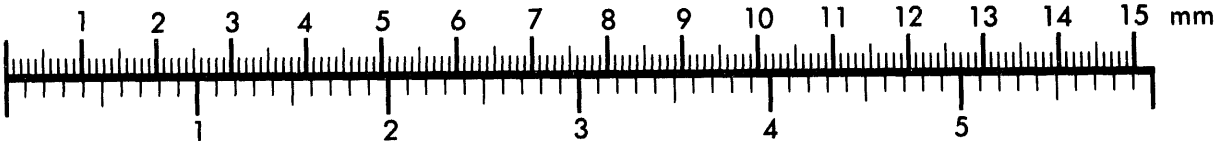

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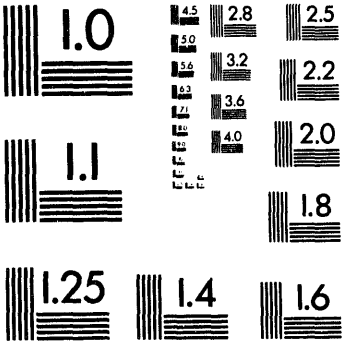

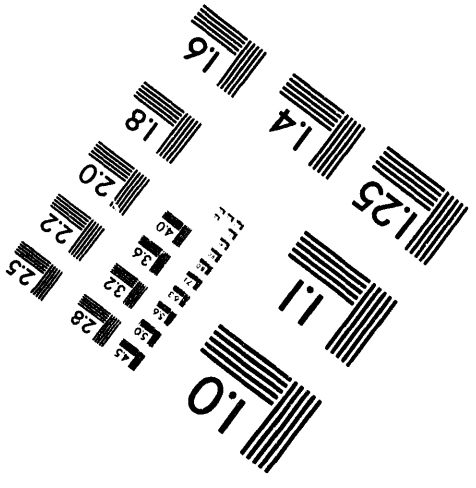

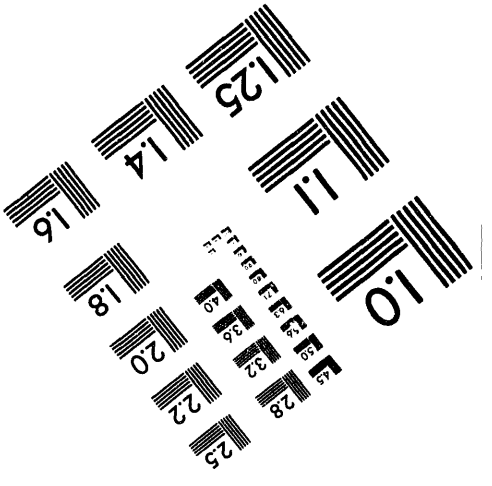

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Development, Fabrication, and Metrology of the Electro-Optical Breadboard Model for the Reflection Grating Array of the XMM Grating Spectrometer

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ABSTRACT

A prototype array consisting of eight diffraction gratings has been fabricated for the XMM Reflection Grating Spectrometer. A component of the full spectrometer is an array of approximately 200 diffraction gratings. The diffraction gratings were produced using lightweight silicon carbide substrates and a replication technique. The prototype array was developed and assembled using the same tolerances as the flight arrays which have typical tolerances of 3 μm in translation and sub-arc seconds in rotation. The metrology applied during inspection and assembly included precision linear measurements, full aperture figure measurements, and angular interferometry.

Key words: X-ray spectrometers, diffraction gratings, light weight optics, precision measurements, snap-together optics.

1. INTRODUCTION

This paper will describe the development and assembly of the Electro-Optical Bread Board (EOBB) module, a prototype diffraction grating array. The module was part of the EOBB x-ray experiment conducted at the Panter test facility in November 1993. A description of the integrated x-ray test is given in Bixler, et al[1]. The EOBB module represents a small portion of the Reflection Grating Array (RGA). In this paper, the RGA and its components will be described, followed by a description of the EOBB module including its flight and non-flight components. In order to assemble the EOBB module to the tight tolerances of the flight array, specific equipment and metrology techniques were utilized during the assembly process. After assembly of the EOBB module, a grazing incidence optical light test was performed and the results analyzed to verify the assembly process.

