

SCDU (Spectral Calibration Development Unit) Testbed Narrow Angle Astrometric Performance

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ABSTRACT

The most stringent astrometric performance requirements on NASA's SIM(Space Interferometer Mission)-Lite mission will come from the so-called Narrow-Angle (NA) observing scenario, aimed at finding Earth-like exoplanets, where the interferometer chops between the target star and several nearby reference stars multiple times over the course of a single visit. Previously, about 20 pm NA error with various shifts was reported¹. Since then, investigation has been under way to understand the mechanisms that give rise to these shifts. In this paper we report our findings, the adopted mitigation strategies, and the resulting testbed performance.

Key words: SIM, SCDU, Interferometer, Astrometry, Spectral Calibration, Narrow Angle

1. INTRODUCTION

SIM-Lite is a space-borne stellar interferometer capable of searching for Earth-like exoplanet in the habitable zones of nearby stars. This search will require measurement of astrometric angles with sub micro-arcsecond accuracy and optical pathlength differences to 1 picometer by the end of the five-year mission². Various systematic errors that can affect the performance of SIM-Lite have been addressed in the technology program for SIM over the past decade. A remaining one is the spectral calibration (systematic errors due to spectral differences between planet-finding targets and their nearby reference stars). SCDU is designed to show that the chromatic effect encountered by SIM-Lite can be calibrated to the sub-microarcsecond level.

With the 6 meter baseline of SIM-Lite, 1 microarcsecond error is equivalent to 30pm single measurement accuracy, and 42pm differential accuracy which is applicable to NA error. If this system error is white noise, it will be reduced by averaging more samples, i.e., following the $1/\sqrt{N}$ line, where N is the # of samples. The goal of SCDU is to demonstrate the feasibility of achieving 1pm Allan Deviation after 200 visit of SIM narrow angle observations. Although current SIM AEB does not have specific allocation for SCDU which covers across several AEB branches, this requirement suggests that effective SIM AEB allocation for SCDU is around 14pm. The second requirement on NA error is to show that it is close to the white noise hence can be reduced with more NA visits (observations).

Previously in November 2007, SCDU team demonstrated about 20 pm NA error across 2 months of measurement with big bias shifting (>30pm) observed. Since then, extensive investigations have been done to improve the performance. By March 2010, we have achieved about 13pm NA error across 5 month of measurement with much less bias shifting (~10pm) that is explainable.

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In SCDU, a typical NA visit (called short stroke in SCDU jargon) is consist of 13 target looks and 12 reference looks, taking about 20 minutes, including the time spent on slewing between starts, settling the instrument, and acquiring the stars in the angle tracker cameras.

In this paper, we will cover various sensitivities studies on NA performance in section 2, and present the current NA performance in section 3, followed by the summary in section 4.

2. SENSITIVITIES ON NA PERFORMANCE

2.1 Long stroke

A spectral calibration algorithm³ is developed to estimate the white light fringe and evaluate the NA performance. A typical spectral calibration set (called long stroke in SCDU jargon) includes the spectral source calibrations and the instrument calibrations. Spectral source calibrations measure spectra of the target and reference (determine the stellar spectra ratio). Instrument calibrations measure the instrument's spectral response. A series of long stroke sensitivities on NA performance have been studied⁴, where the stroke length, the stroke speed, the model bandwidth, and the metrology cyclic error are discussed and optimized. Another important error related to long stroke is the random calibration errors arise from photon shot noise, FTC CCD read noise, and random vibrations. The upper bound to the random errors can be determined using multiple long stroke instrument calibrations for the same narrow angle observation. For SCDU, this random error is estimated to be around 10pm. Figure 3 shows two such tests.

