Corner cube model for internal metrology system of Space Interferometer Mission (SIM)

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ABSTRACT

A corner cube (CC) articulation model has been developed to evaluate the SIM internal metrology (IntMet) optical delay bias (with the accuracy of picometer) due to the component imperfections, such as vertex offset, reflection coating index error, dihedral error, and surface figure error at each facet. This physics-based and MATLAB-implemented geometric optics model provides useful guidance on the flight system design, integration, and characterization.

The first portion of this paper covers the CC model details. Then several feature of the model, such as metrology beam footprint visualization, roofline straddling/crossing analysis, and application to drive the sub-system design and the error budget flow-down, are demonstrated in the second part.

Key words: Corner cube, laser metrology, picometer metrology, and interferometer.

1. INTRODUCTION

A field-dependent (FD) delay bias in the SIM\textsuperscript{[1]} science interferometer could be contributed by the corner cube articulation. The corner cube model is developed to capture the following physical effects: (1) Offset between siderostat surface and corner cube vertex. (2) Dihedral errors in the corner cubes. (3) Reflection phase shift due to the gold coatings on the corner cube surfaces. (4)Surface figure error on the corner cube facets. In this paper we will describe the details of the corner cube model and demonstrate its application to drive the sub-system design, especially the CC parameter requirement derivation to meet the error budget allocation.

2. MODEL DESCRIPTION

Figure 1 shows the SIM metrology system configuration as of 9/2005\textsuperscript{[2]}. Among those six nodes, only node 1 and 2 are of interested in this paper since internal metrology is only measuring the star light path along this science baseline which only consists of DCC1 and DCC2. The DCC1 and DCC2 dimensions are described in reference\textsuperscript{1}. Figure 2 shows the CC shape when we look down to the base-plate (with a scaling factor of 1.3721 hence the final CC size is 161mm). With the surface normal of these two DCC and the whole metrology system layout (including the siderostat attached at those nodes) provided, we can define these DCC configurations within the SIM IntMet system.

For SIM IntMet system along the star beam propagating path, there are also several beam masks served to separate the metrology beams for various purposes. All those mask dimension and shapes have to be optimized by diffraction model\textsuperscript{[3]} to meet cyclic error, heterodyne power, and residual requirements. The mask closely related to the CC model is the Fast Steering Mirror (FSM) mask. The FSM was effectively placed coincident with the corner cube so that the beams seen by the CC have restrained shape and dimension. Figure 3 shows the DCC configuration of IntMet at the center FOR with the FSM mask included. With current design, these two DCC are in mirror symmetry.

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Figure 1. SIM Metrology system.

Figure 2. DCC shape illustration

Figure 3. IntMet DCC configuration
The corner cube model is a physics-based and MATLAB-implemented geometric optics ray-trace program (except reflection phase shift part). It captures the following physical effects:

- Offset between siderostat surface and corner cube vertex
- Dihedral errors in the corner cubes
- Reflection phase shift due to the gold coatings on the corner cube surfaces.
- Surface figure error on each facet of the corner cubes

The first three defects had been analyzed and documented in detail in a previous paper. The outline of these three defect models lists as follows: (1) Vertex offset caused optical path delay (OPD) turns out to be a function of the offset and the angle between siderostat normal and metrology beam. (2) Dihedral error caused OPD is obtained from tracing single ray along the CC facets and calculating the extra OPD caused by the dihedral imperfection. (3) Reflection phase OPD caused by the imperfect coating is a function of the incident angle, coating index, and the reflection sequence inside the CC. For surface figure error caused OPD, the details is shown as following.

For surface figure, the OPD is calculated from tracing multiple rays launched from the FSM mask and then averaging roundtrip OPD of those returning rays at the FSM again. Figure 5 shows how we trace the optical path of the ray for a single reflection when the mirror surface is not perfect (with some surface figure errors). Here we assume that OPD is entirely due to change in the surface height and the beam incidence location as well as the direction of the reflected beam can be calculated using the perfect reference surface with zero surface figure error. The justification of this assumption is based on the fact that the deviations of the local surface normal (dependent on the local surface slope) from that of the perfect surface are small and cause negligible changes of the beam footprint location on mirror surface from that based on the perfect surface. Hence the surface figure error is accounting for the OPD change due to the change of surface height from the perfectly flat surface. Figure 5 also shows the angle compensation factor.

