Cryogenic system for interferometric measurement of dimensional changes at 40 K: Design and performance

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ABSTRACT

This report describes the facility, experimental methods, characterizations, and uncertainty analysis of the Cryo Distortion Measurement Facility (CDMF) at the Goddard Space Fligght Center (GSFC). This facility is designed to measure thermal distortions of structural elements as the temperature is lowered from 320K to below 40 K over multiple cycles, and is capable of unattended running and data logging. The first measurement is to be the change in length and any bending of composite tubes with Invar end-fittings. The CDMF includes a chamber that is efficiently cooled with two cryo-coolers (one single-stage and one two-stage) rather than with liquid cryogens. Five optical ports incorporate sapphire radiation shields – transparent to the interferometer – on each of two shrouds and a fused silica vacuum-port window. The change in length of composite tubes is monitored continuously with displacement-measuring interferometers; and the rotations, bending, and twisting are measured intermittently with theodolites and a surface-figure interferometer. Nickel-coated invar mirrors and attachment mechanisms were developed and qualified by test in the CDMF. The uncertainty in measurement of length change of 0.4 m tubes is currently estimated at 0.9 micrometers.

Keywords: : cryogenic, cryo-cooler, interferometer, ISIM, JWST, metrology, sapphire windows

1. INTRODUCTION

The James Webb Space Telescope Instrument Support Integration Module (ISIM) is being designed and developed at the Goddard Space Flight Center (GSFC). The ISIM Thermal Distortion Testing (ITDT) program was started with the primary objective of validating the ISIM mechanical design process – by demonstrating the ability to predict thermal distortion in composite structures at cryogenic temperatures using solid element models.

The first items to be tested were tubes designed with the same dimensions, laminate, and invar fittings as the proposed structure Figure 1. The distortions were to be measured in the transitions between 293 K and 40 K. The metrology requirements are listed in table 1.

Plug
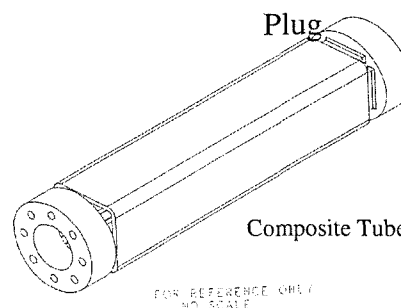
Composite Tube

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Figure 1 ISIM composite tube

Table 1. Tube metrology requirements

Tube length	404 mm
Tube cross-section	75 mm
Materials	Graphite/epoxy laminate 2 square plugs invar 36 Epoxy adhesive
Expected length change from 293K to 40K	~ 36 μm
Required uncertainty in measurement of length change	1.5 μm
Required uncertainty in measurement of bending and twist	6 sec

2. FACILITY DESIGN

The Cryo Distortion Measurement Facility (CDMF) was designed to meet the requirements of this first cryo-distortion test of ISIM tubes, and to be generally useful in anticipated future tests. The basic concept is that a cryochamber or dewar with several ports would enclose and control the temperature of the test articles, which would be populated with reflecting targets. Displacement-measuring interferometers (dmi's) would continuously record the change in displacement of the two ends, yielding the ΔL measurement; and theodolites or other position-sensing detectors would measure the rotations of attached targets.

2.1 Cryochamber

A mechanically-cooled cryo-chamber was chosen in preference over a liquid-cryogen dewar, since it could, in safety, be left running overnight. We have continually made subsequent improvements in the hardware and computer controls to move closer to the ideal of unattended round-the-clock operation. The runs would likely be slower, with cooling rates lower than could be achieved with cryogens, but the labor and expended material costs would be lower.

The inner test volume would be xx by yy by zz, anchored by a cold plate, on which the test objects would rest, and to which they could be thermally strapped, if desired. Surrounding the cold plate would be two shrouds of increasing temperature, all enclosed by a vacuum enclosure, with windows of fused quartz.

The design of the chamber included two inner shrouds, thermally isolated, with the outermost of the two shrouds cooling to about 100K (ck*), and the inner shroud cooling to 20K (ck). The outer shroud would be thermally connected to the first stage of a tk cooler, and the inner shroud connected to the second stage. Later in the program, a second cooler was added for additional cooling power.

