Polarization effects aboard the Space Interferometry Mission

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ABSTRACT

For precision displacement measurements, laser metrology is currently one of the most accurate measurements. Often, the measurement is located some distance away from the laser source, and as a result, stringent requirements are placed on the laser delivery system with respect to the state of polarization. Such is the case with the fiber distribution assembly (FDA) that is slated to fly aboard the Space Interferometry Mission (SIM) next decade. This system utilizes a concatenated array of couplers, polarizers and lengthy runs of polarization-maintaining (PM) fiber to distribute linearly-polarized light from a single laser to fourteen different optical metrology measurement points throughout the spacecraft. Optical power fluctuations at the point of measurement can be traced back to the polarization extinction ratio (PER) of the concatenated components, in conjunction with the rate of change in phase difference of the light along the slow and fast axes of the PM fiber. Thermal variations are one of the major contributors to this change and can lead to tight spacecraft design requirements. In this presentation, we will discuss our experimentally-validated model which predicts the polarization behavior for various distribution designs, as well as present the thermal performance of various PM components and how this levies thermal control requirements on the spacecraft.

Keywords: Fiber distribution, temperature sensitivity, polarization maintaining fiber, PM, polarization extinction ratio, PER, intensity fluctuation, misalignment.

1. INTRODUCTION

SIM PlanetQuest, a National Aeronautics and Space Agency mission, scheduled for launch within the next decade, will be the most powerful planet-hunting space telescope ever devised. Using two telescopes separated by 9 meters and combining their light with a technique known as interferometry, SIM PlanetQuest will able to detect planets nearly as small as Earth. These are the kind of planets that scientists believe have the most potential to support life. Although more than 150 planets have been discovered beyond our solar system since 1995, the Earthlike planets located in the habitable zone - remains beyond the reach of current telescopes.

Figure 1: The Space Interferometry Mission

SIM PlanetQuest will perform the first census of nearby Earth-like planets by observing the "wobble" in each parent star's apparent motion as the planet orbits, to an accuracy of one millionth of an arcsecond. This accuracy requires that the optical pathlength between the two telescopes and locations of key fiducial points of the instrument must be known with sub-nanometer precision. This is achieved by a metrology system that implements an optical truss to meter the

structure connecting the two telescopes and measures the relative optical delay between the two telescopes. Figure 1 shows the spacecraft and the schematic of the optical truss. The metrology system consists of 17 high-precision interferometric range gauges fed by a common laser source.

The Fiber Distribution Assembly (FDA) is used to distribute the outputs of a single source to the gauges located throughout the 9-meter structures. The 50 picometer precision of the gauges imposes strict requirements on the optical loss and intensity fluctuations at the output of the FDA. The metrology gauges require well polarized light and therefore outputs of the polarization maintaining fiber network are passed through the polarizers, as a consequence, any polarization fluctuations within the extensive fiberoptic network are converted to intensity fluctuations at the output of the FDA. To keep the intensity fluctuations below allowable 1.5% (1-sigma over 90 seconds) the entire FDA is implemented with carefully aligned polarization maintaining (PM) components and fibers.

A schematic of the portion of the FDA is shown in Figure 2 . Single input is split into multiple outputs by a series of concatenated polarization maintaining fiberoptic splitters made by Canadian Instrumentation and Research, Ltd. The multiple outputs are delivered to the metrology gauges by the variable lengths of polarization maintaining fiber cables. The cables pass throughout the spacecraft structure and are subject to thermal and mechanical disturbances. The degree of polarization maintenance is determined by the quality of individual components and precision of angular alignment between them. Given a never perfect alignment and quality of components, the thermal and mechanical environmental disturbances modulate the state of polarization within the fiberoptic system and result in intensity fluctuations after the polarizers. The magnitude of intensity fluctuations is determined by the quality of polarization alignment, sensitivity of fiber to environmental disturbances, and magnitude of environmental disturbances.

