Assembly of thin gratings for soft x-ray telescopes

Mireille Akilian[1], Ralf K. Heilmann and Mark L. Schattenburg
Space Nanotechnology Laboratory, MIT Kavli Institute for Astrophysics and Space Research,
Massachusetts Institute of Technology,
77 Massachusetts Avenue, Cambridge, MA 02139, USA

Abstract

Diffraction gratings used in space telescopes are desired to provide high diffraction efficiency and large collecting area while maintaining minimal mass to meet cost limitations. As a result, the method of assembling such gratings into modules such that all requirements are met becomes critical. We report on the development of a new assembly scheme that densely stacks thin reflection grating substrates using precision spacers. A custom-designed, optically-polished vacuum chuck is used to constrain the substrates for grating surface metrology during assembly. This rigid subassembly composed of the vacuum chuck and grating is manipulated in space until the grating surface final angular and lateral positions are obtained, at which point the grating is transported from the chuck onto the spacers and glued in that final position. This method not only precisely aligns the gratings with respect to each other, but also improves the overall surface flatness of the substrates, since they are constrained by a flat vacuum chuck within the assembly process. This helps reduce the tolerances on the substrate shaping methods followed prior to assembly.

Keywords: X-ray telescope, thin reflection gratings, Shack-Hartmann metrology, thin optic metrology truss, precision spacers, vacuum chuck, grating assembly.

1 Introduction

Telescopes launched into space place additional demands on the optics and electronics used for imaging stars, since these components must be able to withstand launch forces and vibrations and the harsh environment once in space. When it comes to the optics and gratings used for the imaging and spectroscopy of light from stellar objects, high resolution, high efficiency and a large collecting area are desired. To meet these goals in the soft x-ray band, large areas of substrates used for both reflective optics and reflection gratings must be shaped to a tight tolerance requiring the substrates to be extremely flat. This is achieved by either using large substrates, or by stacking thousands of relatively smaller-area substrates, while keeping the overall mass of the substrates at a minimum to reduce telescope cost. Once the substrates are worked to their final shape, they have to be aligned and assembled into ready-to-fly modules with high accuracy and precision to avoid optic surface degradation during assembly.

This article discusses a new method of assembling numerous thin grating substrates using precision spacers. The substrates used have dimensions of 140 mm $\times$ 100 mm $\times$ 0.4 mm. The target application for the assembled modules using this scheme is the *Constellation-X* [1] x-ray telescope, which requires a resolution of 10 arcsec for the imaging mirrors and on the order of a few arcsec for the reflection gratings [2], placing extreme demands on the grating surface flatness.

The gratings are connected to one another using three precision spacers epoxied on each individual grating, as shown in Figure 1. Identical spacers are used to attach all the gratings to a rigid starting block, which is to be mounted on the telescope structure. This scheme allows for a rigid assembly with a high natural frequency, yet the additional mass due to the small cross-section spacers is maintained low.

2 Assembly tools and parts

2.1 Shack-Hartmann metrology tool

Metrology plays a critical role in assembly, since it provides feedback throughout the process. The Shack-Hartmann metrology system is used to obtain surface maps of grating substrates with a repeatability of 0.4 arcsec [3].

[1]email: makilian@mit.edu. URL: http://snl.mit.edu

Space Telescopes and Instrumentation II: Ultraviolet to Gamma Ray, edited by
Martin J. L. Turner, Günther Hasinger, Proc. of SPIE Vol. 6266, 62663O, (2006)
0277-786X/06/$15 · doi: 10.1117/12.672037

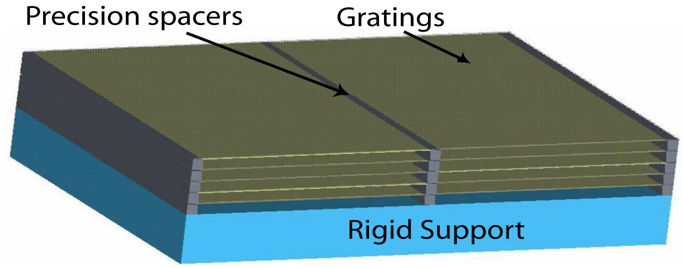

Figure 1: Assembled gratings epoxied to one another and to a rigid support using precision spacers

2.2 Thin optic metrology truss

The first step in assembly is to measure the surface of the unconstrained grating before its assembly as a reference for comparison with the surface of the grating after it is assembled. This will help in evaluating the deformations introduced during the process. In order to measure the surface of the pre-assembled grating, it has to be constrained in a such a way that the effects of forces such as gravity, friction and thermal stresses are minimized. This is done by using the *thin optic metrology truss* shown in Figure 2, which was developed at the *Space Nanotechnology Laboratory* at MIT. This tool can constrain 100 mm diameter circular or 140 mm $\times$ 100 mm rectangular optics having a nominal thickness of 0.4 mm with a repeatability of 1 arcsec using a series of monolithic flexures [4].