The final cooling capabilities were xx W for the first stage and yy W (ck) for the inner shroud.

Figures 2 and 3 show the design of the cryochamber.

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* Draft's journalistic abbreviations: ck = to be checked; tk = to come
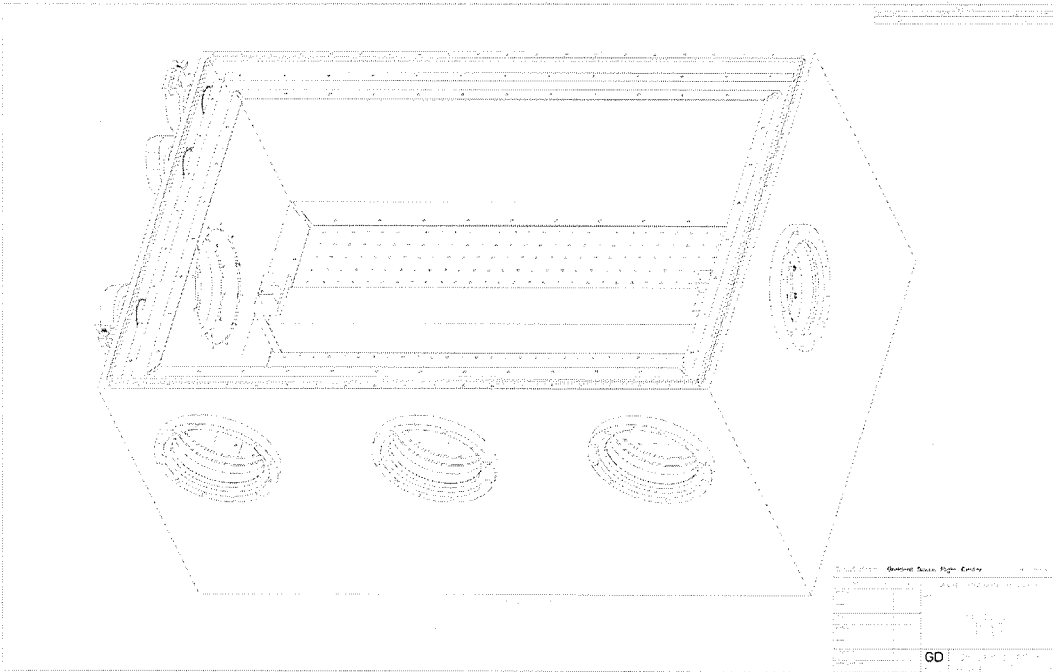
Figure 2. Isometric view of the CDMF cryochamber, showing a tube placed on the cold plate.
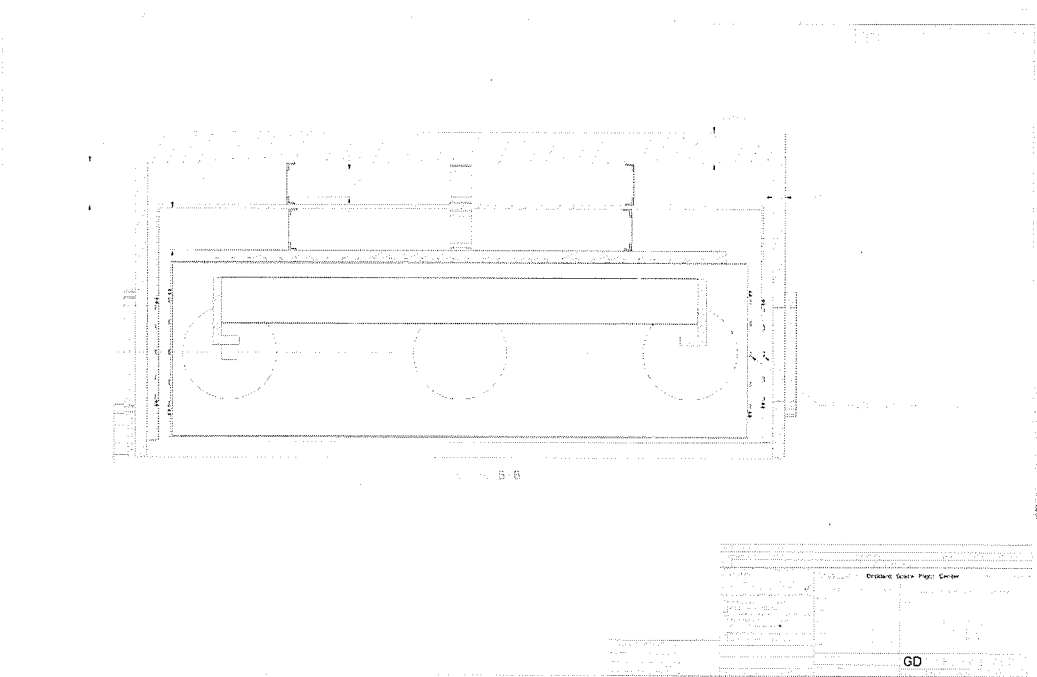

