Sensitivity of Optical Metrology Calibration to Measured Corner Cube Retroreflector Parameters for the Space Interferometry Mission

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ABSTRACT

Picometer scale optical metrology specifications for the Space Interferometry Mission require precision calibration functions involving the optical and orientation characteristics of corner cube retroreflectors. Accurate knowledge of such parameters as the index of refraction of the reflective coating, dihedral between facets, and the orientation of the retroreflector with respect to the interrogating metrology beam and its polarization state is critical. Knowledge errors result in optical path differences that are shown to be on the order of nanometers. These sensitivities are determined from Zemax-generated models and measured parameters. Due to the stringent requirements of SIM, accurate and consistent experimental measurements of corner cube characteristics are required for improved calibration of mission metrology systems. Initial dihedral measurements to within 0.05 arcsecond and refractive indices to within 1% are obtained and integrated into the models.

Keywords: Corner cube retroreflectors, corner cube, optical metrology, stellar interferometry, Space Interferometry Mission

1. INTRODUCTION

Stellar interferometers, on both terrestrial and space-borne platforms, often require interferometers for local metrology. Corner cube retroreflectors are frequently used to mark siderostat positions and allow accurate measurements of optical path lengths (OPL) for each telescope and their optical path differences (OPD). Corner cube retroreflectors, however, are not perfect in that they suffer from manufacturing defects such as the quality of the reflective surface, dihedral between surface pairs, and non-uniform refractive indices of the reflective coatings. For long baseline interferometers these corner cube characteristics can be manufactured to within acceptable tolerances such that resulting OPD's are not the limiting factor of metrology performance. However, in a short baseline interferometer where performance requirements call for picometer-level metrology, optical phase delays as a result of these retroreflector characteristics must be considered and accounted for.

1.1. SIM Requirements

The Jet Propulsion Laboratory's Space Interferometry Mission (SIM)[1] is an astrometric interferometer with a maximum baseline of $10m$ and a 5 micro-arcsecond[2] astrometric accuracy goal. This astrometric accuracy requires local metrology baseline measurements to have an absolute accuracy of $3\mu m$ rms and a relative accuracy of $15pm$ over several hours.[2] Current SIM development testbeds, such as the Kite Testbed, have single baseline measurement requirements of less than $50pm$.

Integral to SIM astrometric measurements is the ability to point the "science" and "guide" siderostats at target and guide (or reference) stars, respectively. Each siderostat has a corner cube centered on the siderostat surface. The act of pointing a siderostat consequently rotates its corner cube, thus altering the incident angle of the local, or internal, metrology beam impinging on the cube. With a perfect corner cube the change in the incident angle has no effect on either

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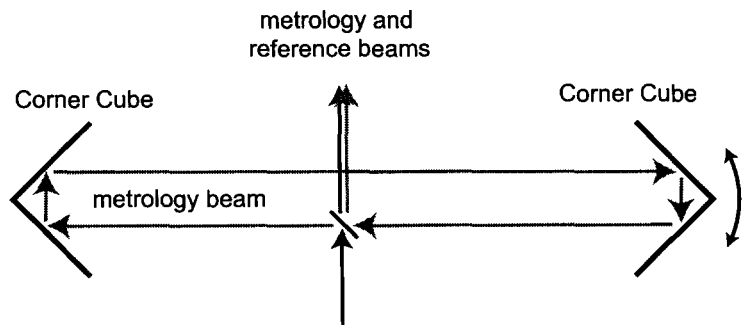

Figure 1. simple local metrology system

the absolute or relative interferometric phase measurement. However, real corner cube retroreflectors have surface pairs with relative angular deviations from the orthogonal (dihedral) and reflecting surfaces with complex refractive indices. Slight beam deviations due to dihedral and phase shifts due to reflections from a surface with a complex refractive index impart measured optical path differences indistinguishable from real path length changes due to structural motion.

Consequently, corner cube specifications and characterizations must be measured and modelled to allow for calibration of local metrology systems, shown in Figure 1, as a siderostat and its corner cube are rotated. Uncertainty in our knowledge of corner cube dihedrals and orientation, and the index of refraction of each reflective surface may contribute to relative optical path difference (OPD) errors on the order of nanometers, up to two orders of magnitude above picometer-level performance requirements.

In this paper, we compare our experimental measurement capabilities of corner cube retroreflector characteristics to metrology performance limitations as indicated by optical ray tracing models of a local metrology system. These models also provide sensitivity of corner cube specifications necessary to meet system metrology requirements.