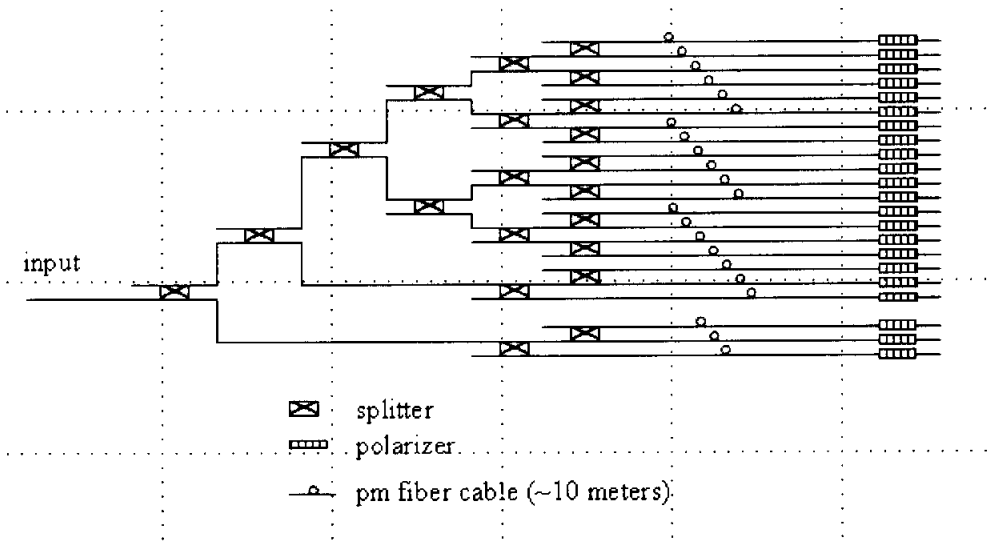


Figure 2: FDA subset schematic

To implement a system that meets our intensity stability requirements we had to develop method for precise alignment and characterization of polarization maintaining components and characterize sensitivity of fiber polarization properties to temperature changes.

In this paper we briefly describe an experimentally verified xPM model used to align the system and characterize polarization maintaining properties of components; present measured polarization maintaining properties of fiberoptic couplers, fusion splices and connectors; and describe experiments to characterize thermal sensitivity of fiber polarization maintaining properties.

2. xPM MODEL AND BACKGROUND OF PM PROPERTIES

2.1 PM background

To preserve the linear polarization of the launched signal, the proposed couplers and optical fiber cables that comprise the FDA will be based on polarization maintaining (PM) fibers. These fibers use asymmetry to induce an index difference for two perpendicular polarizations traveling through the fiber. This birefringence creates two principle transmission axes in the fiber, known as the fast and slow axes, with electric field magnitudes *b* and *a*, respectively. As the light propagates through PM fiber the amount of optical power traveling along the two polarization axes is constant, but the relative index difference, and hence phase difference, changes due to stress or temperature. The ratio of optical intensity between the two axes is defined as the Polarization Extinction Ratio or:

$$X = \frac{b^2}{a^2} \tag{1}$$

This can also be called the Polarization Cross-talk, and in both cases, it is given in decibels: PER = 10 logX. A typical value for PER in a PM fiber is -40 dB for a length of 4 meters. It is common practice to drop the negative sign.

In addition to the fiber itself, how well a system comprising PM fiber maintains polarization will predominantly depend on how well the input light is aligned to the principle axis and how well two discrete fibers brought together are aligned to one another. This is shown in Figure 3 where we assume that a perfectly polarized signal is launched along the slow axis of a PM fiber at point A, which has slow and fast axes defined by s_1 and f_1. Then at point B there is an angular misalignment θ, with respect to the slow axis, to a second fiber that causes the PER = -10 log ($\tan^2\theta$) in the second fiber at point C. The second fiber has the slow and fast axes defined by s_2 and f_2. In this work, we define this angular misalignment as the launch misalignment and give values in dB.