Figure 3. Side view of the cryo-chamber, showing the thick vacuum walls, the two thermal shrouds set off by insulating flexures, the cold plate with attached test article, and in the back walls, three metrology ports.

2.1.1 Radiation shields

With these cooling rates, several large openings, with views of the vacuum chamber port windows, would overwhelm the cooling with their thermal radiation. Possible solutions include stopping down the ports to the smallest possible apertures with sheet metal. Our choice was to fasten radiation shields: thin, thermally conductive crystal which is transparent to the wavelengths used in the metrologies. The material chosen would have to be amenable to the fabrication techniques of a standard optical shop, and capable of being fabricated to $\lambda/4$, with high transmission. Suitable candidates included single-crystal sapphire, quartz, and lithium flouride. Since all interferometry requires control of polarization of the probing beam, the bi-refringence of the crystal must be minimized. Table 2 gives properties of window materials.

Table 2. Radiation shield material properties

Material	Thermal conductivity at 100 K	Transmissivity at 632 nm	Bi-refringence at 632 nm
Fused quartz	Xx	Xx	Xx
Sapphire, cut perpendicular to the ordinary axis (C-direction)	Xx	Xx	Xx
Single-crystal quartz	Xx	Xx	Xx
Single-crystal LiF	Xx	Xx	Xx

We chose single-crystal sapphire, C-cut, 3 mm thick x 6" diameter.

2.1.2 Radiative v. conductive v. molecular cooling

Since cooling by radiative heat transfer scales as the fourth power of the temperature, when the temperature of the cold plate and inner shroud fall below 100K, the expected cooling of the test article by radiation is always expected to be low. One could increase the transfer rate by introducing a tiny amount of helium into the vacuum chamber, not so much as to create convective heat transfer, but an amount such that the atoms have a long free path. With a calculated window heat load of xxx (tk), the calculated cooling rates of the test article in figure 1 would be:

Table 3. Cooling rates of ISIM tube at 100K

regime		
Radiative cooling	Xx	Xx
Molecular cooling	Xx	Xx
Thermal Strap	Xx	Xx

We needed to use thermal strapping at both ends of the tube. Thermal straps connected the invar plugs to the cold plate.

2.1.3 Stability

As will be discussed in section 3 on uncertainty, the greatest source of uncertainty comes from the Abbe error created when the tube rotates in the plane of the cold plate. A strong effort was made to design the cold plate and the support of the test article such that rotations would be minimized. The two shrouds and the cold plate stack up on each other in a sequence starting at the vacuum chamber floor. Each step up was created by four symetrically-placed insulating flexures, placed such that the cold plate would stay centered in its own plane. Naturally, it would be expected to fall as the supports shrink with the lowering temperature, but the plate was designed to stay true with respect to rotations.