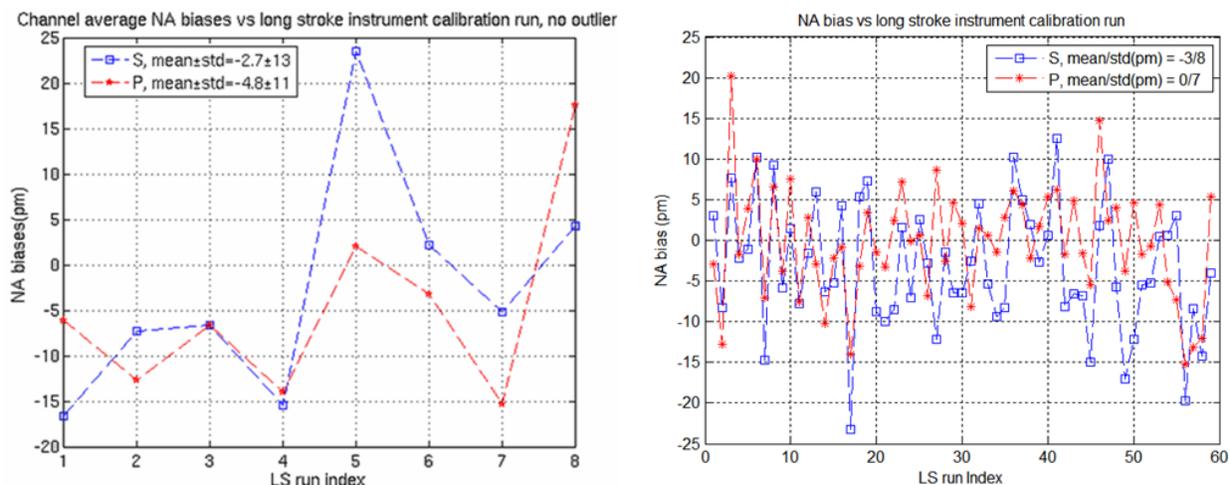


Figure 3 Long stroke random calibration error

2.2 Color dependent centroid shifts (CDCS)

While monitoring ATC tracking quality during the filter chopping, a color dependent centroid shifts (CDCS) was discovered. It was found that the ATC tracking centroid is changing when we change one filter to another, i.e., the pointing measured at ATC has a color-dependent shift. Since the siderostats are controlled using the ATC data, a situation can occur where there is in fact no pointing change in going from one color star to the next, but the ATC reports a change and the angle tracker commands a tilt for a siderostat. Such a color dependent, systematic tilt error in the siderostat can couple with a shear between the white light and the metrology to result in an error of the form⁵: $d = 2S_{WM}\theta_{sid}$

where S_{WM} is the shear and θ_{sid} is the siderostat tracking error. SCDO team have investigated the CDCS issue thoroughly and traced it down to the testbed wavefront error⁶. Figure 4 shows its impact on NA performance by comparing the NA error with or without correcting CDCS.

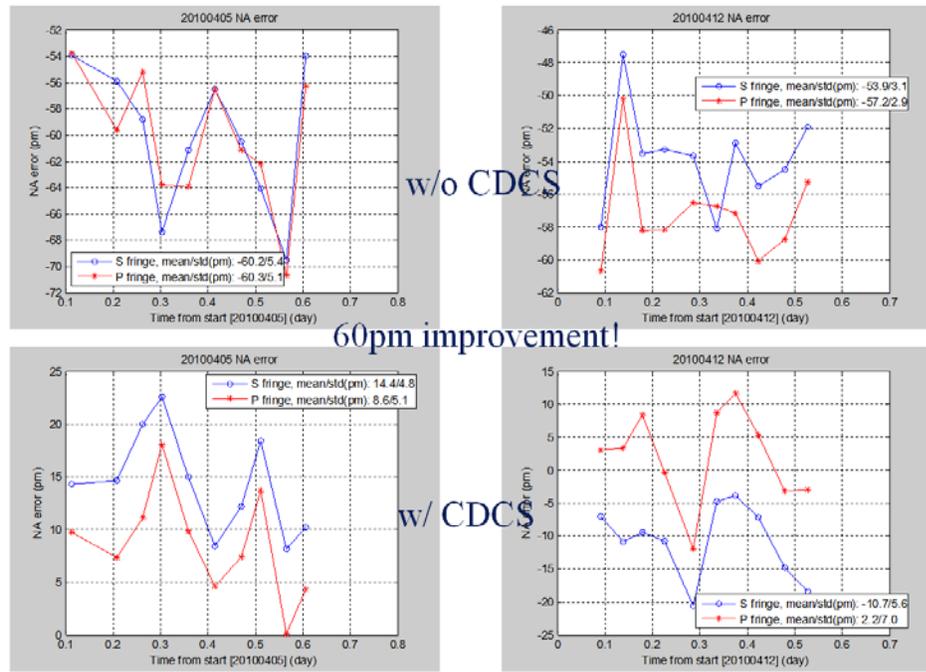


Figure 4 Comparison of NA error with and without CDCS applied.

2.3 Pointing sensitivity

Pointing sensitivity (PS) arises from a shear error between starlight and metrology at the siderostat. To quantify it, we can modulate the siderostat in triangle wave pattern and look at the linear response to the pointing change in the white light fringe OPD. $d(OPD)/d\theta$ gives the pointing sensitivity in pm/urad (effective unit at μm). We have developed a methodology to minimize these shears, either commonly by moving starlight mask, or differentially by using the R4/L4 mirrors. Figure 5 shows the PS improvement. For example, differential PS between left and right arm in X direction is reduced from $>300\mu m$ to $20\mu m$.

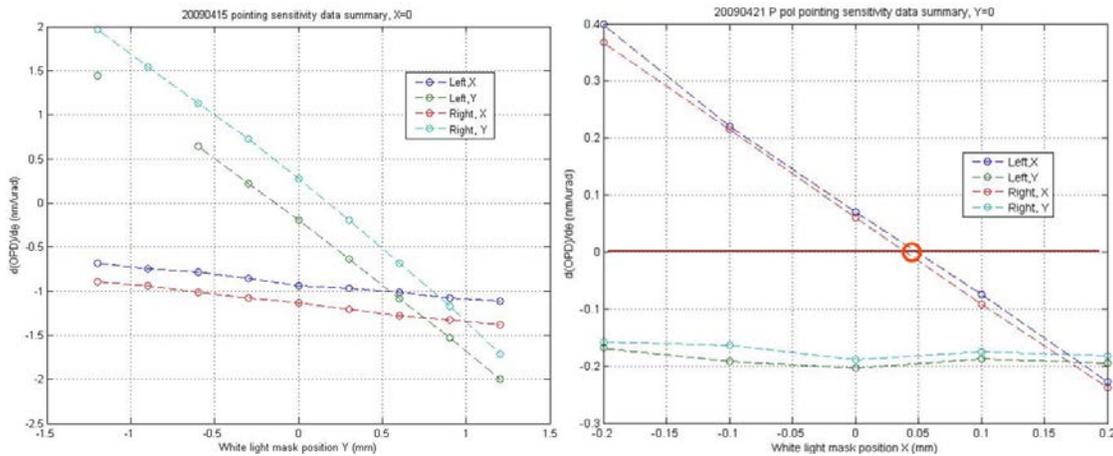


Figure 5 Pointing sensitivity improvement

We have found that the absolute PS has less importance than differential PS on NA performance. For example, in Figure 4, the absolute PS on 4/5/2010 run and 4/12/2010 run are 0.2mm and 1.1mm, respectively, but the NA error is about the same with the differential PS at each batch found to be about the same (both are at $\sim 30\mu\text{m}$).