2. EXPERIMENTAL CHARACTERIZATION OF CORNER CUBE RETROREFLECTORS

In order to properly characterize the corner cube dihedral angle error and wave front error (WFE) a Zygo GPI phase shifting interferometer was used. The corner cube Application software, developed by Zygo Corp, was employed to calculate the dihedral and WFE. A double pass setup (Figure 2) was used, in which half of measurement beam of the Zygo GPI is masked off. This forces the measurement beam to retrace its path through the corner cube and cancels any WFE incurred from the internal optics of the Zygo GPI.

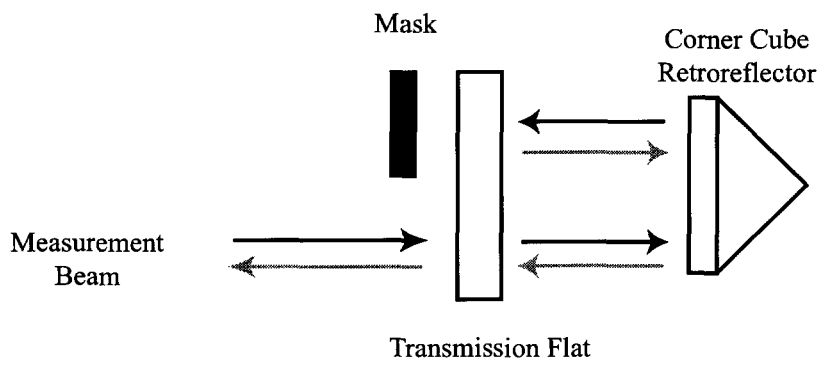

Figure 2. Zygo corner cube measurement in double-pass configuration.

2.1. Clocking Dependent Error

To check the repeatability of the reported dihedral error and WFE values the corner cube was rotated about its symmetry axis and a measurement was taken at each increment of 60 deg through a total range of 720 deg. As a roofline is tracked along the rotation sequence one would expect the measured dihedral to remain constant. Yet, when such a procedure was implemented the reported dihedral values are seen to vary in a sinusoidal manner with respect to the rotation angle as seen in Figure 3.

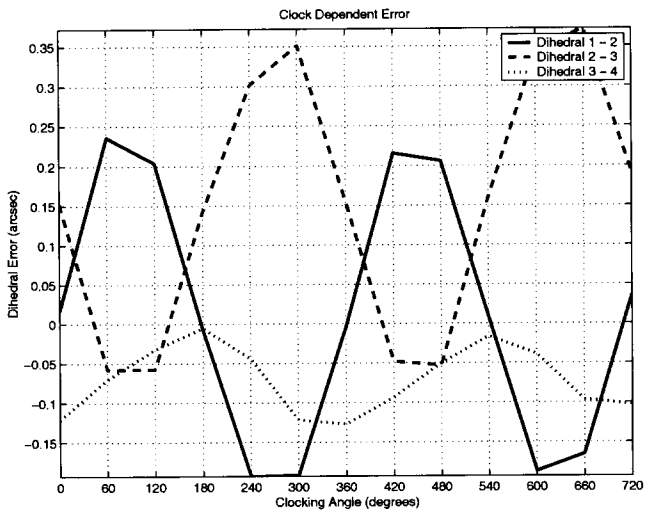

Figure 3. Clocking Dependent Error

Removal of the sinusoid from the dihedral measurements exhibiting clocking dependent error reduces the measurement error. Residuals following removal of a sinusoidal fit are shown in Figure 4 to be less than 0.05 arcseconds peak-to-peak.

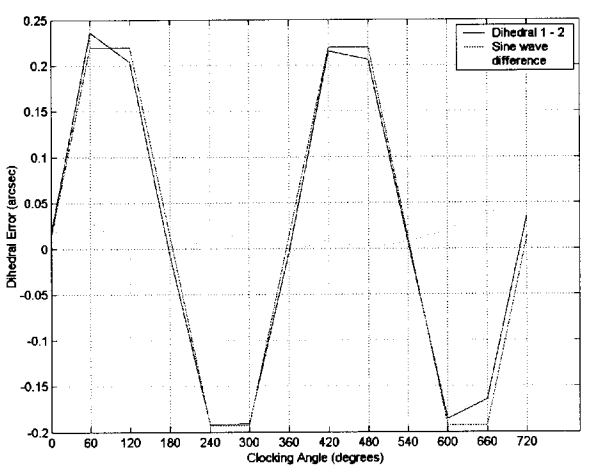

Figure 4. Sinusoidal fit to clocking dependent error of Dihedral 1-2. Residuals are ± 0.025 arcseconds.