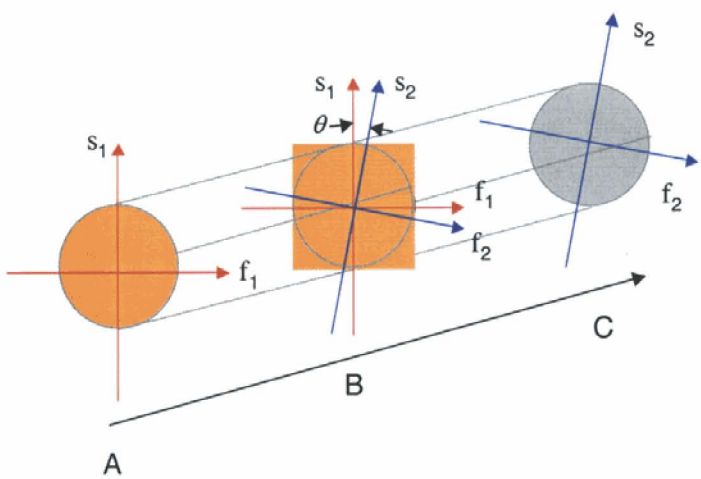
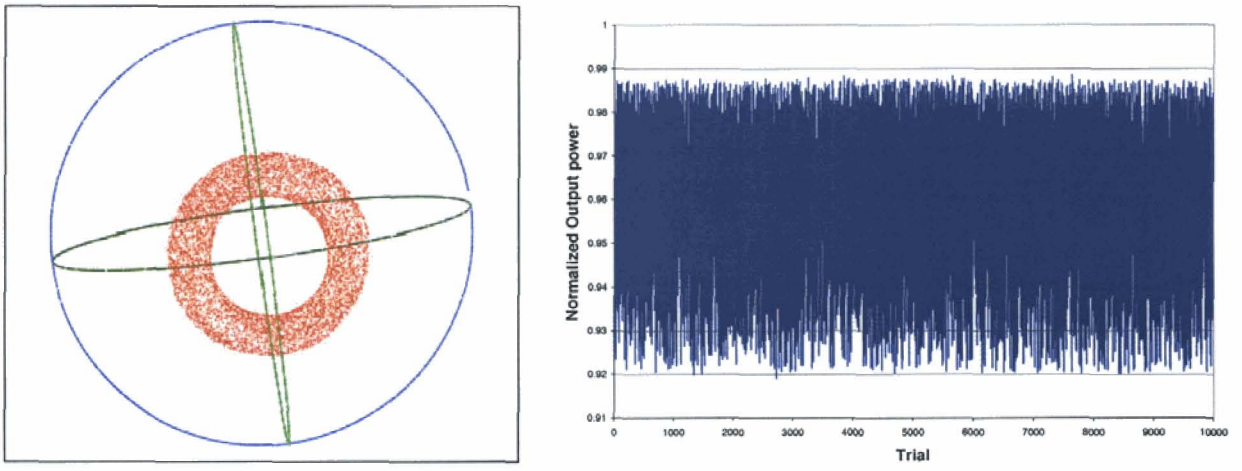


Figure 3: Launch misalignment geometry

2.2 xPM Model

In an effort to predict the output polarization for a series of polarization maintaining components with various angular misalignments, a model was developed and implemented that predicts the output PER for any number of concatenated components with specific misalignments, as well as the amplitude modulation of the signal after it passes through a polarizer. The model propagates electric field via Jones Matrices generated for all components. At the output it generates Stokes vectors, and then places these vectors on a Poincare Sphere to diplay resultant polarization state. The exact state of output polarization state is highly sensitive to the environmental disturbances which modulate the phase delay between the slow and fast axes of the fiber. Therefore in any practical situation the polarization is never constant; instead it varies its state with a range determined by the system PER. The higher the PER, the small the range of polarization changes. To account for this we run the model repeatedly with varying phase delays between the two axes. Any phase evolution can be put into the model, but we use uniform random distribution to reach all states of

polarization possible for a given system. The display on the Poincare Sphere is the evolution of the polarization under a random disturbance that causes the polarization to reach as many different states as possible. The model then calculates the power transmitted through a polarizer for light with this polarization property. Figure (a) shows an example of a model output for a simple system consisting of two PM patchcords and a subsequent polarizer. In this example the launch misalignment into the first patchcord is characterized by a PER of 14 dB, and a misalignment to a second patchcord is 25 dB. Figure 4 (b) shows the intensity fluctuation after a polarizer with a polarizing strength of 35 dB and a misalignment of 30 dB, which gives a 1-sigma of 1.73% at the output.