2.3 Rigid support and precision spacers

Once the surface of the free grating is measured, it can be assembled onto the rigid support, the starting block, which is comprised of a plate, optically polished to a flatness of 50 nm. The first elements stacked on this support are three precision spacers, which have a cross-section of 2 $\times$ 2 mm^2 and a length of 100 mm, the length of the gratings. It is important to have the spacers as narrow as possible because the part of the grating making contact with the spacer can no longer see the incoming x-rays. For the dimensions chosen for these spacers, the area on the grating that does not see the x-rays is less than 5% of the overall surface area of the grating. Decreasing the width of the spacers any more would decrease its bending stiffness, and the spacers can be easily warped and damaged. The height of the spacers, which provides the gap through which x-rays can pass and hit the surfaces of the gratings, is chosen to be equal to the width to avoid any orientational placement errors during assembly.

2.4 Vacuum chuck

The key component in this scheme is the vacuum chuck, a plate with similar dimensions as the rigid support, that has been further machined to be left with four windows and three ribs, as shown in Figure 3. The ribs are 2 mm wide each. Three holes are drilled from one edge of the plate to meet with the three ribs, which have grooves machined on their surfaces. By connecting these grooves to the holes, a vacuum channel is formed on each rib, with the vacuum tubes connected to the edge of the plate where the holes were drilled. The part is optically polished to 50 nm flatness such that the ribs with the vacuum channels are flat. The vacuum chuck is what transports the grating from the thin optic metrology truss, where its free surface was measured, to the rigid support. This is done by placing the grating surface of interest, i.e. the x-ray reflecting surface, against the flat ribs and turning the vacuum on, as shown in Figure 4. Because the ribs are flat, the overall flatness of the thin gratings is improved once they are rigidly constrained by the vacuum chuck. It should be noted that as the thickness of the gratings increases, their compliance decreases, and this method eventually will no longer work. The windows between the ribs allow for metrology of this surface while the grating is rigidly constrained and maneuvered in space until it is in the right position to be assembled onto the spacers on the rigid support.

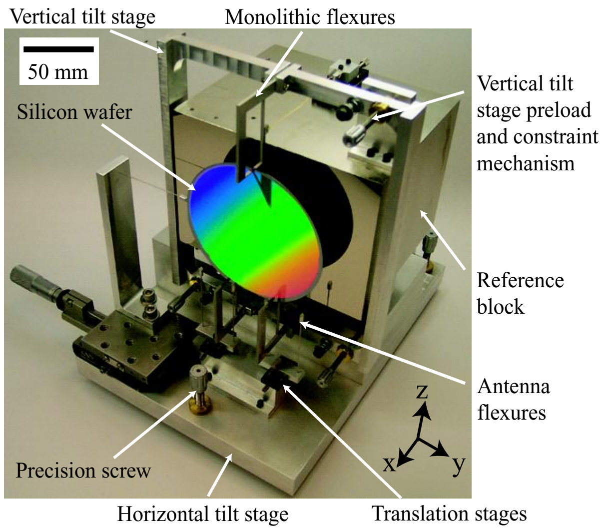

Figure 2: The thin optic metrology truss utilizing a series of monolithic flexures to constrain circular and rectangular optics with minimal distortion

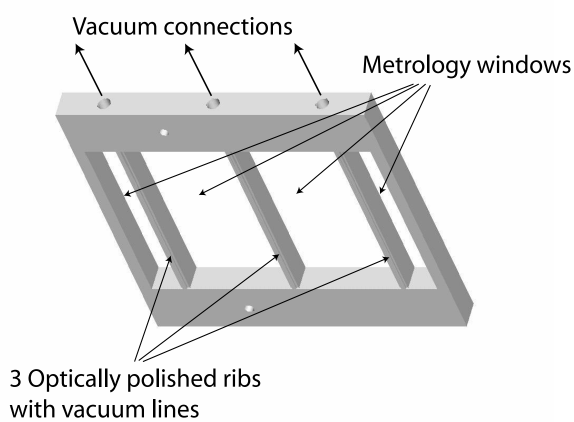

Figure 3: Optically polished vacuum chuck showing the three flat ribs with vacuum lines and the metrology windows