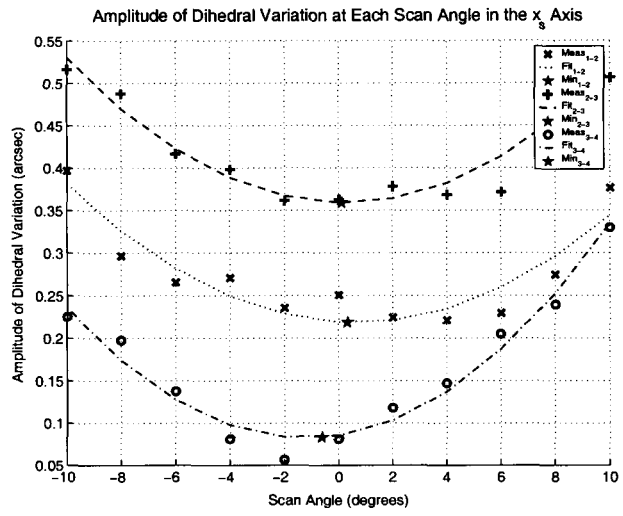

Figure 5. Dihedral Amplitude Dependence on Clocked corner cube Orientation

2.2. Alignment Issues

Ai and Smith[3]investigated the effects of symmetry axis alignment. They showed that alignment of the corner cubes symmetry axis and the measurement beam (the Zygo GPI beam in our case) has a significant effect on the measured dihedral angles. In our experimental setup we have three axes to be concerned with aligning: the corner cube symmetry axis, the rotation stage axis, and the axis of the incident measurement beam.

The corner cube symmetry axis will not necessarily be aligned to the axis of the rotation stage when the cube is bolted (via its mount) to the stage. A tip/tilt stage mounted between the corner cube and the rotation stage was used to minimize variation of the corner cube clear aperture as viewed on the Zygo CCD camera output. When this variation was minimized the symmetry axis rotation axis alignment was complete.

Next the corner cube assembly must be aligned with the incident beam of the interferometer. In order to perform this alignment the corner cube assembly was mounted on a graduated rotation stage where the 0 deg position was nominally pointed at the incident measurement beam. The corner cube assembly was then scanned across the field of the measurement beam from -10 deg to $+10$ deg in 2 deg increments. The corner cube was clocked through 360 deg in 60 deg steps at each incremental step of the scan (as shown in Figure 3). In this way the symmetry axis of the corner cube will at some point be nominally incident with the beam of the Zygo. If the variation in measurement is purely an artifact of alignment, then the amplitude of the variation should be minimized near the nominal position.

Figure 5 below is a plot of the peak-to-peak amplitude variation with respect to the scan angle. A polynomial fit was done (dashed line) of which the minimum was found. The calculated minimum is very near the 0 deg position yet the values do not agree well. This is likely due to the large separation of data points (2 deg).

2.3. Ellipsometer Measurement of Complex Refractive Index

A Sentech Model SE850 Ellipsometer is used to determine the complex index of refraction the gold coating used on the corner cube faces. This value is found to be $n = 0.3522 - i8.7918$ at a wavelength of $1319nm$. According to the manufacturer's specifications, this measurement is good to $< \pm 1\%$.

3. ZEMAX MODEL OF MEASURED CHARACTERISTICS AND PERFORMANCE

A corner cube retroreflector has the desired property of reflecting an incident ray along a path that is parallel and in the opposite direction as the original. The total round trip optical path length from an arbitrary plane to the corner cube and back is twice the distance from the plane to the corner cube vertex.

3.1. Sources of OPD

Using optical interferometry to measure distances between corner cube retroreflectors has great potential for accurate measurements. However, even the most precisely manufactured commercially available corner cubes have properties that introduce errors to optical metrology systems.

3.1.1. OPD Due to Dihedral

Ideally, each corner cube face is orthogonal to the others. However, if the corner cube facets are not perfectly orthogonal then the reflected ray is deflected at an angle dependent on the dihedrals present between each facet pair. As a result, an optical path difference (OPD) is introduced that is dependent on the corner cube dihedrals, the corner cube orientation, the radial distance of the incident ray from the vertex, the angle of incidence on the corner cube, and the distance of the detection plane from the vertex.

The OPD as a result of dihedral on the corner cube can be compensated for with a ray tracing model provided we have knowledge of the parameters listed above. The accuracy of this calibration model is dependent on our knowledge of these parameters.