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2. REFLECTION GRATING ARRAY

The RGA consists of approximately 200 diffraction gratings, mounted behind a grazing incidence telescope, arrayed on the surface of a torus such that the angle of incidence of the incoming converging light is the same for each grating (see Figure 1).

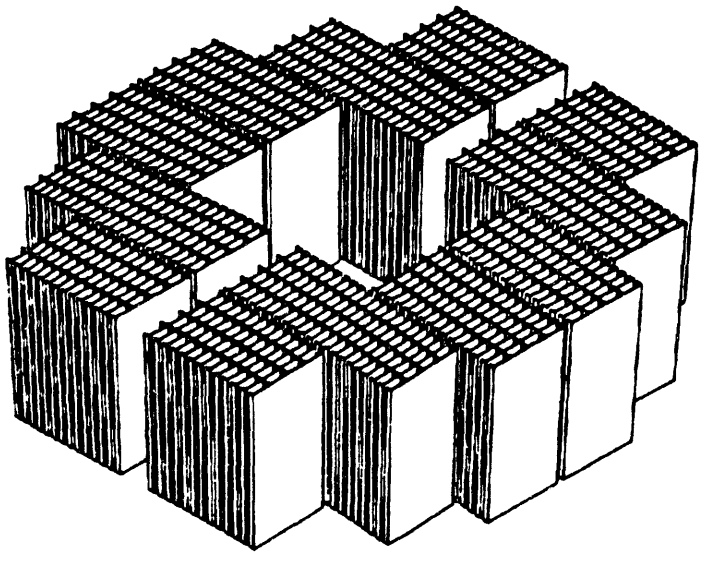

Figure 1 - Grating Array without Structure

The components of the array are the diffraction gratings, precision rails, integrating structure, and structure supports. The diffraction gratings are replicated on 100 x 200 mm silicon carbide (SiC) substrates. Each 92 gram substrate has five stiffening ribs running along its 200 mm length, perpendicular to the facesheet. The 1 mm thick facesheet is fabricated to 1 λ (λ = 6328 Å) and 10 λ flatness in the long and short direction, respectively. A cross section of the replicated grating is 1 mm SiC, 25 μm of epoxy, and 1000 Å of gold[2]. The gratings are held at each of the four corners with spring clips against diamond-turned bosses that protrude from the precision rails. The rails are mounted to the top and bottom of the structure and serve to accurately position the gratings in the array, as shown in Figure 2.