(a) (b)

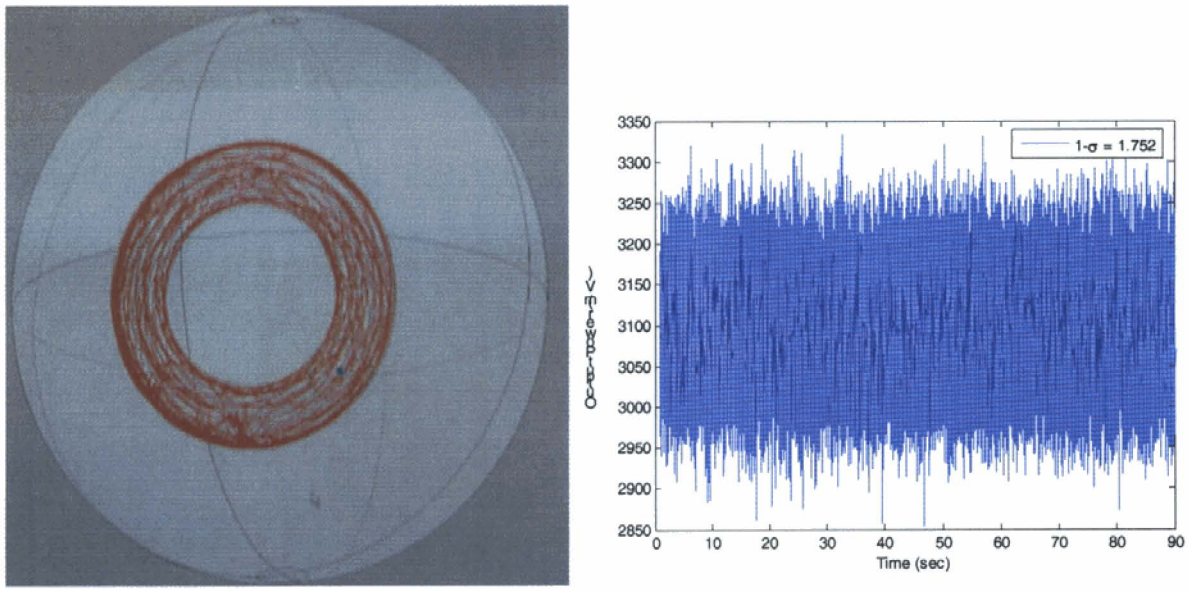
Figure 4 (a, b): Modeled polarization state displayed on Poincare sphere (a) and output power fluctuations after a polarizer (b). Normalized output power vs. trial (time) for: 1m fiber with input misalignment of 14dB, second 1m fiber with misalignment of 25dB, polarizer of strength 35dB and misalignment of 30dB. The predicted intensity fluctuation is 1.73%.

2.3 Model verification

To validate our model, we built and tested several variations of polarization-maintaining components connected together in series, which we call strings. We tested strings comprising one to three patchcords in series, or one to three couplers in series, and compared our experimental results with our model.

The experimental set-up is a 1319 nm output from an NPRO laser launched into a polarizing (3M - PZ) fiber that linearly polarizes the signal to better than 35dB. This light then passes through a polarization controller that allows us to manually adjust the launch misalignment, M, of the linearly polarized light with the slow axis of the first fiberoptic String Under Test (SUT). We tested single components (patchcords and couplers) as well as strings of up to 3 components. The output side of the SUT is connected to either the polarimeter (HP 8509B) polarization analyzer that measures the Stokes vectors and generates a projection on the Poincare Sphere (from which the PER is determined), or passes through a second polarizing fiber into a high speed InGaAs detector. This second technique allows us to measure the amplitude fluctuation from which we can obtain the mean and standard deviation of the intensity, and therefore the fractional 1-σ variation, which is defined as the standard deviation divided by the mean. To ensure that the fiber is stressed enough to result in strong phase fluctuations, thereby guaranteeing a display of all possible PERs, the fiber is stressed by either stretching or rapidly heating the fiber by using a heat gun.