3.1.2. OPD Due to Refractive Index

Another source of OPD is a consequence of using optical interferometric metrology. The interferometric phase of recombined reference and metrology beams at the detection plane is dependent on the propagated phase of the metrology beam. Its phase depends not only on the total physical path length it traverses, but also on the index of refraction along the path of propagation and the state of polarization of the metrology beam.

The angle of incidence on each facet of a hollow corner cube retroreflector imparts phase shifts onto the metrology beam that, upon interference with the reference beam, is indistinguishable from a path length change in the system. Varying phase delays are induced simply by tilting the corner cube, thus altering the angle of incidence on each surface.

If the refractive indices of the reflective coatings and the angles of incidence are known, a model can be created to calibrate out the phase shifts as a result of reflections from a metal surface. However, the accuracy of the calibration model is dependent on the accuracy of our knowledge of the refractive indices and the angles of incidence.

3.2. Effect of Measured Parameters on the Model

3.2.1. Precession Effect Modelled

The sinusoidal variation of dihedral measurements, as seen in Section 2,is also observed in a ray-tracing model of the measurement process. A corner cube with dihedral values of $(1.0, 0.5, -0.25)$ arcseconds is illuminated with a plane wave. Interfering the return wavefront with the original reference wavefront yields a six-sided interferogram. Extracting the x- and y-tilt of each segment, we use Equation 1 to calculate the measured dihedral values similar to the Zygo corner cube Application.

$$\varepsilon_{ij} = \frac{(Tilt_{ix} - Tilt_{jx})\cos\theta_{ij} - (Tilt_{iy} - Tilt_{jy})\sin\theta_{ij}}{3.27n} \tag{1}$$

By tilting the corner cube axis of symmetry (the $(1, 1, 1)$ vector) 10 deg from perpendicular to the measurement wavefront and rotate the corner cube about this axis, we simulate the clocking experiment. The dihedral calculations are shown in Figure 6. The same sinusoidal effect is evident. The offset of each sinusoid is the "true" dihedral value inherent to the model.

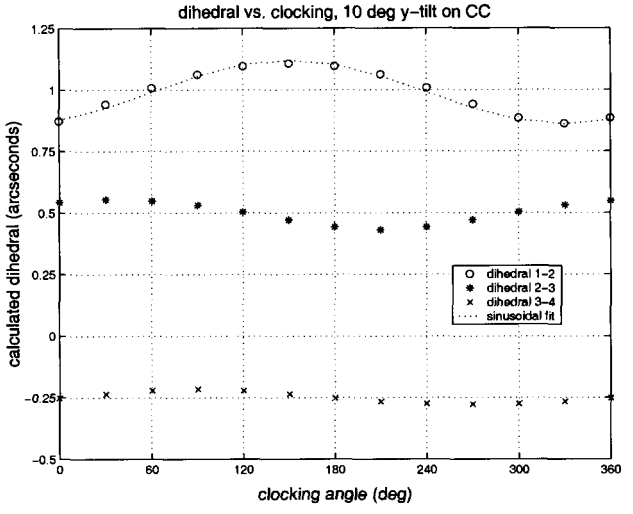

Figure 6. Zemax model of corner cube precession and calculated dihedral values.

3.2.2. Effect of Dihedral Knowledge Error

In Section 2 precession of the corner cube axis of symmetry during dihedral measurements is seen to generate dihedral values that differ as the corner cube is clocked as seen in Figure 3. The correct dihedral values, determined to be the offset of the resulting sinusoid of each roofline, are $(0.025, -0.075, 0.15)$ arcseconds. If only a single measurement were made while the corner cube is clocked at 300 deg, the dihedral values would be $(-0.2, 0.35, -0.125)$ arcseconds.

Each of these sets of dihedral values are entered into the model, where the distance from the corner cube vertex to the detection plane is $1m$, the wavelength is $1319nm$, and the refractive index is $n = 0.3522 - i8.7918$. The OPD's for a range of x- and y-tilt angles from -3.75 to $+3.75$ deg are generated. Wide-angle viewing in SIM specifies a 7 deg conical field of regard, which converts to a 3.75 deg conical field of regard for the corner cube. The difference between the two data sets are shown in Figure 7.