Since the test article is thermally strapped, there was also a requirement to mount it kinematically. A kinematic mount was designed for the tube. Three invar flexures were mounted to the aluminum cold plate (Figure 4 Invar flexures. The top surfaces of the flexures were flat, and to them were bonded ceramic hemispheres in such a pattern as to provide a kinematic positioning rest for three ceramic hemispheres bonded to the bottom surfaces of the tube end plugs (Figure 5 Kinematic

The resultant success of the design in preventing rotations of the test article is given in the discussion on uncertainty.
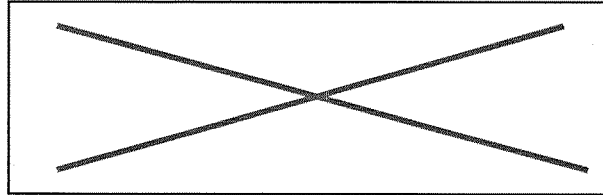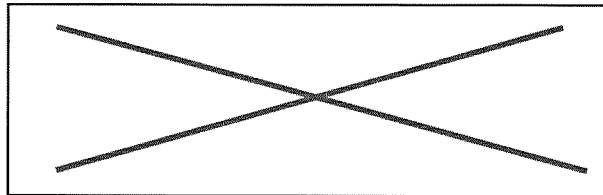

Figure 4 Invar flexures

Figure 5 Kinematic positioning

2.2 Displacement-measuring interferometry

To measure the relative displacement of the two ends of the tube, heterodyne displacement measurement interferometry (dmi) was utilized, since heterodyne dmi is less sensitive to target tilt than pure Michelson interferometry. We used the Zygo ZMI 1000 system that we have had in the lab for many years. Two compact interferometers (model 2001), each measuring both displacement and one axis of tilt, were trained on flat mirrors fastened to each end of the tube. The interferometers were independently measuring displacement of each mirror from its start-up position; and the two displacements were subtracted to get the change in length.

The Zygo compact interferometer [i]splits the incoming beam several times and sends four beams to the target (Figure 6 Diagram of compact interferometer). The displacement measured is the average displacement of the top two beams (*ie*, point A). In our set-up the four beams are arrayed vertically. The tilt between the points A and B is calculated in the computer system using the known value of the distance h (about 12.7 mm).

Figure 6 Diagram of compact interferometer

2.3 Targeting

Initially, we thought of using alignment cubes on the top surface of the plugs, and developed some invar alignment cubes, which worked quite well. But early modelling of the tubes indicated that at 40K, the composite tube, shrinking down, and squeezing the bonding tangs of the invar plug, would tilt the top surface of the plug backwards by 6 arcsec, which didn't seem like a lot until we realized, using simple geometry, that the measurement points midway in the two cube faces would be displaced towards each other from the center points of the tube faces by 2.5 μm each, giving an Abbe error of 5 μm. This illustrated for us the importance of keeping the measurement points as close to the central axis of the tube as possible.

The second targeting scheme was to use a flat mirror across the back of the tube, measured by a beam running down the center of the tube, passing through a hole in a flat mirror across the front plug face. The second interferometer would target the front "donut" mirror, placing its beam at a horizontal offset of 14.5 mm ± 0.3 mm.

The mirrors were made of invar, since our plan was to fasten through holes to the invar plugs. At first, the invar was polished in the optics shop, but the reflectance was only 35%; and with four reflections, the power returning to the detector was too low. So now, both sides of each mirror needed to be polished and coated with protected aluminum. At this point we might have wished we had developed ULE or Zerodur mirrrors for the test, but we pressed on with Invar.

The distortion of these mirrors at cryo is obviously a source of errror that needed to be evaluated (Section 3).