The model prediction shown above in Figure 4 was verified . The experimental results are shown in Figure 5. This is the output on the HP Polarimeter using the test setup that was modeled, as well as the intensity data captured after a polarizer connected to a high speed detector. The xPM model predicts 1.73% fluctuations which agrees well with the experimentally observed 1.75%



(a) (b)

Figure 5 (a,b): Experimental output on HP polarimeter (a) and the power flucutions recorded after a polarizer recorded with a high speed detector (b). The launch misalignment, connector misalignment, fiber lengths, and polarizing properties are the same as in figure 4. The experimentally observed intensity fluctuations are 1.75% (1-sigma).

The results of additional series of tests to check intensity fluctuations are shown in Figure 6, where two patchcords are connected together along with a polarizer to create the fluctuations. Figure 6 demonstrates excellent correlation between our model and the experiment.

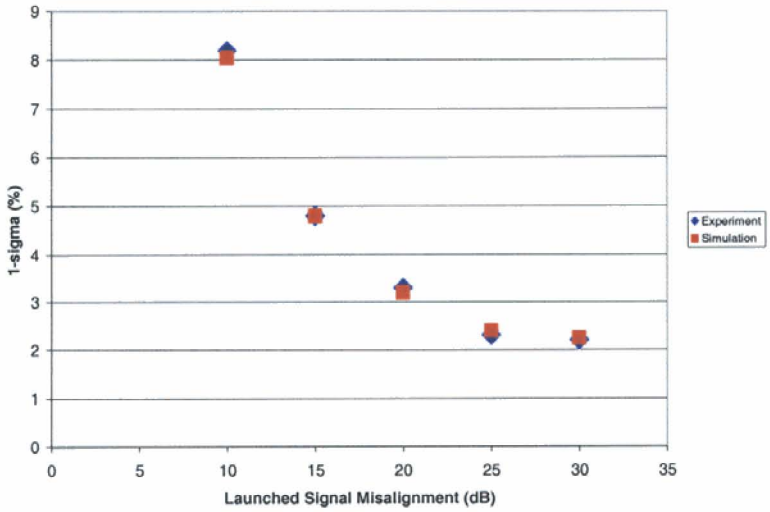


Figure 6: Fractional 1-sigma intensity fluctuations from two patchcords for various launch misalignments

Based on the results obtained as part of these experiments, we feel confident that we have a strong model that can predict the output polarization properties from a fiber-based string comprising polarization-maintaining components.

3. SYSTEM RESULTS

The various components of the FDA needed to be individually tested to determine their actual PER. This was done using the HP polarimeter and comparing the results with above mentioned model. A length of Corning PANDA PM fiber, CIRL couplers, fusion splices and connectors were all tested and the results can be seen in Table 1. The connectors have a large range of PER and this is due to the poor tolerances and inaccuracies involved in manually connecting two fibers. Also the ability to repeat a specific misalignment angle when using a connector is nearly impossible without the aid of a measurement device.

	Typical PER (dB)	Equivalent Angular Misalignment (degree)
Corning PANDA PM Fiber	40+	
CIRL Couplers	25-35	
Fusion Splice	30-35	1.8 – 1
Connectors	10-30	17.5 – 1.8

Table 1. Typical PER values for various FDA components

4. EFFECT OF TEMPERATURE

The intensity fluctuations after a polarizer are determined by both the quality of polarization alignment, as measured by the PER, and the strength of environmental disturbances of the components, usually dominated by temperature fluctuations. Once the model was derived to predict the PER of series of concatenated components, the actual effect of temperature on these fluctuations needed to be determined. A large change in temperature would cause a large fluctuation, but this fluctuation has an upper limiting bound for any particular PER. As expected, the purity of polarization alignment (PER) determines the maximum possible extent of polarization fluctuations. The strength of thermal disturbances determines the actual amount of polarization fluctuations, and therefore intensity fluctuations, within the envelope set by the PER. For example, a small change in temperature will cause the intensity fluctuations to be very small or even negligible.