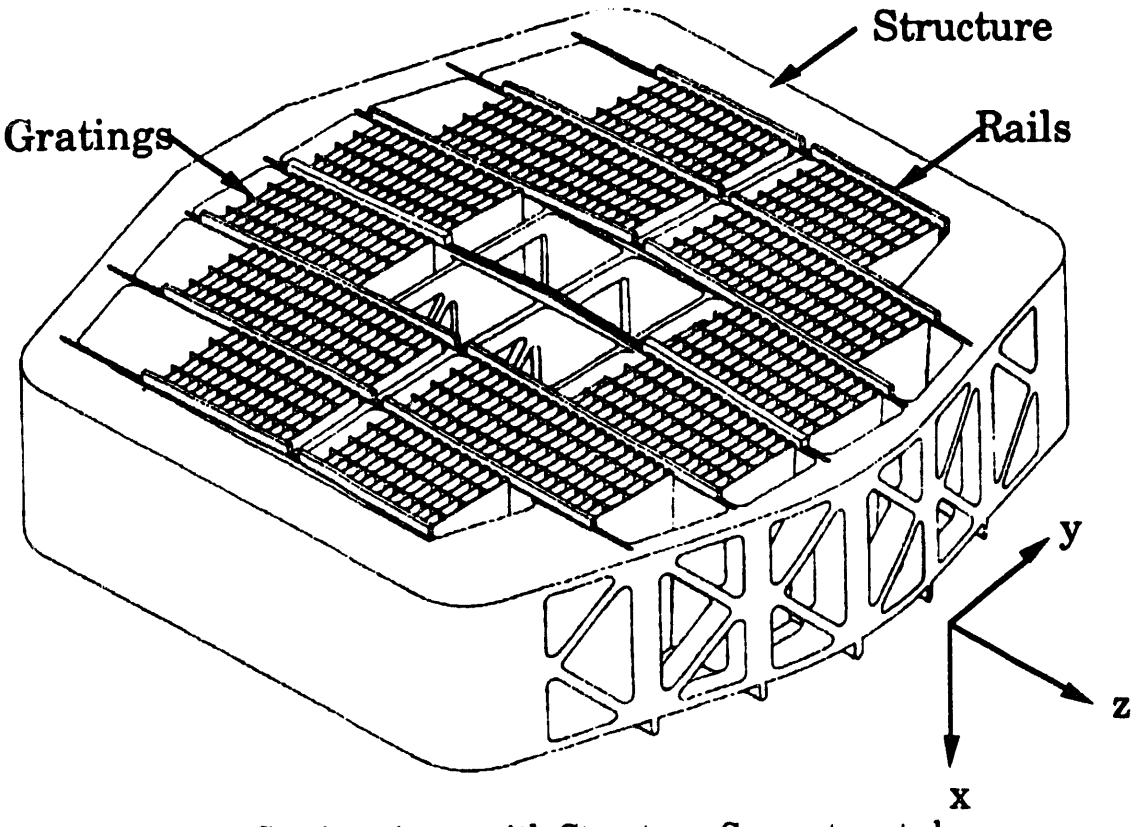

Figure 2 - Gratings Array with Structure. Supports not shown.

The top and bottom sets of bosses are aligned to be coplanar before the installation of the gratings by translating the rails along their mounting surfaces. These four bosses form the primary datum for mounting the grating. This datum is in the x-y plane. The secondary datum are end stops that set the height of the grating in the array, x direction. For the tertiary datum, the gratings are not held against a fixed point. The grating is free to translate in the direction parallel to the rulings by ± 25 μm. This does not cause a blur or shift of the diffracted image. The grating is captured between two fixed edges in order to insure the grating is properly seated on the bosses.

The integrating structure is critical to preserving the alignment of the rails and therefore the position and figure of the gratings. This structure serves as the stiff and stable optical bench for assembly and alignment of the array. Due to the sensitivity to twists or distortions on the order of arc-seconds, the structure is supported using exact constraints, i.e. kinematic mounts. The supports are designed to constrain all six degrees of freedom while not inducing stress or distortions in the structure. The supports are configured such that they simulate balls in vees oriented at 120°.

3. EOBB MODULE PROTOTYPE

The primary goals for the engineering effort during the design and building of the EOBB module were to prove the flight mounting method of the gratings and the ability to align the gratings to flight build tolerances. The prototype array consists of eight gratings assembled into a stiff Invar structure. The Invar structure was not intended to represent flight hardware, only to match the coefficient of thermal expansion (CTE) of SiC. It was not cost or time effective to design a stiff, lightweight structure for use on EOBB that would not have further applicability to a flight structure. The flight-like aspects of the EOBB module were the gratings, mounting method, which includes the spring clips, and the tolerances used to fabricate the precision rails. The four rails of the EOBB module are shown in Figure 3.