2.4 Temperature

Typical SIM thermal environment is estimated to be around 1.3mk/hr RMS (From SIM thermal mode of ABC bench over 100 hour). Unfortunately, typical SCDU thermal environment is much worse than that. It is expected that temperature will play an important role on the drifting of the system status. That is why we have many temperature sensors at various places of the testbed. A few notable findings on the correlation between hardware and temperature are listed in Figure 6.

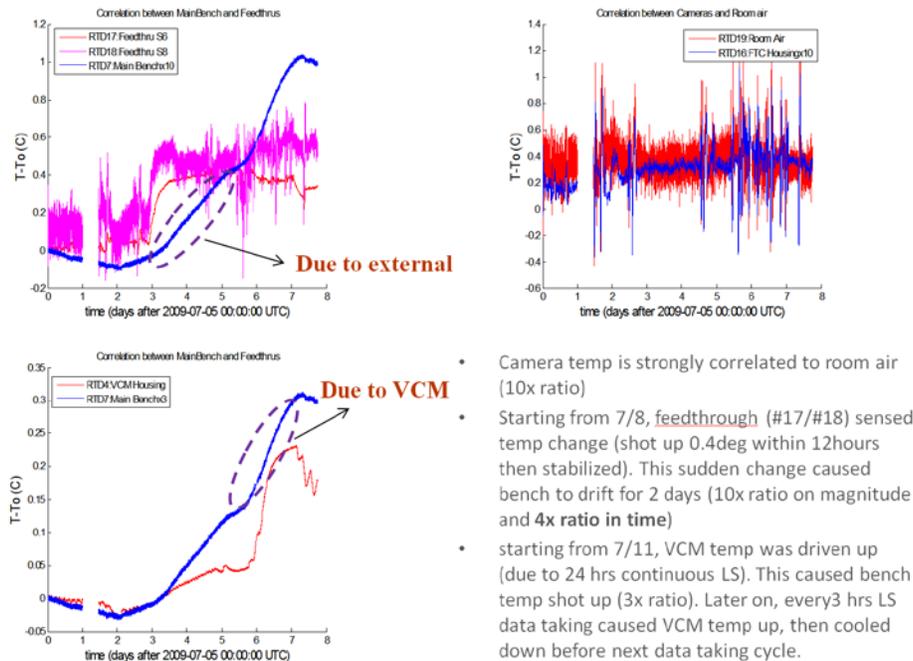


Figure 6. SCDU hardware vs chamber temperature correlation findings

To quantify the sensitivity of temperature on the NA performance, we have measured the NA error at various thermal environments (Figure 7). It clearly shows that the standard variation of the NA error almost linearly correlated to the temperature (2-3 pm per mk/hr). Figure 8 shows the strong correlation found between the testbed alignment status (tilt/shear) and temperature.

2.5 FTC centroid placement

This temperature correlation study led us to rethink a better way to operate the testbed given that we have very limited control on the thermal environment due to various reasons. SCDU relies on ATC to control the pointing and ensure both left and right arm not moving on the FTC. This so-called ATC-FTC registration is degraded in the presence of the thermal gradient. In SCDU, a stabilized He-Ne source is incorporated into the white light source through a mechanical switch to get single spot at FTC, ensuring the accurate centroid measurements.