4.1 PM fiber sensitivity to thermal variations

The change in temperature of a PANDA PM fiber has an effect on the index difference between the two axes of the fiber. The index difference is defined as $\Delta n = n_s - n_f$, where n_s and n_f are the refractive indices of the slow and fast axes respectively. The index difference directly affects the phase difference between the two axes by

$$\Delta\phi = \frac{2\pi}{\lambda}\Delta nL \tag{2}$$

where λ is the wavelength, and L is the length of the fiber. An experiment was performed to find a quantitative relationship between the change in temperature and the change in phase difference in such a fiber.

The experiment performed consists of an NPRO laser, with wavelength 1319 nm, being launched into a polarizing (3M - PZ) fiber to ensure constant polarization in the fiber under test. Next a standard Corning PANDA type PM fiber of length 5m and with an 8μm core is coupled to the PZ fiber and placed within a box, to dampen acoustic effects. To measure temperature inside the box several type-k thermocouples are used. The PM fiber is then attached to an HP 8509B Polarization Analyzer for data collection. The polarization analyzer has the ability to output the Stokes vectors which were then logged by a separate computer. The computer monitors the Stokes vectors and temperatures from the thermocouples at 30 second intervals. Data was collected for approximately 24 hours to ensure an adequate change in temperature and polarization.

The temperature data was fitted with a linear regression in sections to eliminate the noise of the thermocouples. The saved Stokes vectors were then plotted on a Poincare sphere and sections of quarter, half and full circles were marked, corresponding to a change in phase difference of $\pi/2$, π and 2π, respectively. The temperature change for the sections allowed for the calculation of $d\Delta\phi/dT$ for eight segments (I don't understand what the preceding phrase means), when averaged was found to be 1.44 rad/ °C-m. The change in index $d\Delta n/dT$ was found to be 3.03×10^{-7}/ °C. Figure 7 shows a section of the temperature plot along with its corresponding change in phase shown on the Poincare sphere.

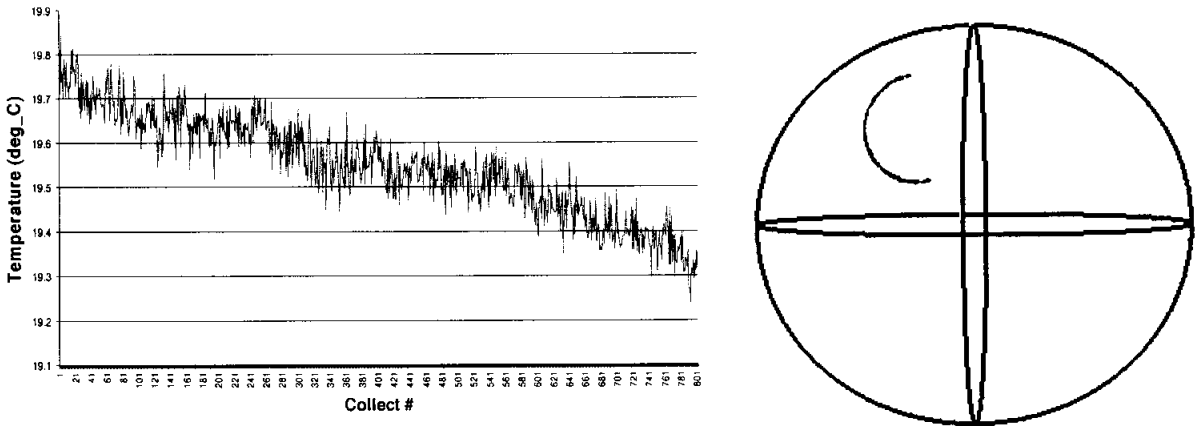


Figure 7: Light output on Poincare sphere and corresponding temperature data.