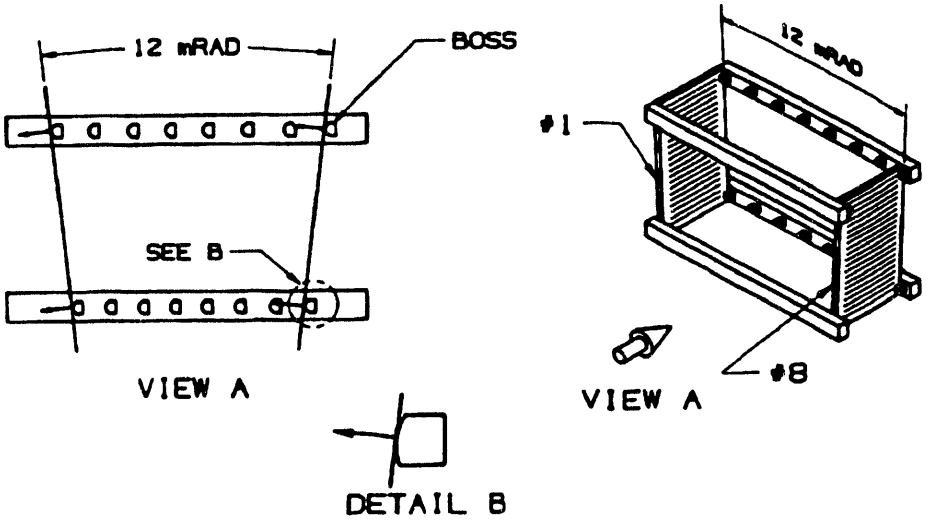

Figure 3 - EOBB Configuration (two of eight gratings shown)

The rails were also fabricated from Invar to match the CTE of the substrates and the module. The basic geometry of the rail was electric discharge machined (EDM) and then the two mounting surfaces of the rail were lapped to 5μm in straightness. Copper plating was applied to bosses for the diamond turning of the cylindrical profile. A sketch of one boss is shown in Figure 4.

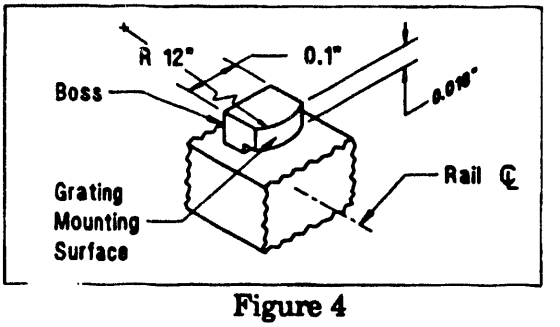

Figure 4

A radius of curvature of 300 mm was determined by Herztian contact stress calculations and experimentation with cylindrical profile on replicated substrates. The allowable tolerance for boss to boss spacing is ±0.38 μm. The

four EOBB module rails were fabricated and inspected at LLNL and the error was ±0.28 μm with an RMS of 0.12 μm on 32 bosses[3].

The mounting of the gratings to the bosses was designed to validate the flight design mounting method. The gratings are brought in contact with the bosses which removes the inherent twist of the substrate. Beryllium copper spring clips clamp the grating to the boss at each of the four corners with a calibrated load. The spring clips for the EOBB module were designed to hold the gratings during the acceleration and random vibration spectrum expected during launch even though the EOBB module array would not see loads or stresses associated with the launch environment. Due to the precision of the diamond turning and the alignment of the four rails to produce four coplanar bosses, the gratings are not adjusted after mounting. Essentially, the array is a snap-together assembly of gratings.

The non-flight Invar structure was designed to be very robust and thermally matched to the SiC substrates. The structure is supported in a cone, vee, and flat for exact constraints, with a micrometer adjustment on the flat for rotation adjustment around the x-axis. Figure 5 shows eight gratings installed in the module with spring clips holding the gratings to the bosses. Two of three kinematics supports are shown.