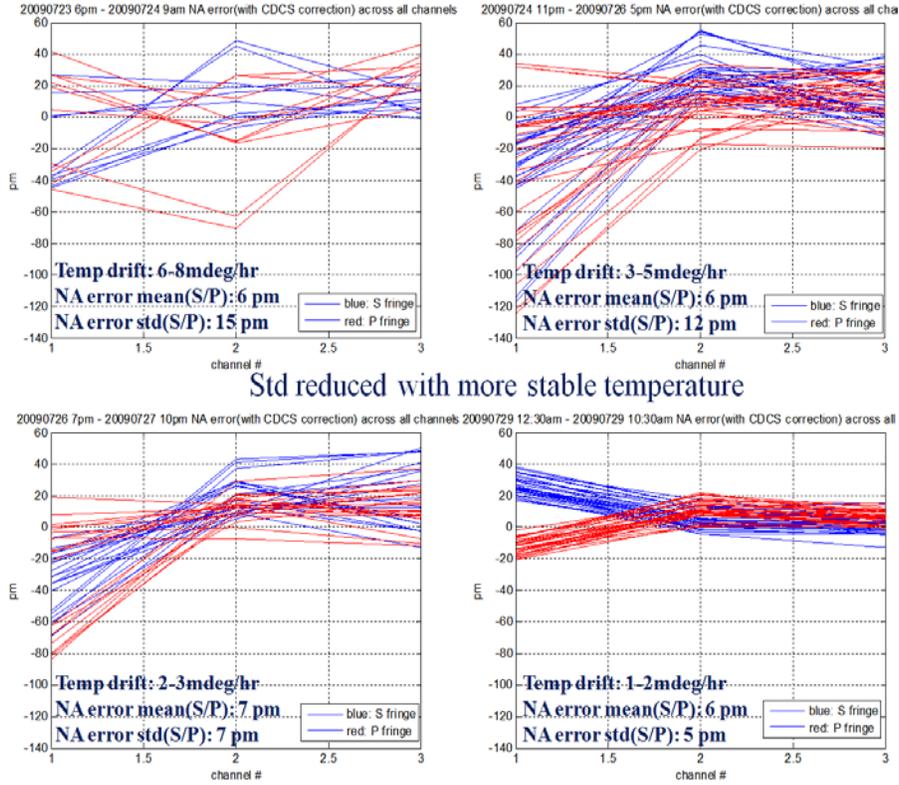


Figure 7 NA performance on various temperature environments

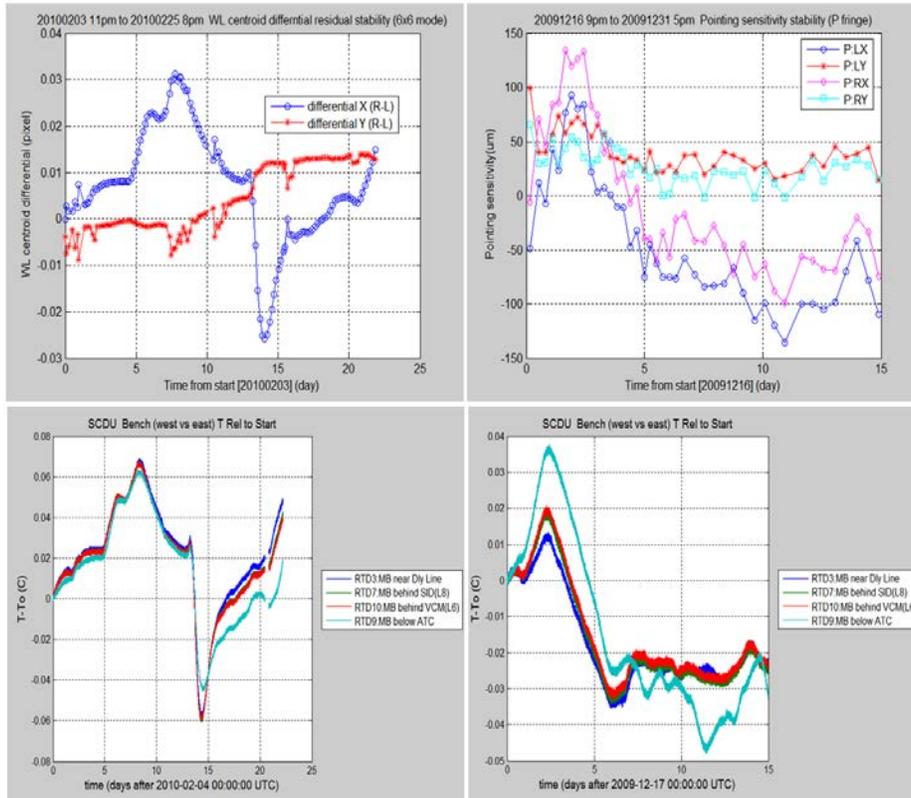


Figure 8 Correlation between WL centroid, pointing sensitivity, and temperature

Two types of change (common or differential) on ATC-FTC registration could happen, and neither is immune from the calibration error. Common-mode change from long stroke to short stroke makes the phase dispersion function from long stroke not accurate, causing a calibration error. Differential-mode change makes the phase difference between the left and right arm varying, and tends to cause larger calibration error. Figure 9 shows the measured NA error as the FTC fringe placement is changed from a nominal starting point.

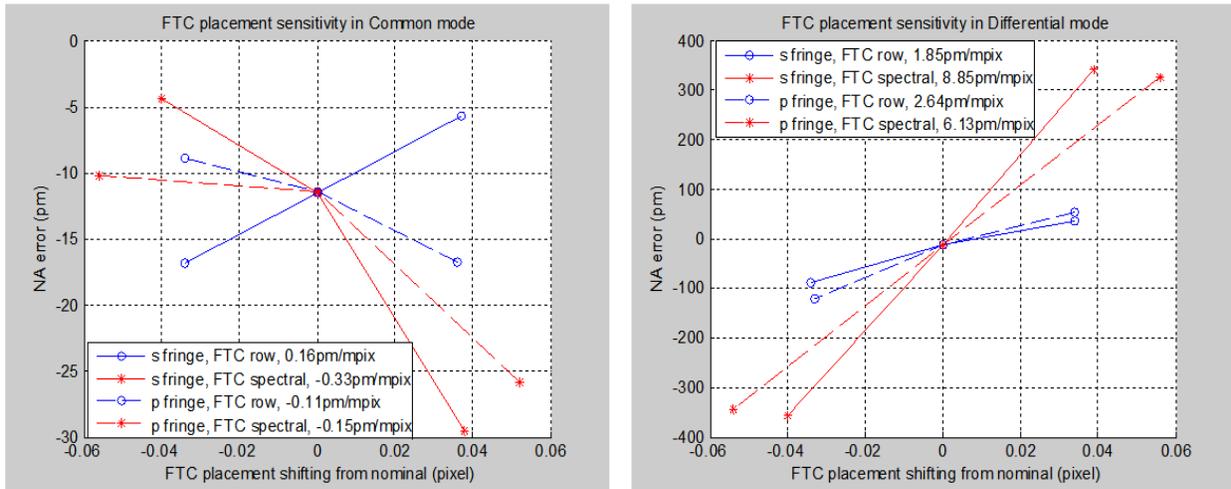


Figure 9 FTC fringe placement sensitivity (common mode and differential mode)