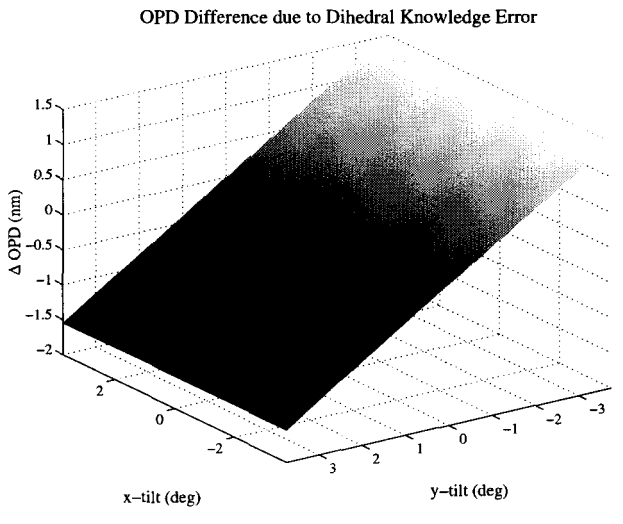

Figure 7. Delta OPD due to corner cube dihedral measurement error.

The resulting OPD error metric is up to $\pm 1.5nm$, much greater than the specified error budget. Even allowing for data analysis techniques, such as detrending the measured, and corrected, relative metrology OPD measurements, leaves a $15pm$ margin of error. This is still too great when other sources also contribute to the total error metric.

A single dihedral measurement using a interferometric wavefront analyzer when the corner cube symmetry axis is not orthogonal to the transmission flat can be incorrect such that a metrology calibration function which compensates for corner cube dihedral is off on the order of nanometers. Care must be taken to minimize the precession of the corner cube symmetry axis in order to accurate determine corner cube dihedral values.

3.2.3. Effect of Refractive Index Knowledge Error

Reflection of an optical ray from a surface with a complex index of refraction imparts a phase delay that is dependent on the angle of incidence on the surface.[4] A ray incident on a corner cube, with its three reflecting faces, experiences phase delays that vary with the orientation of the corner cube.

The reflective surfaces of the corner cubes used in SIM for internal metrology are bare gold. In many cases, the angle of incidence on a single surface can be up to 70 deg from the perpendicular. The phase delay due to these reflections are not static, however, since the corner cubes embedded on the siderostats articulate as different stars are targeted and therefore the amount of optical phase delay induced on the local metrology beam changes as the instrument orientation changes.

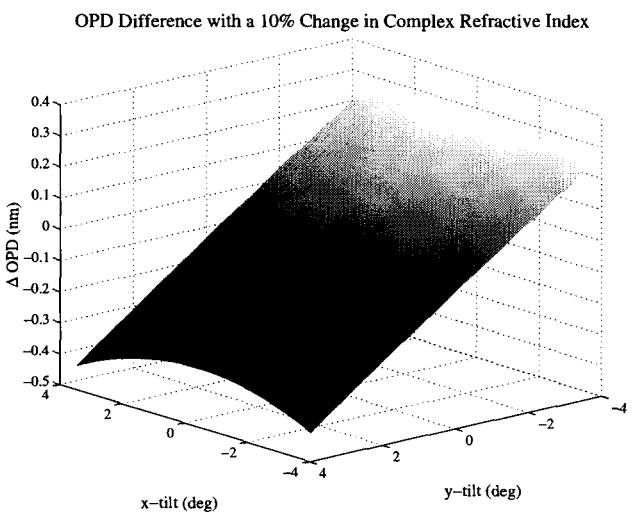

Figure 8. Delta OPD due to 10% knowledge error in the complex refractive index.

Large variations of phase induced OPD are seen for large variations of angle of incidence on a corner cube. However, when calibrating for this OPD in a single corner cube pair it is the measurement accuracy of the complex refractive index that is critical. In Figure 8, the OPD error in the calibration function is seen to be up to $\pm 400pm$ for a 10% increase in refractive index over a field of view of ± 3.75 deg. Measurement performance of $< \pm 1\%$ reduces this OPD model error to $\pm 40pm$.

4. CONCLUSIONS

Metric errors in optical interferometric metrology systems in the Space Interferometry Mission include measured optical path differences resulting from characteristics of corner cube retroreflectors. These characteristics include dihedral angles between faces and the refractive index of the reflective coating.

Calibration functions are only as good as the model from which they are derived. The model, in turn, is only as good as the measured parameters of the represented experiment.

While ellipsometer measurements of gold coatings can be accurate, changes in the refractive index over time due to environmental conditions can also degrade the performance of calibration functions. Dihedral values may also change with time due to environmental conditions such as temperature, stress, and strain. Consequently, current SIM technology development goals include development of a self monitoring system in which corner cube parameters, including dihedral and refractive index, can be measured and the calibration function updated to maintain system performance.

ACKNOWLEDGMENTS

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