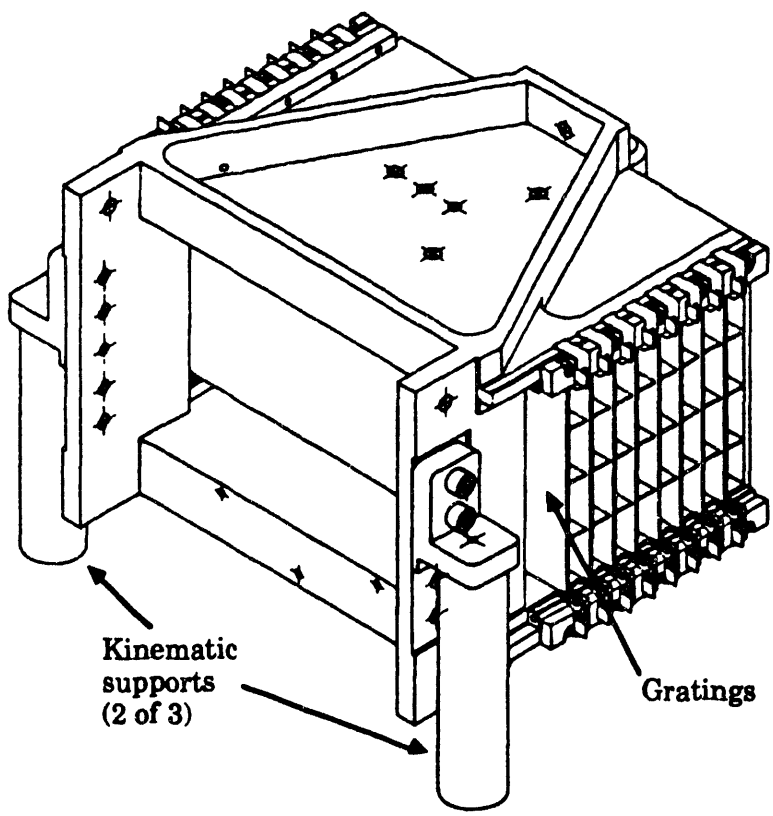

Figure 5 - EOBB Module

4. COMPONENTS OF THE ASSEMBLY PROCESS

The handling procedures for the gratings are strictly controlled, commensurate with a class 1000 or better clean room. The clean room provides a stable environment for grating assembly and for the sensitive metrology equipment used during assembly. The clean room utilized during the assembly of EOBB module is a class 1000 vertical flow, temperature, and humidity controlled environment. Temperature is set to 20° ±1°C and humidity is controlled to 45%.

Figure measurements of each grating are accomplished with a 12" diameter Zygo interferometer. As an acceptance criterion, the figure of each grating is measured with the Zygo in a calibration fixture that constrains the grating against four corners of a diamond-turned fixture that is flat to better than 0.1 μm. This fixture is also used to measure the temporal stability of the figure of the gratings. We have not seen any degradation of the figure after testing for more than a year on several different gratings. The Zygo is also the main component of the assembly process. Its primary use during grating insertion is to document the grating figure after installation that is then used in post-assembly analysis for resolution and performance predictions. In a later section, the use of the Zygo to align the four precision rails will be described.

During assembly, a metrology interferometer is used for angular measurements between gratings. The tolerance for angular positioning of one grating with respect to another is ± 0.4 arc-seconds. The angular interferometer is calibrated to an accuracy of 0.15 arc-seconds. For the EOBB module assembly, the retroreflectors for the angular measurement reside on the centerline of rotation of the modified vertical axis air bearing spindle, directly under the center of the EOBB module array, as shown in top view in Figure 6.