As expected, the differential mode has much larger sensitivity than that of common mode. It is also found that the sensitivity in spectral direction is 4 times larger than that in row direction. Figure 10 shows one measurement on the stability of FTC centroid placement and its correlation to the thermal environment. It is found that the centroid placement in spectral direction correlates with camera temperature, and the centroid placement in row direction correlates with bench temperature below ATC. Given $\sim 8\text{pm/mpix}$ sensitivity and $\sim 10\text{mpix}$ drifting, the NA error could be shifted by 80pm! This ATC-FTC registration drifting is believed to be the main contributor to the big shifting on NA error previously observed in November 2007.

So, if we can fix the ATC-FTC registration throughout the measurement, the NA performance should be stable or less sensitive to the thermal environment. To control the AT-FT registration, we routinely measured centroid of the He-Ne spot, and triggered the control loop if it was off the target by offsetting ATC to a new tracking point. Figure 11 shows the effectiveness of the FTC fringe placement control. The strong correlation between NA error and temperature observed in the left column (no placement control) is gone in the right column (with placement control), meaning the temperature sensitivity is significantly reduced. Looking at the channel-by-channel errors, the variation in the controlled case is much smaller for channel 2-4 where the NA errors are weighted most. While promising, to meet the SIM requirement, FTC centroid placement control need to reach $\sim 1\text{mpix}$ accuracy, which turns out to be not feasible with the current SCDU hardware. Instead, a passive approach (interpolation LS) in the data processing is finally adopted to mitigate the drifting of ATC-FTC registration. This interpolation removes a temporal linear trend in the fringe placement error, and was found to be adequate for meeting SIM requirements.