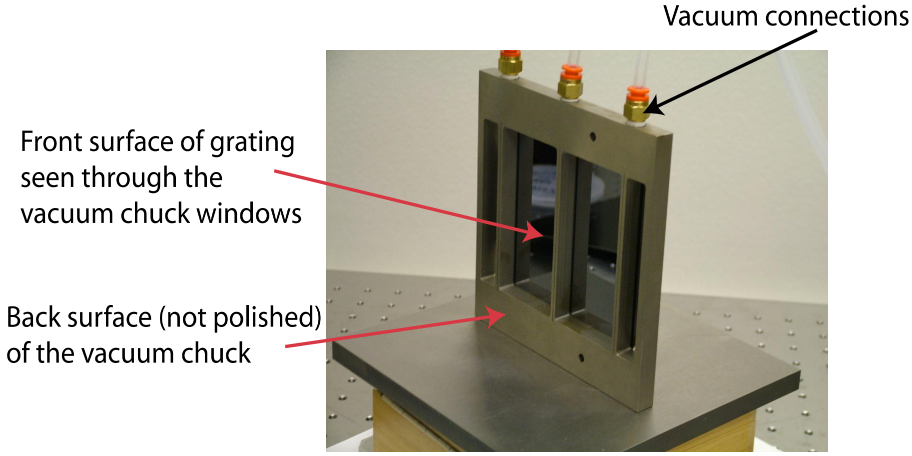

Figure 4: A silicon grating sucked against the vacuum chuck. The front surface of the grating is seen through the windows in the vacuum chuck. This surface is placed against the optically polished surface of the vacuum chuck, which is facing away from the camera in this picture.

3 Assembly steps

Once the free grating surface is measured, it is ready to be assembled onto the rigid support. The assembly starts with placing three precision spacers on the three ribs of the vacuum chuck. Spacers and ribs have the same width of 2 mm. When the vacuum is turned on, the spacers are fully constrained by the vacuum chuck. At this point, a thin layer of epoxy can be placed on the exposed surface of the spacers, as shown in Figure 5*(a)*. Spacers and ribs are placed against the rigid support and held at that position with the vacuum on until the epoxy fully cures. The vacuum is turned off, the vacuum chuck is removed leaving the precision spacers epoxied on the rigid support. The grating can now be placed on the vacuum chuck, as shown in Figure 5*(b)*. Since the gratings are thin and thus compliant, and since the stiff ribs on the vacuum chuck are optically polished, the overall flatness of the gratings improves once the vacuum is turned on in the chuck, and the areas of the grating substrate in contact with the ribs conform to the flatness of these ribs.

Metrology on the front surface of the now constrained grating can still be performed through the windows in the vacuum chuck, which is maneuvered in space until the grating is at its final position with respect to the rigid support and the precision spacers. At this point, the vacuum chuck is moved slightly closer to the spacers so the grating makes contact with the epoxy on the spacers, as shown in Figure 5*(c)*. The vacuum is left on until the epoxy fully cures to counteract shrinkage forces associated with the epoxy curing process. When the epoxy is fully cured, the vacuum is turned off and the vacuum chuck is removed from the system. The front surface of the now assembled grating is ready to be measured to evaluate the process, as shown in Figure 6.

More gratings can be stacked on top of the first one by repeating the same steps, as shown in Figure 5*(d)*.

4 Results and discussion

The role of the vacuum chuck is not only to improve the overall flatness of the gratings, but also to transfer the grating onto the precision spacers without compromising this flatness. Figure 7*(a)* shows the surface map of a grating with 9.4 μm peak-to-valley (P-V) and 1.7 μm rms. Figure 7*(b)* shows the same grating after it has been constrained by the vacuum chuck with 3.1 μm P-V and 0.6 μm rms. A significant improvement in the overall flatness is observed as a result of the grating compliance to the flatness of the ribs on the vacuum chuck. Figure 7*(c)* shows the grating once it has been epoxied on the precision spacers. A slight improvement is observed in the surface flatness, which is measured to be 2.4 μm P-V and 0.5 μm rms.