For this surface figure analysis, we first used the Zygo interferometer to measure the surface figure of each facet of CC. Figure 4 shows the measurement maps for DCC1 (top) and DCC2 (bottom).
Figure 4. Zygo maps of the surface figure at each facet (prism/base-plate/prism) for DCC1 and DCC2. The RMS of the each facet is scaled to 4nm/2nm/4nm.

Total delay OPD caused by the CC could be obtained by adding up all these sub-modules assuming these errors are linearly independent. Notice there do have some convolving issues during the summation process. For example, when we are calculating index error caused OPD, adding dihedral error makes the incident angles of corner cube surfaces changed slightly, which will slightly changes the final value. Also, when we calculate surface figure OPD, adding dihedral error makes the metrology seeing different portion of the surface figure, which could also changes the result. To handle these issues, we have to be careful to make it consistent, i.e., not count the defect twice. For example, dihedral error can be considered to be a special case of surface figure error, i.e., 1-D linearly changed surface figure height across the facet is equivalent to generate a dihedral error whose value equals to the slope. For that issue, we checked the linearly addition of dihedral OPD with perfect surface figure and the surface figure OPD with perfect CC is equal to the surface figure OPD from the CC with the same dihedral error presented. So, either approach is fine but only one approach can be adopted at each time. Finally, metrology beams travel round trip while starlight travels one way so we have to put a 2 factor in the final formula to get overall OPD. So

\[ \text{Tota}_{\text{OPD}} = \text{vertex offset}_{\text{OPD}} - \frac{\text{index}_{\text{OPD}} + \text{dihedral}_{\text{OPD}} + \text{surface figure}_{\text{OPD}}}{2} \]

Two observation schemes are included: Wide Angle (WA) metric and Narrow Angle (NA) metric.
WA FOR is a 7.5° radius circular region where we distribute 57 grid points evenly to cover the whole area. Figure 6 shows the WA grid points scanning pattern. After calculating the OPD at each field point, we fit this 2D OPD map with 36 Zernikes. Then we remove the first 15 Zernikes for each field point OPD and take the RMS of these residuals to get the final metric.

Narrow angle fields are 2° circular regions (1° radius) centered anywhere within 3° radius of the center of the wide angle FOR. The procedure to get NA metric is as follows:

1. Calculate the WA OPD for the 57-point WA map in Figure 6.
2. Fit the result of Step 1 to the first 15 Zernikes and store the coefficients.
3. Create 9x9 grid array (with X&Y=±3°) and mask with 3° radius circle->49 effective grids.
4. For each grid point, calculate the OPD at 6 neighboring reference field points distributed in a straw-man\[5\] shape (see Figure 7) around this corresponding center.
5. Subtract all OPD in Step 4 with those 15 Zernikes obtained from Step 2.
6. Fit the result from Step 5 with first 3 local Zernikes, remove these 3 Zernikes out the corresponding OPD, and calculate the RMS OPD residuals.
7. Repeat Step 4-6 for all 49 effective grid points.
8. Record the mean, minimum, and maximum RMS OPD residual over all 49 grid points.

![Figure 7. NA Straw-man pattern](image)

3. APPLICATION

3.1 Beam print visualization
The CC model essentially is a ray-trace model so the ray interception coordinate at each facet could be recorded and shown for the visualization. This feature can help us figure out the metrology beam prints distribution on each corner cube facet during the whole Field of Regard (FOR). With that information, we just need the corner cube to have good surface wavefront error and good coating on the effective region that metrology beams will “see” during the whole FOR. This relaxation could potentially improve the DCC manufacturing yield. Figure 8 left portion shows the beam pattern boundaries at each facet when CC articulates to cover the full WA FOR and the right portion shows the centroid locations of beam pattern at each facet. Overall, the centroid falls into a 2x3mm ellipse region for 15° FOR. Notice that external metrology have different requirements due to their beam location distribution. So we have to include both considerations when evaluating/checking the optical quality of the DCC.
Figure 8. Beam print region during whole FOR