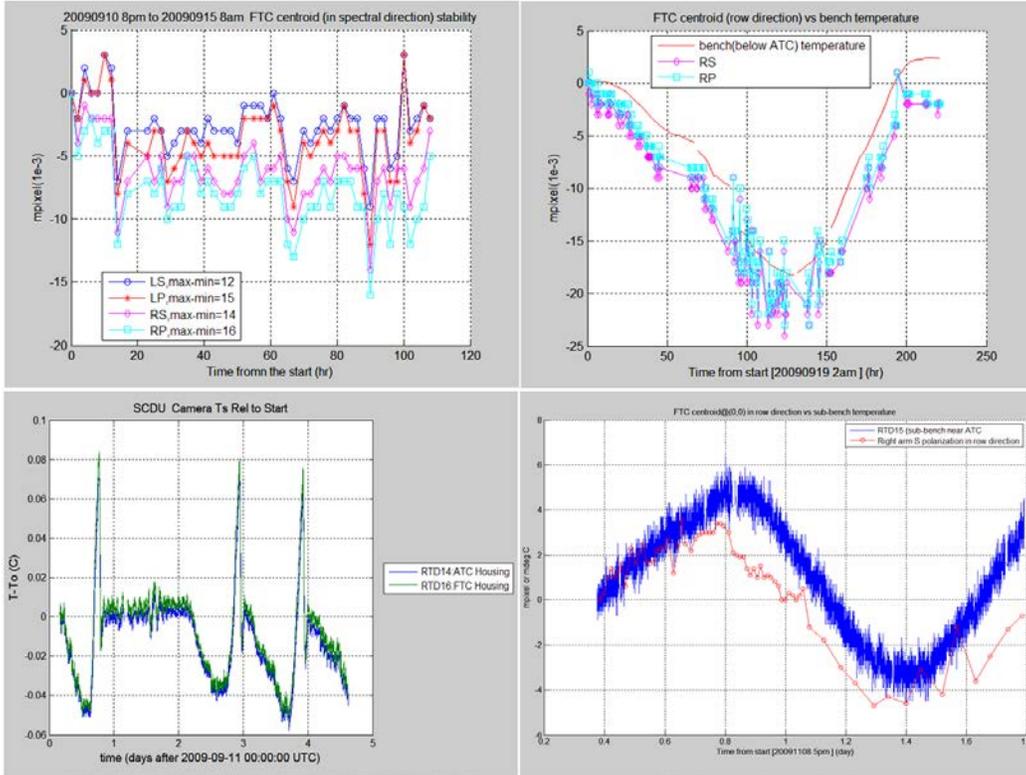


Figure 10 FTC fringe placement correlation on temperature

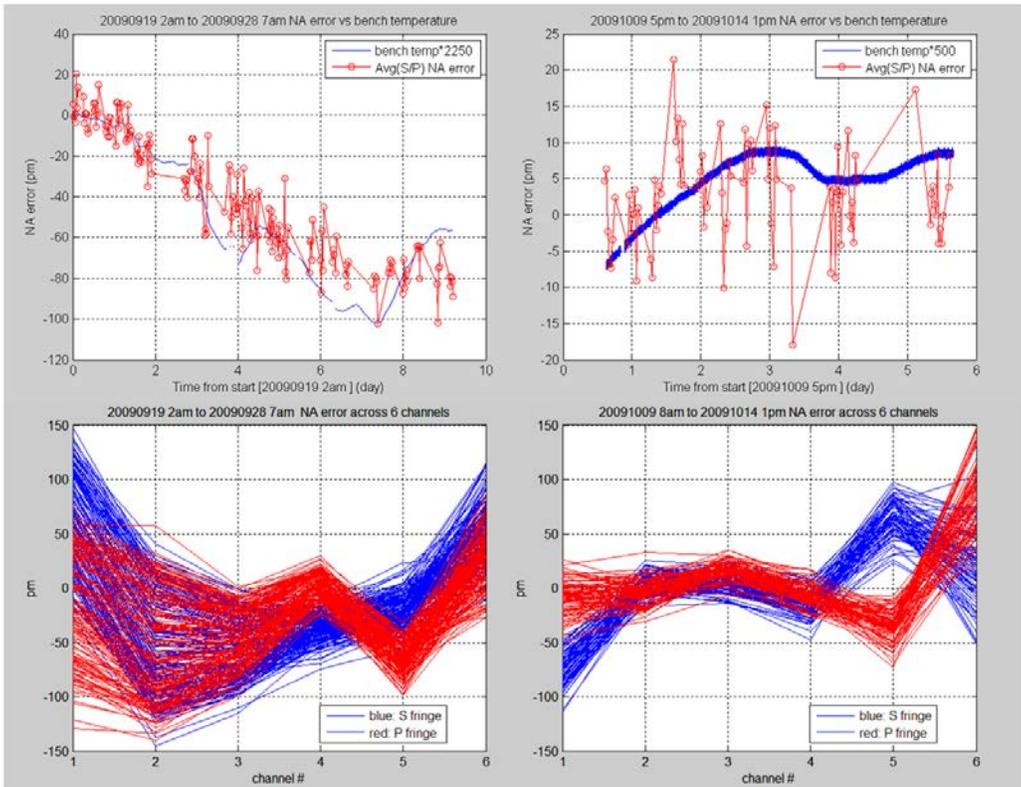


Figure 11 Impact of FTC fringe placement control (left: no control; right: controlled)

3. CURRENT NA PERFORMANCE

3.1 SCDU data

By the end of 9/2009, testbed configuring was mainly done. A set of measurement tools on various system status had been developed and put in place⁷. This characterization capability not only helped us to align the system to its optimal, but also greatly helped us to understand the measured NA performance. Starting from 10/2009, we began to concentrate on getting enough statistic of the measurement data to meet the SIM requirement. Among the 5 months of testbed operation, we experienced huge temperature variation, troubleshot/fixed ATC electronic problem, changed lightbulb twice, vented/pumped the SCDU chamber 3 times, and realigned the system numerous times in between. In the end, we have collected ~50 days of data from which demonstrate the feasibility of achieving 1pm Allan deviation after 200 NA visit. Figure 12 shows various SCDU testbed activities from 10/2009 to 2/2010.