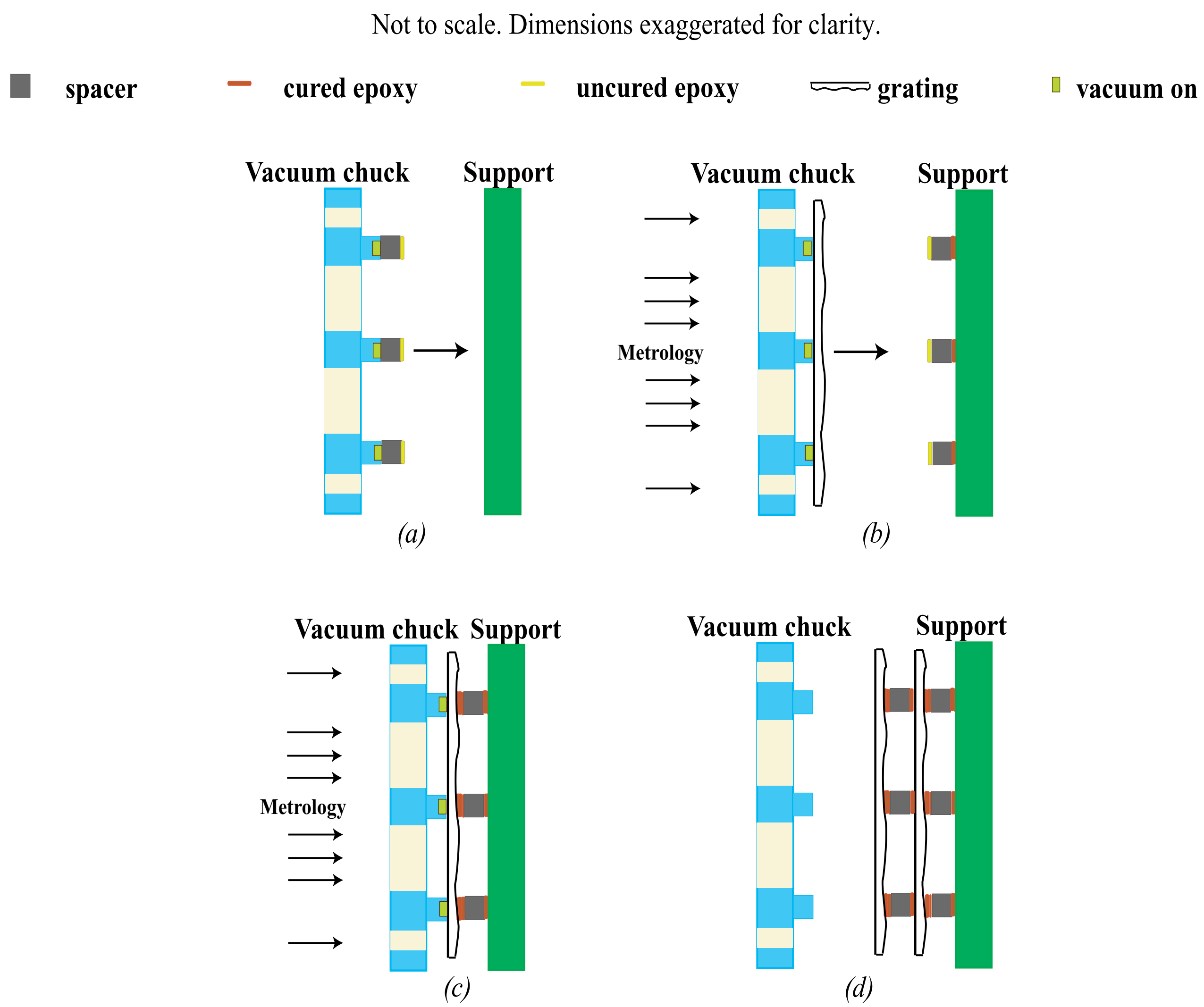

Figure 5: Grating assembly steps. *(a)* Spacers constrained by vacuum chuck, and a thin layer of epoxy applied on one face. *(b)* Spacers mounted on rigid support with a fresh layer of epoxy on their exposed face and grating constrained by vacuum chuck. *(c)* Grating assembled on spacers and vacuum chuck retracted after curing of epoxy. *(d)* Second grating assembled following previous steps.