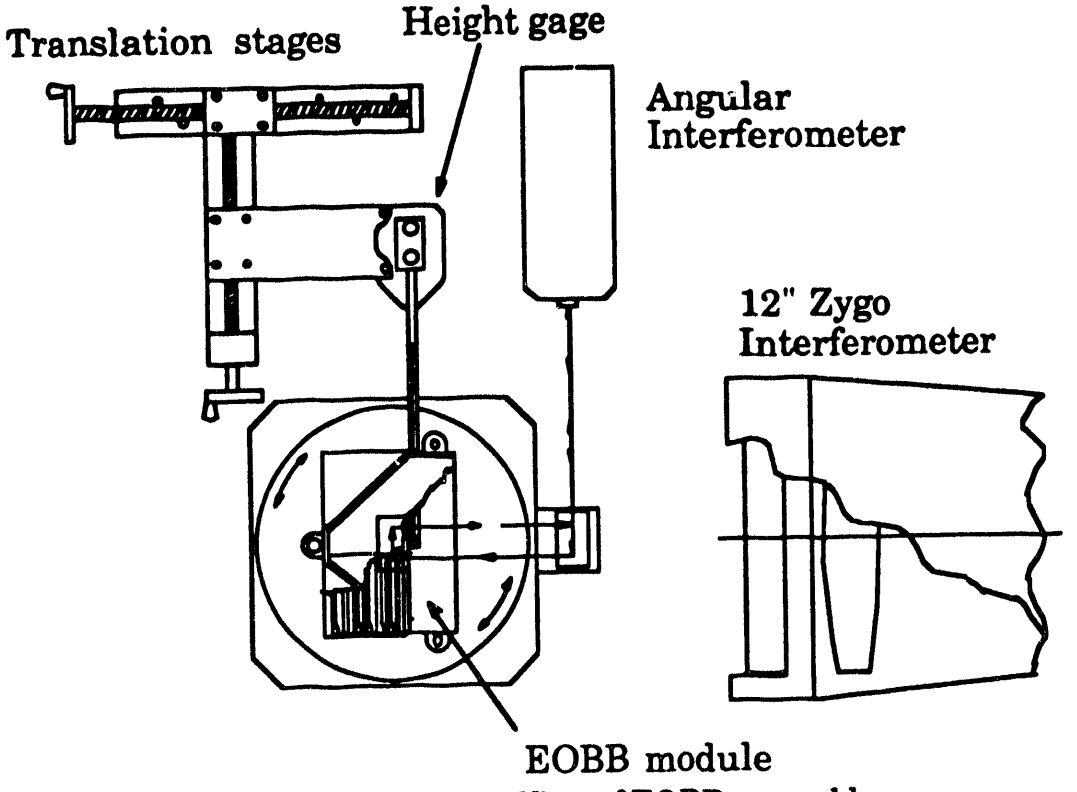

Figure 6 - Top View of EOBB assembly

As with the figure measurement, the data from the angular measurements is used to verify the position of the gratings and used in post-assembly predictions. Once the rails are positioned (which is done prior to permanently placing the first grating) individual gratings cannot be adjusted.

To insert the grating, a mechanical device with three translational and two rotational degrees of freedom (DOF) was constructed, shown in Figure 6. The main component is a mechanical inspection height gage that provides the vertical translation of the grating. The inspection tip was replaced with a vacuum chuck that holds the grating with its short axis oriented vertically. The vacuum chuck was designed to fit in the space between two ribs and allows for two DOF of rotation near the grating center. The base of the gage was modified into an aerostatic bearing for nearly frictionless translations in the horizontal plane. A sheet of glass provides the smooth, flat base on which the bearing operates. The gage is driven through a flexure attached to the nut on a standard lead screw. The flexure serves to remove any influence of the nut radial and tilt motions on the grating as the grating is inserted into the array.

5. ASSEMBLY PROCEDURE

Before the gratings were inserted into the EOBB module, each grating was fully characterized through figure measurements and x-ray efficiency testing. Only gratings passing acceptance criteria were used in the array. Also, the precision rails had to be accurately placed to produce eight coplanar grating positions with minimal errors. Since the diamond-turned boss positions were not perfect, the errors from one rail could combine with the errors of a second rail to produce a less than optimal array. Therefore, the combinations of errors had to be minimized. This was accomplished by using a grating with very good figure, approximately 0.5 λ and 4 λ flatness in the long and short direction, respectively, inserting the grating in each of the eight locations and documenting the figure at each location. Analysis of the eight locations would reveal which one of the four rails should be adjusted and by how much. A linear variable differential transformer (LVDT) was placed on the rail in order to accurately measure rail translation. After adjustment of the rail, the same grating used initially would be inserted into all eight positions for a second iteration on the process. Since the RMS of the boss positions was 0.12 μm from nominal position, convergence to optimal configuration required only three iterations.

The resolution of the EOBB module is a function of how well the gratings are aligned with respect to each other. The errors proportioned to the build tolerances apply to individual gratings. There are three error tolerances that require particular fabrication techniques to be utilized. These are rotation of the grating about the ruling, Ry; translation of the grating perpendicular to the plane of the grating; Tz, and out of plane twist on any one of the four corners, Wxy. Refer to Figure 7 for coordinate system of gratings.