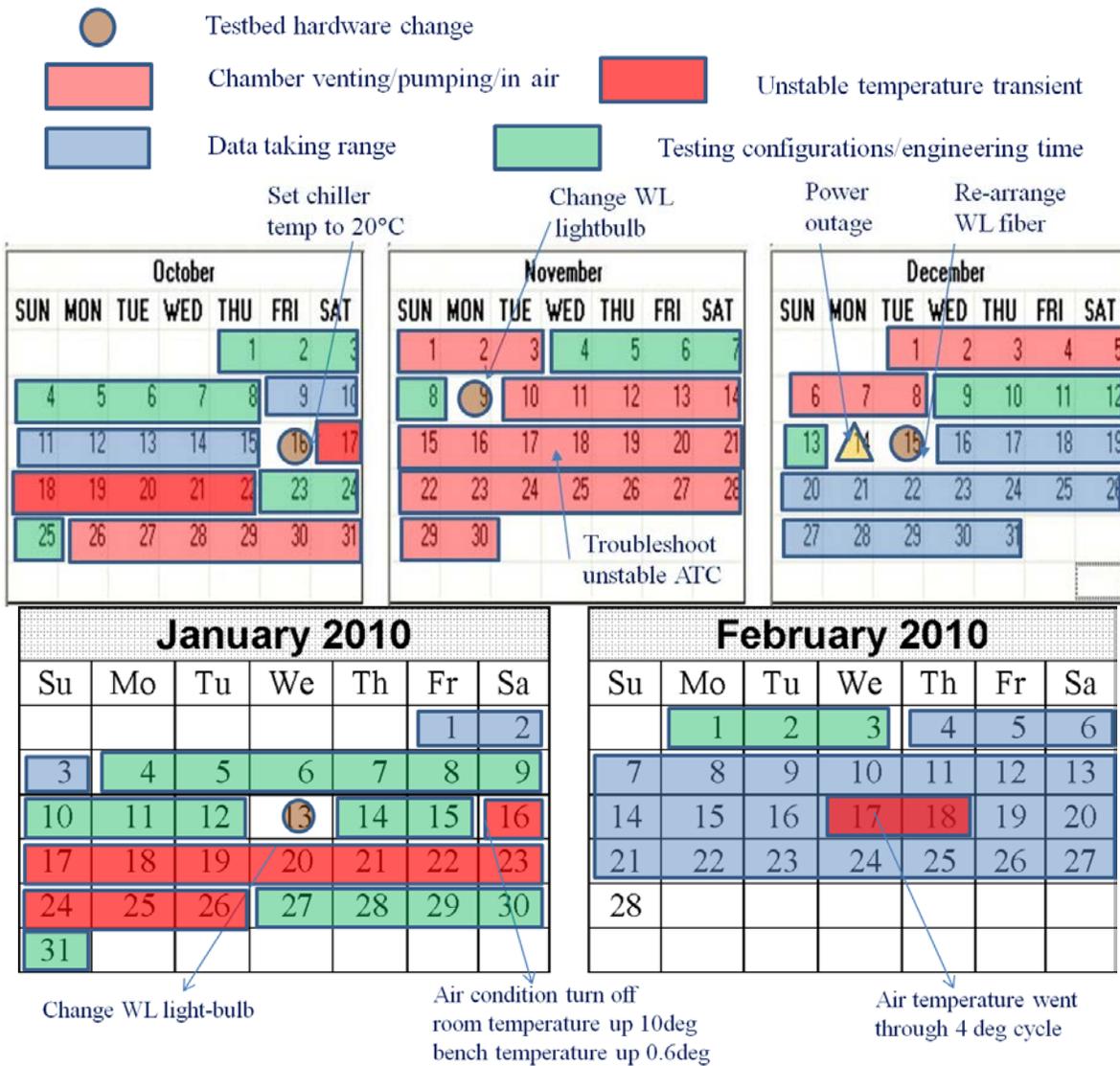


Figure 12 SCDU testbed activities from 10/2009 to 2/2010.

3.2 SCDU data processing schemes

To estimate the NA error, several calibration schemes have been proposed. The key difference is how often the long stroke (LS) calibration is done or which LS we will use for each NA run. 1) Nearest LS is to process a NA run using its closest (in time frame) LS. It could have the best calibration on drifting aspect, but could be hit by the randomness of LS calibration as shown previously in Section 2.1. 2) Same LS is to process all NA runs at each data batch with the same LS. It is the other extreme and just opposite to the nearest LS. 3) Daily LS is to process a NA run using its preceding LS, and only one LS is calibrated per day. 4) Interpolation LS is to interpolate the instrument calibration results from the preceding and succeeding instrument calibrations to arrive at a calibration effective to the time of the NA visit and use this interpolated calibration to process that NA run.

Choice of processing scheme has to be decided from SIM perspective and should be consistent with SIM observation scenario. Per SIM operation, the first two schemes are not feasible or practicable. The last scheme applied the interpolation technique and could help greatly if the drifting is linear. Figure 13 shows the improvement that interpolation brings in. The same 33 NA runs are processed with either daily LS or interpolation LS.

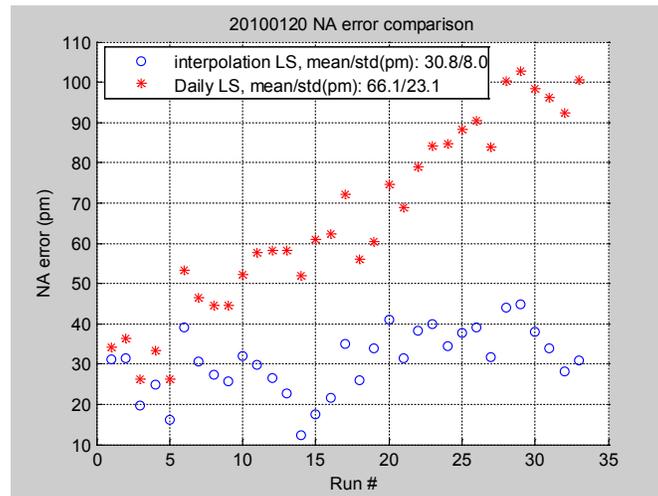


Figure 13. Effectiveness of interpolation LS on NA error

To simulate the SIM operation of 200 NA visits, with daily LS scheme which was adopted initially as the official data processing approach, we need to take at least 200 days of data. This makes it impractical for SCUDU. Later on, a new data processing scheme was implemented. Previously, we were concentrated on NA run: fix the NA and find the matching LS. Now let us concentrate on LS run: fix LS and find the matching NA. To get 200 “effective” NA runs (processed by daily LS), we can just create a pool of daily LS pair (>200) by collecting many instrument calibration runs interleaving with NA visits, then find the NA embedded within each daily LS pair from that pool. This “compressed” SIM mission (random NA per daily LS pair) not only makes it possible for SCUDU to get enough data to mimic SIM operation, but also take advantage of averaging LS instrument calibrations to reduce its own random error. Since the random NA per daily LS pair concept was not adopted until very late of the SCUDU measurement, only the last few data batches were collected with that concept in mind. Hence the ratio of NA per LS is much larger for earlier data batches.

Here is the detail/procedure of random NA per daily LS pair scheme.