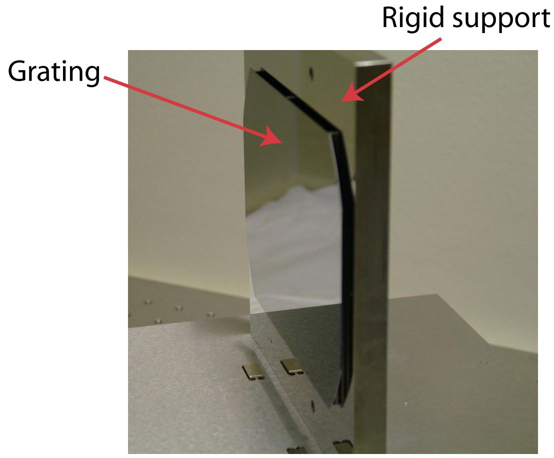

Figure 6: A rectangular grating (silicon substrate) bonded to the rigid support

To further evaluate the assembly scheme, angular histograms of the grating surface are compared. Figure 8 shows the histograms of the grating in its free state, while it is constrained by the vacuum chuck and once it is bonded to the precision spacers. Figure 8*(a)* shows the free grating surface to have a 52 arcsec rms with data points ranging between ±90 arcsec. Once the grating is constrained by the vacuum chuck, the rms drops to 30 arcsec, as shown in Figure 8*(b)*. The final assembled grating has 27 rms flatness, shown in Figure 8*(c)*, which means the overall flatness of the grating has improved by almost 50% after the assembly process. Figure 8*(d)* is the histogram of the same bonded grating, measured one week after the bonding process. It shows a slight degradation in the flatness, mostly caused by epoxy creep. The effect of epoxy creep with time for different types of epoxy will be studied to eliminate this small variation for future gratings. The grating chosen for this experiment was randomly picked from commercially available 6" diameter silicon wafers. It has been die-sawed to its final rectangular dimensions. No shaping processes were conducted on this substrate before it was assembled, and that explains the large initial non-flatness. Commercially available 6" diameter silicon wafers that are ∼0.4 mm thick have a typical surface topography ranging between 10 μm and 30 μm P-V, whereas glass substrates with the same dimensions have a surface topography that can reach to up to 0.6 mm P-V. As a result, silicon has been chosen for this experiment.

Although the assembly process significantly improves the surface flatness of the silicon substrate, it still does not meet the requirement for the *Constellation-X* telescope. Working with better substrates that have an initial surface warp much smaller than this one will provide results closer to what is required. A surface shaping process is needed. Silicon wafers are usually double-side polished after they are sawed, but that only improves the overall thickness uniformity of the wafer and not its flatness, since once the wafer is removed from the tool, it springs back to its original shape. Magnetorheological finishing is one method that can be used to improve the overall flatness of the wafer surface. Magnetorheological finishing was performed on two 4" diameter prime silicon wafers, starting with a surface warp of $\sim 3\ \mu$m P-V and 20-35 arcsec RMS until their final surface had a flatness $< 0.2\ \mu$m P-V and < 4 arcsec RMS [5]; however, this process was extremely time consuming (one day per wafer) and expensive. The advantage of following this assembly scheme is that the tolerances on the shaping processes can be loosened, the free grating does not have to meet the required few arcsec flatness, since the assembly step will correct for that and improve the overall flatness of the individual gratings.

Acknowledgments

We acknowledge the technical support of all staff and students at the Space Nanotechnology Laboratory at MIT. This work is supported by NASA grants NAG5-12583 and NAG5-5405.