The two compact interferometers in the CDMF are targeted on the front and back mirrors as illustrated in Figure 7 Beam locations of the two compact interferometers
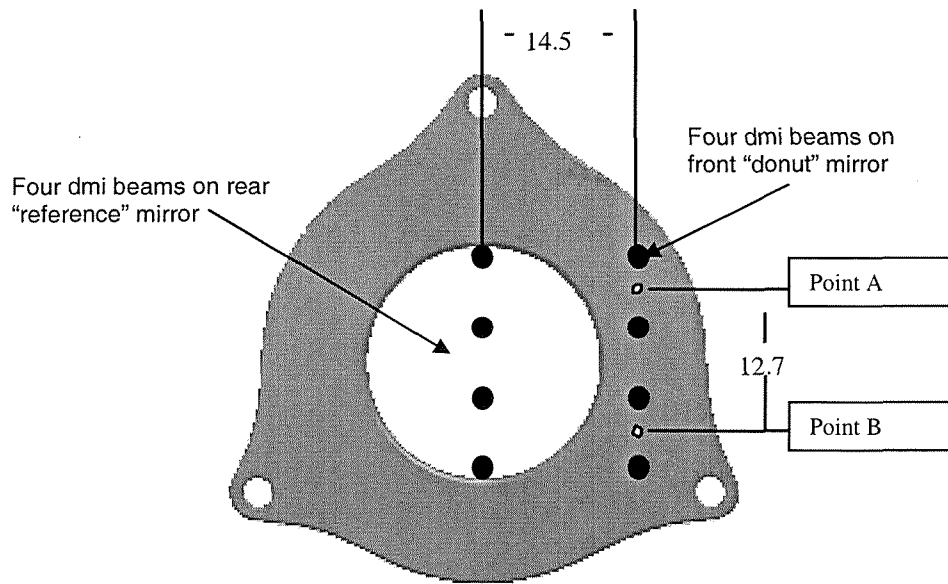
Figure 7 Beam locations of the two compact interferometers

2.4 Control

A control system, written in LabView, was developed for us. The system monitors temperatures, cooling system status, valve positions, interferometer readings, interferometer error signals, and other data. When an error is detected, the interferometer system is reset to zero, and the measurement continued, if possible. An automated phone call is sent out to the test personel on call.

3. FACILITY CHARACTERIZATIONS

3.1 Temperature gradients

Tk: diagrams and charts of temperature distributions in the ISIM tube and surrounding cold surfaces at the cold hold around 4oK

3.2 Test article rotations and mirror distortions

The tops of the Invar flexures and the tops of Invar plug ends were populated with our Invar alignment cubes. The test article tubes were placed in their kinematic support points, and trial runs from ambient to 36K were run.

Theodolites were used to measure appropriate angular motion values. The results are listed in Table 4.

These parameters are entered into the calculations of uncertainty given in Section 4.

Table 4 Motions of test article and targets from ambient to 40K

Rotation angles	a_0 = 3 arcmin Horiz. a = 10 arcsec Vert. a = 20 arcsec
Nonparallel angle	e = 10 arcsec
Vertical displacement	dy = 400 μm
Beam parallel separation distance	Horiz. S = 14.5 mm Vert. S = 0.5 mm
Target Figure Error	0.75 waves @ 632 nm