The sensitivity to temperature change found in this experiment agrees reasonably well with other published results. In the Hauer paper a sensitivity of a PANDA fiber is 1.50rad/ °C-m at 1550nm which correlates to 1.76 rad/ °C-m at 1319nm. Jeon and Kim found the change to be 0.236 rad/ °C for a 100mm fiber at 1537nm, which correlates to 2.75rad/ °C-m at 1319nm. The Zhang and Lit research lists several different numbers for the sensitivity found in various other papers. Table 2 shows a table that compares all of the different temperature sensitivity factors for PANDA PM fiber which have been normalized to a lambda of 1319nm. The variation in these numbers could be due to differences in the fiber from the manufacturers.

$d\Delta\phi/dT$	Hauer et al.[1]	Jeon et al.[2]	Zhang et al.[3]	Kersey et al.[4]	This Work
rad/ °C-m	1.76	2.75	3.53	1.26	1.44

Table 2: Table displaying temperature sensistivity results from various works.

4.2 Determination of maximum allowable thermal disturbance

Using the fiber sensitivity derived above we modeled the output power fluctuation due the change in temperature. Since the largest contributor to output power fluctuations is change in phase in the long run of 15m PM fiber after the FDA, this is used in the model to levy a requirement on temperature drift that can experienced by the fiberoptic cables within the SIM PlanetQuest spacecraft. A length of PANDA PM fiber is modeled with an input misalignment, which creates a PER, and a misalignment to a polarizer, which also creates a PER. Using the above 1.44 rad/ °C-m, the phase difference of the light along the two axis of the fiber can be changed for a given change in temperature. As the phase changes over the time interval, the intensity out of the polarizer is calculated through the following equation:

$$I(t) = a^2\cos^2(\theta) + b^2\sin^2(\theta) + ab\sin(2\theta)\cos(\Delta\phi(t))$$
$$= C\left[1 + X_1X_2 + 2\sqrt{X_1X_2}\cos(\Delta\phi(t))\right] \tag{3}$$

$$\text{Where } X_1 = \frac{b^2}{a^2}, \quad X_2 = \tan^2(\theta), \quad C = a^2\cos^2(\theta) \tag{4}$$

Where *a* and *b* are as above, the optical intensities in the slow and fast axis respectively in the PANDA PM fiber, and θ is the misalignment angle to the polarizer. X_1 and X_2 are then the PER's of the misalignment to the fiber and misalignment to the polarizer respectively.

The phase difference, $\Delta\phi$, is cycled through the values it would experience during a temperature change using the following equation:

$$\Delta\phi = \chi \cdot \frac{\Delta T}{\Delta t} \cdot t \cdot L + \Delta\phi_0 \tag{5}$$

In the above equation the χ is the temperature sensitivity, $\Delta T/\Delta t$ is the thermal rate of change, *t* is the length of time, *L* is the length of the fiber and $\Delta\phi_0$ is the initial phase of the polarized light. As the thermal rate of change is swept through a range of values, the phase difference will vary and cause a change in intensity after the polarizer. The standard deviation to a linear fit and to the mean of the output power is then calculated, however it is sensitive to the initial phase difference in the fiber. To compensate for this, various initial phases are used in the model. The standard deviation for a range of phases is then plotted against $\Delta T/\Delta t$.

The above mentioned model was experimentally verified by using a 20m length of PANDA PM fiber and varying the temperature. Again an NPRO 1319 laser was connected to a PZ fiber. This was then connected to the 20m fiber, an inline polarizer and finally the power was measured using a high speed detector. The 20m of fiber was placed in a water bath and the temperature raised with a hot plate, and then allowed to cool by removing the hot plate. The output power was recorded for 60 seconds and the mean, standard deviation and 1-sigma of the output power for this period of time was then logged. The 1-sigma of the output power and the temperature for the test are show in Figure .