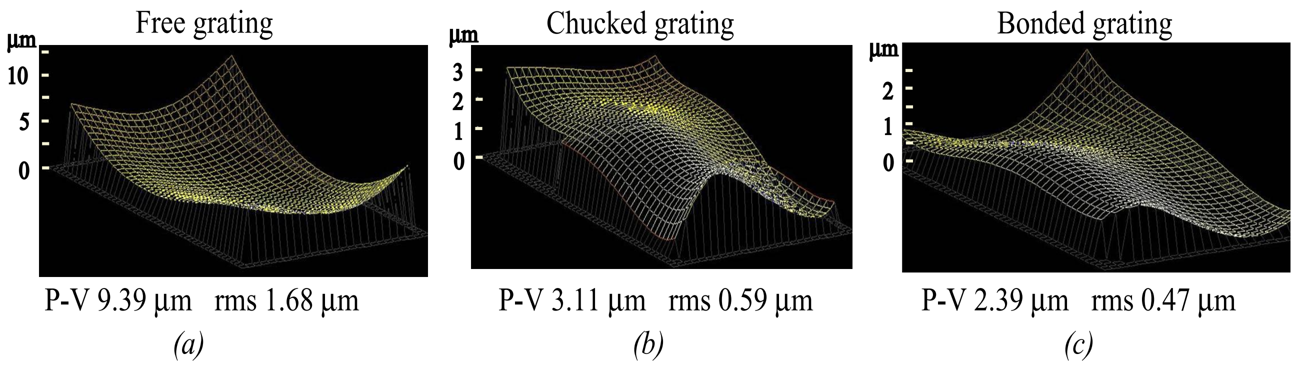

Figure 7: Surface topography of the grating before and after assembly. This is the area of the grating surface seen through one of the windows of the vacuum chuck. *(a)* Free grating when constrained by the thin optic metrology truss. *(b)* Grating constrained by the vacuum chuck leads to a significant improvement in grating surface overall flatness. *(c)* Assembled grating bonded to precision spacers.

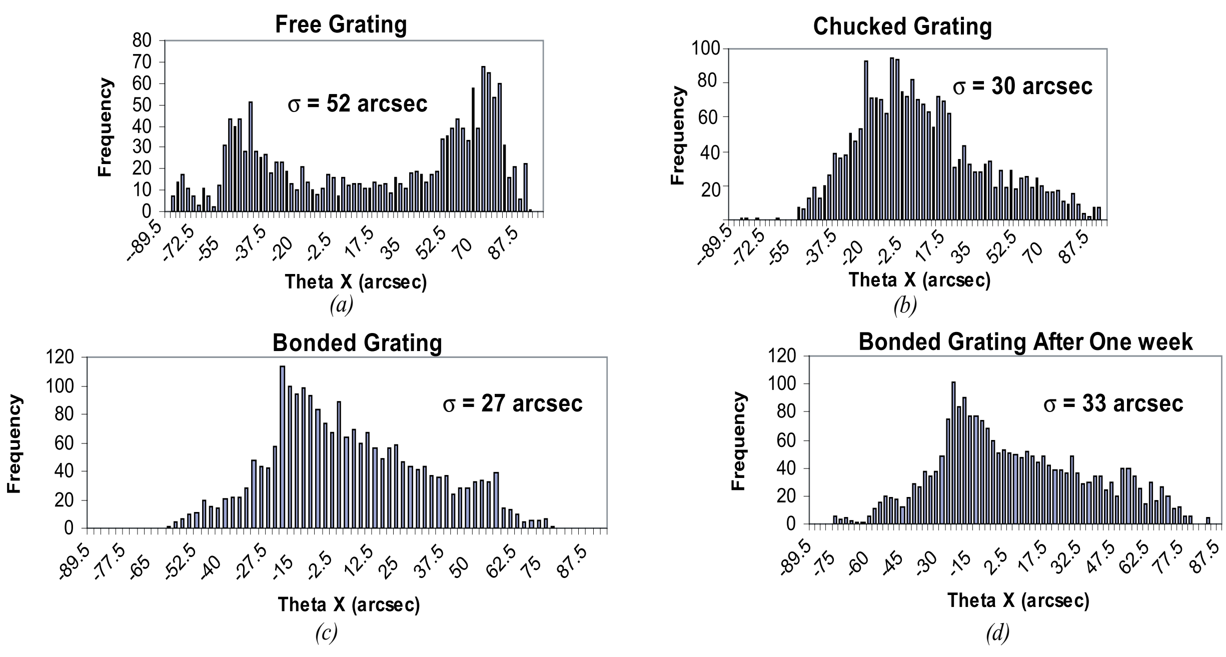

Figure 8: Angle histograms of one grating before, during and after assembly. *(a)* Free grating with 52 arcsec rms. *(b)* Grating constrained by the vacuum chuck with 30 arcsec rms. *(c)* Assembled grating bonded to precision spacers with 27 arcsec rms. *(d)* Same bonded grating measured a week later shows a slight variation of surface flatness with 33 arcsec rms.

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