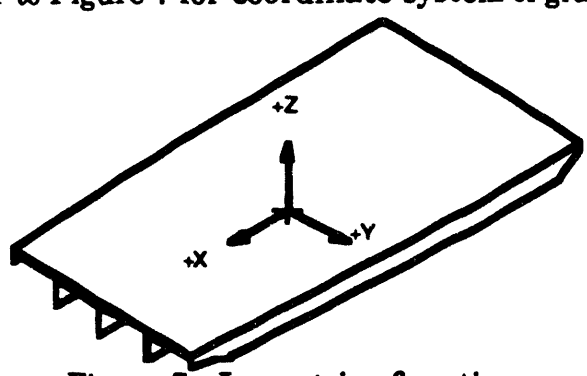

Figure 7 - Isometric of grating

Table 1 lists the *flight* build tolerances for the translations, rotations, and twist for individual gratings that were used to assemble the prototype array.

Table 1

Translations (μm)			Rotations (arc seconds)			Twist (μm)
Tx	Ty	Tz	Rx	Ry	Rz	Wxy
± 150	± 1000	± 3	± 0.8	± 0.4	± 480	± 0.7

Once the rails were in their proper locations, the gratings were inserted starting from the back (#1 in Figure 3) so that the figure of the first grating can be recorded before inserting the second grating and so on. Individual gratings are attached to the vacuum chuck outside of the EOBB module and then translated approximately 250 mm into the module. First the grating is located against the end stops (secondary datum). The grating is then translated forward up against the four coplanar diamond-turned bosses. With the grating contacting the bosses, the figure of the grating is visible, but distorted due to the suction to the vacuum chuck. Vacuum is relieved, but the position of the chuck is held constant to hold the grating in place for the application of the spring clips. The spring clips hold each corner of the grating to a boss with 3.5 N. At this time, the vacuum chuck is backed away from the grating and then removed from the module. With the grating figure and angle (Ry) recorded, the spindle is rotated such that the plane of the next set of bosses is perpendicular to the Zygo. The time necessary to assemble all eight gratings is about two hours. Figure 8 shows the interferograms of gratings 1 through 8 after installation of each grating.

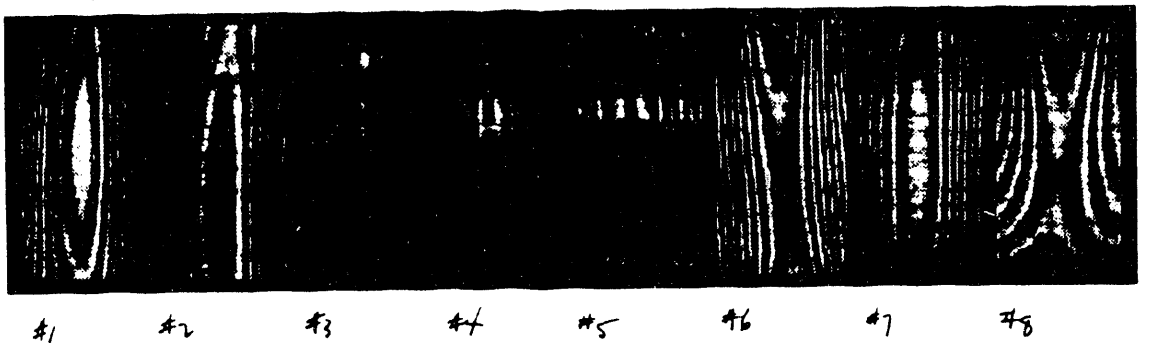

Figure 8

A null is nearly centered on all eight interferograms due to the high precision of the boss locations on the rails and the alignment of the four rails. If one rail was out of plane with the other three, twist would be indicated by the fringes being non-parallel to the long edge of the grating on all eight gratings.

6. OPTICAL LIGHT VERIFICATION TEST

The alignment of the gratings within the EOBB box was verified with an optical light test. The strategy of the test was to sequentially measure the position of the zero order reflected beam from each grating, starting ahead of and finishing behind the zero order focus. The position where the eight beams overlap gives the zero order focal position and an indication of any systematic errors. The lateral dispersion in the overlap points at the best focus indicates the random grating-to-grating rotation and translational errors.