4. UNCERTAINTY CALCULATION

The uncertainties of a measurement of the change in length of a 400 mm composite tube have been calculated, based on the parameters given in section 3. The resultant RSS combined uncertainty for this mesurment is found to be 0.9 μm.
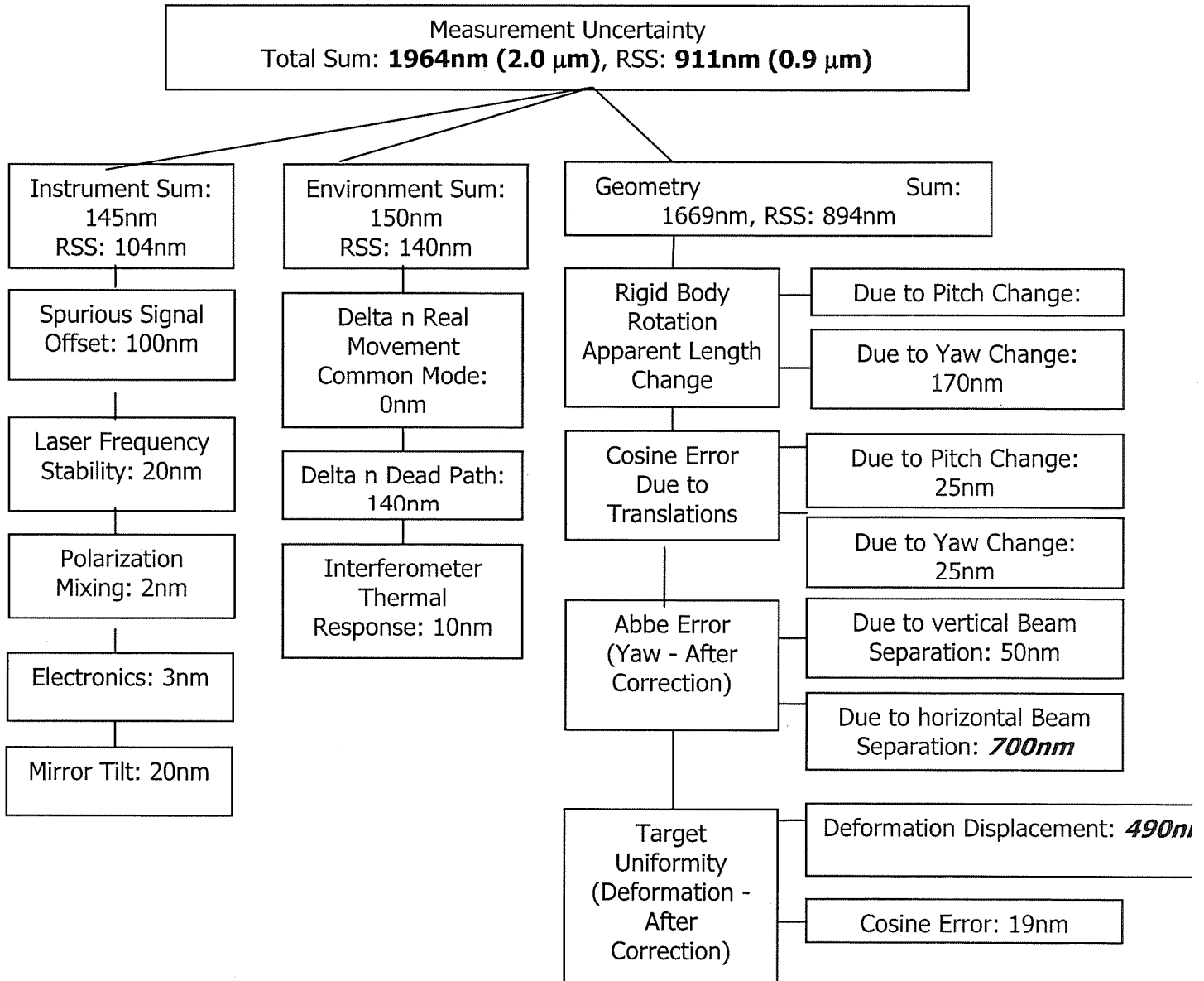
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┌─────────────────────────────────────────────────────────────────┐
│                    Measurement Uncertainty                        │
│     Total Sum: 1964nm (2.0 μm), RSS: 911nm (0.9 μm)              │
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Instrument Sum: 145nm RSS: 104nm
- Spurious Signal Offset: 100nm
- Laser Frequency Stability: 20nm
- Polarization Mixing: 2nm
- Electronics: 3nm
- Mirror Tilt: 20nm

Environment Sum: 150nm RSS: 140nm
- Delta n Real Movement Common Mode: 0nm
- Delta n Dead Path: 140nm
- Interferometer Thermal Response: 10nm

Geometry Sum: 1669nm, RSS: 894nm
- Rigid Body Rotation Apparent Length Change
  - Due to Pitch Change:
  - Due to Yaw Change: 170nm
- Cosine Error Due to Translations
  - Due to Pitch Change: 25nm
  - Due to Yaw Change: 25nm
- Abbe Error (Yaw - After Correction)
  - Due to vertical Beam Separation: 50nm
  - Due to horizontal Beam Separation: *700nm*
- Target Uniformity (Deformation - After Correction)
  - Deformation Displacement: *490nm*
  - Cosine Error: 19nm

ACKNOWLEDGEMENTS

REFERENCES

[i] Zygo Corp Manual, *ZMI Optics Guide*