3.2. Roofline straddling analysis
It is worthwhile to mention that the FSM mask we are using is actually the end product after several iterations of combination/tradeoff study from diffraction model and the roofline straddling analysis. It is intuitive to think that we could have some negative impact when beam is straddling on the roofline. But how bad the consequence could be is not easier to quantity. With the CC model, not only the resulting OPD could be precisely defined, but also various minimization options could be explored explicitly and correspondingly, such as rotation of the FSM mask to avoid the roofline, coating/blacken the roofline, and beveling prism edges to mitigate the roofline impact, etc. Figure 9 shows the comparison of two masks and corresponding residuals. Left is the straddling roofline mask and has much larger residual than that from an avoiding roofline mask which is on the right.

3.3 Field dependent error at WA and NA

Figure 9. Mask straddling roofline and mask avoiding roofline
The corner cube model is a useful tool to derive the CC parameter requirement. To meet the FD error budget\(^6\), we break it down into several sub-error-budgets due to different error sources so that the corresponding CC parameter requirement could be defined. The nominal inputs of the model are: vertex offset is 5\(\mu\)m; dihedral errors are 1 arcsec for each roofline (6 dihedral errors total); gold coating at each facet and the index at 1319nm is 0.419-8.42i; surface figures are obtained from the Zygo measurement on the DCC made by CSIRO (Commonwealth Scientific and Industrial Research Organisation).

Figure 10 shows the CC model WA OPD result. It includes the raw OPD map (3D and 2D), OPD residuals at removing different numbers of Zernikes, and the final OPD residual map after removing 15 Zernikes. An interesting finding from this analysis is that the residual OPD is dominated by the surface figure error. It could be explained by the fact that our WA metric is essentially a high-pass filter. Dihedral error, vertex offset, and reflection phase are low-order errors that could be removed effectively. Surface figure contains many high-order errors that are hard to remove. It suggests that we should put emphasis on getting good CC surface quality. The current specification is expected to be \(\lambda/25\) to \(\lambda/30\) PTV. The WA residual RMS is 10pm. It is much less than the WA error budget allocation of 162pm. But notice that these results are obtained from single tile with the nominal CC parameters (for example, surface figure RMS is 4nm for prism and 2nm for the baseplate). WA error budget allocation is targeting for multi-tiles with CC parameters changing over implementation, over mission lifetime, and over observation time. Also, a more conservative data processing scheme will be adopted, for example, only Z1, 2, 5 are removed for each tile and Z3, 4, 6-15 are removed for every 100 tiles. It is expected that the final residual will be larger.

Figure 11 shows the CC model NA OPD result. It includes the histogram of raw OPD, raw OPD removed by 15 WA Zernikes, and raw OPD removed by 15 WA Zernikes and 3 Local Zernikes. The right lower corner graph is the final NA residual distribution within all NA regions. As we can see, the worst case happens at the southwest region of the 3° radius circle. It seems that the maximum RMS of the NA residual is about 4pm, less than 6pm allocation. Again, we have to
understand the story behind it. We know the residual is dominated by the surface figure OPD contribution due to its high order effect. For current calculation, the RMS of the surface figure is scaled to 4nm for prism facet and 2nm for baseplate. Had these numbers been changed, the results will be different. We also calculated the residual with more dense reference pattern than straw-man and it turns out the result difference is negligible.

Figure 11. NA OPD results

As a final note, due to the scope limitation of this paper, several analysis using CC model had also been done but not discussed in here, such as FSM mask misalignment sensitivity, comparison of multiple rays and single ray on surface figure OPD, Zygo map data registration/interpretation, and combining diffraction model and CC model by weighting the CC OPD through the beam diffraction pattern. We will cover those issues in the future.

4. SUMMARY

We have developed a complete corner cube model to include all the pertinent corner cube phenomena (offset, index, dihedral, surface figure) we are aware of at this time. Several features and applications of this model, such as beam prints visualization, roofline-straddling analysis, and FD error budget analysis, have been demonstrated. This model will be used as the design tool for the SIM flight system integration, assembly, and characterization.

5. REFERENCES

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