A convex lens was mounted on the four inch diameter leg of the Zygo to provided a converging 8000 mm focal length beam. A CCD camera was used to measure the focal spot size and determine the focal point of the lens.

Using an infrared range finder, the grating box was positioned so that the box center was at the design distance of 6700 mm from the focal point. The box incidence angle was established by autocollimating the end grating to set it perpendicular to the optical axis and then rotating the box to put the central grating at the design angle of incidence of 1.576°.

The CCD camera was moved to the zero order focus and the grating box masked to allow light from only one grating to emerge. The camera was stepped through the zero-order focal region, recording the lateral position of the incident beam. Figure 9 shows the resulting data plotted for all eight gratings.

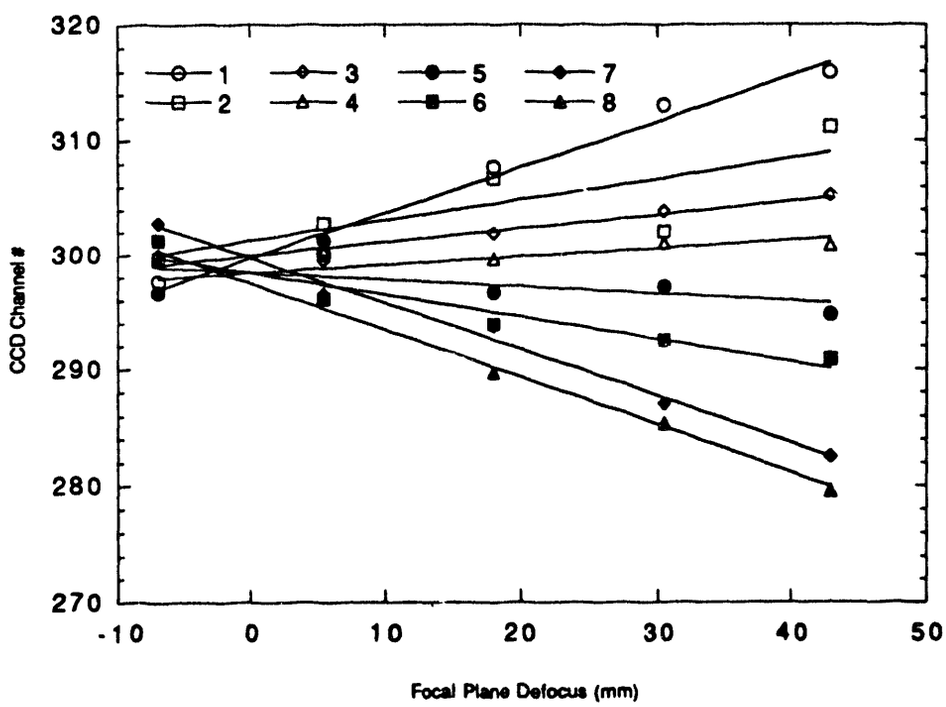

Figure 9

The spread in the data from individual gratings is due mainly to the non-uniformity of the air over the distance of 6700 mm.

A least squares fit was applied to each grating data set and the point of the minimum spread of the beam positions determined. The best fitting focal spot position indicated a systematic angular error over the eight gratings of 0.52 ± 1.4 arc seconds and a random grating to grating error of ±0.23 arc seconds.

7. CONCLUSION

The assembly of the EOBB module was accomplished within design tolerances. The diamond-turning of the rails and precision metrology that was utilized proved to be integral to the success of the EOBB module. The mounting method for constraining the grating was also successful and can be easily extrapolated to flight hardware. Design of the flight hardware utilizing the basic methods describe here is currently in process.

8. ACKNOWLEDGMENTS

All the engineering effort was done at Lawrence Livermore National Laboratory (LLNL) under contract with NASA. Darrell Carter of LLNL configured the equipment, set up the metrology, and assembled most the gratings. Randy Hill of LLNL built the grating insertion device. Special appreciation goes to Pete Davis, Bob Donaldson, Layton Hale and Jeff Klingman, all of LLNL.

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