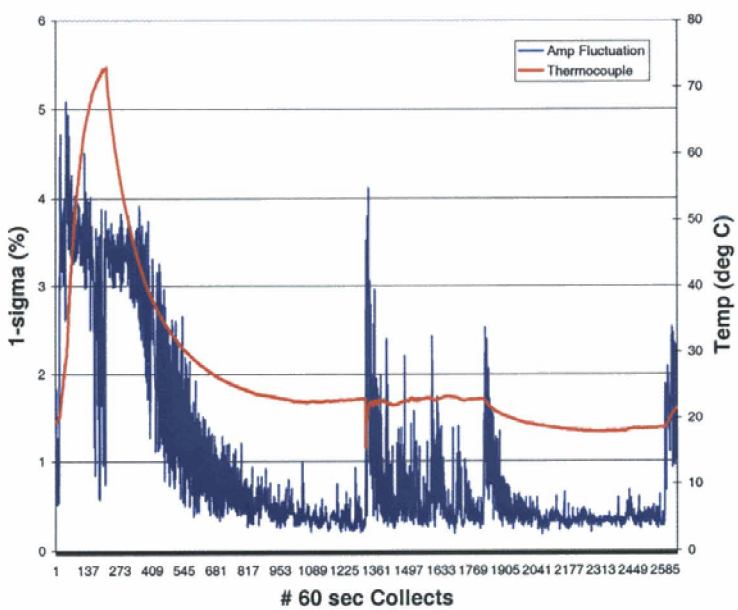


Figure 8: Ampltiude fluctuation data in 1-σ and temperature data for a 20m PANDA PM fiber.

The average 1-sigma for a given dT/dt (change in temperature per change in time) is then plotted. This experimental data matches up with the model and is shown in Figure 9. The experimentally verified model was used to set a requirement on thermal drift seen by the fiber cables about the spacecraft. .
Given the quality of components and alignments specified in Table 1, the 1-sigma intensity fluctuations can be kept below the required 1% provided the thermal drift experienced by the fiber cables are kept below 20 mK/min. The derivied requirement of 20mK/min includes a margin.

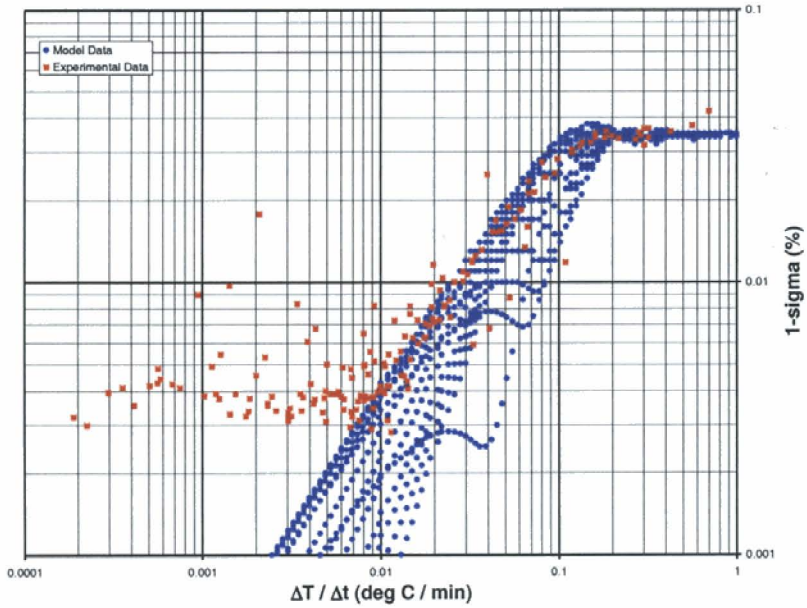


Figure 9: Intensity fluctuation (1-sigma, %) vs. temperature drift (ΔT / Δt), modeled and experimental data (multiple model plots represent different phase starting points)

5. CONCLUSION

In this paper, we have described and experimentally verified the xPM model, which propagates polarized light through an arbitrarily long chain of polarization maintaining components and determines both the state of polarization at the end of a chain and the output power fluctuation if the chain is terminated with a polarizer. The model was then used to determine the actual polarization maintaining properties of couplers, fusion splices and connectors which would be used in the SIM PlanetQuest Fiber Distribution Assembly. Through a series of experiments the temperature sensitivity of Corning PANDA PM fiber was found to be 1.44 rad/ °C-m at 1319 nm. This value was used to derive a maximum allowable temperature drift that can be seen by the fiber cables and yet meet the prescribed intensity stability requirements.

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