1. Create one pool of LS and one pool of NA runs.
2. from the pool of LS, randomly select a daily LS pairs, consisting of 2 LS that are separately by about 24hours. Repeat this random selection until all possible unique daily LS pairs are defined.
3. for each daily LS pair, from the pool of NA runs, randomly select a number of NA runs(2, 4, or 8) within (in time frame) the selected daily LS pair.
4. Once a NA run is selected, remove it from the pool of NA run; each NA run is used only once. This ensures NA run is evenly distributed relative to the LS. Repeat this step until all daily LS pairs are used up
5. Process the selected data set (daily LS pair and NA run). Interpolate the daily LS pair to get an effective calibration at the time of the NA visit and use that interpolated calibration to process the NA run.

3.3 NA Performance

Figure 14 shows the current NA performance with 10/2009, 12/2009 and 2/2010 data on the same chart which plots the Allan deviation of the NA error vs number of visits. The NA error is about 13pm for single visit and got averaged down by $1/\sqrt{N}$, following the white noise line. After about 200 NA visits, the NA error reaches 1pm range. All three batches are along the white noise line, which suggests the repeatability of different data batches. Figure 15 has repeatability test on data selections, where NA errors of 5 selections from the same data batch (Feb 2010) are plot all together. It doesn't show much difference among these 5 selections. Figure 16 plots NA error sensitivity on # of NA run selected per LS pair. It shows small difference after 200 visits.

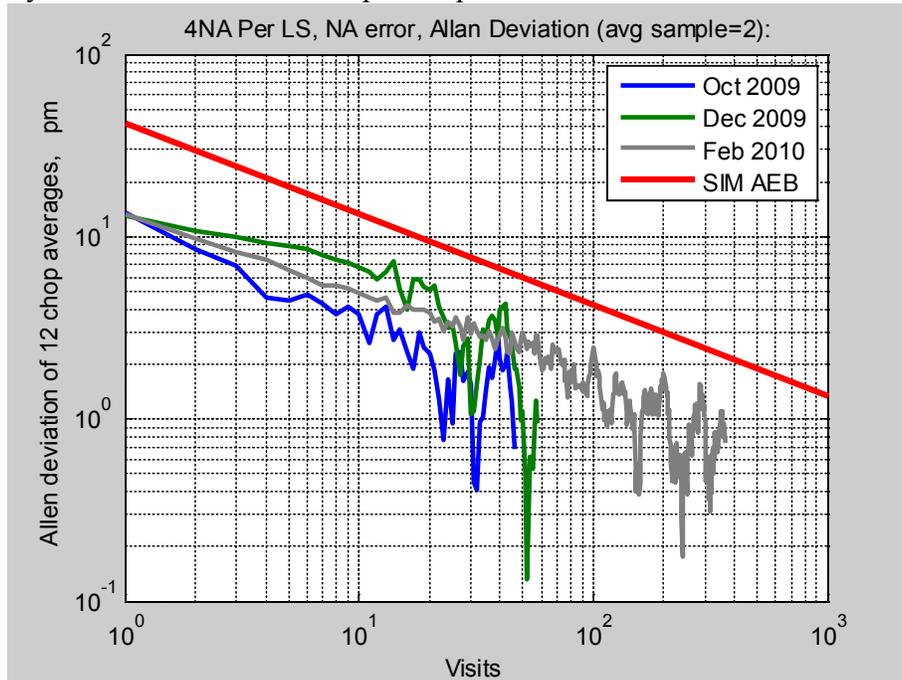


Figure 14 NA error is averaged down nicely along the white noise line

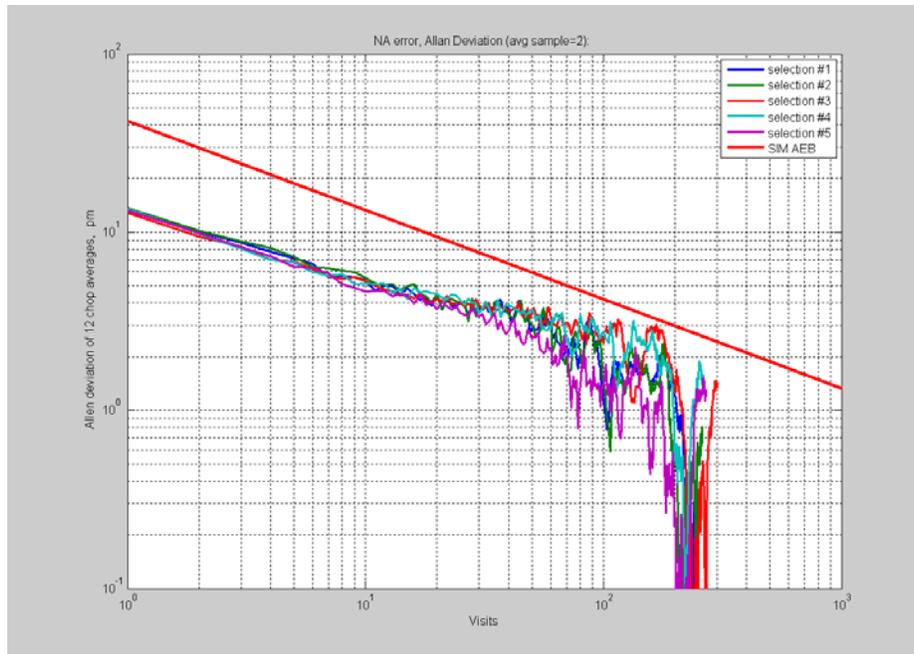


Figure 15 Repeatability test on different selections out of same data batch

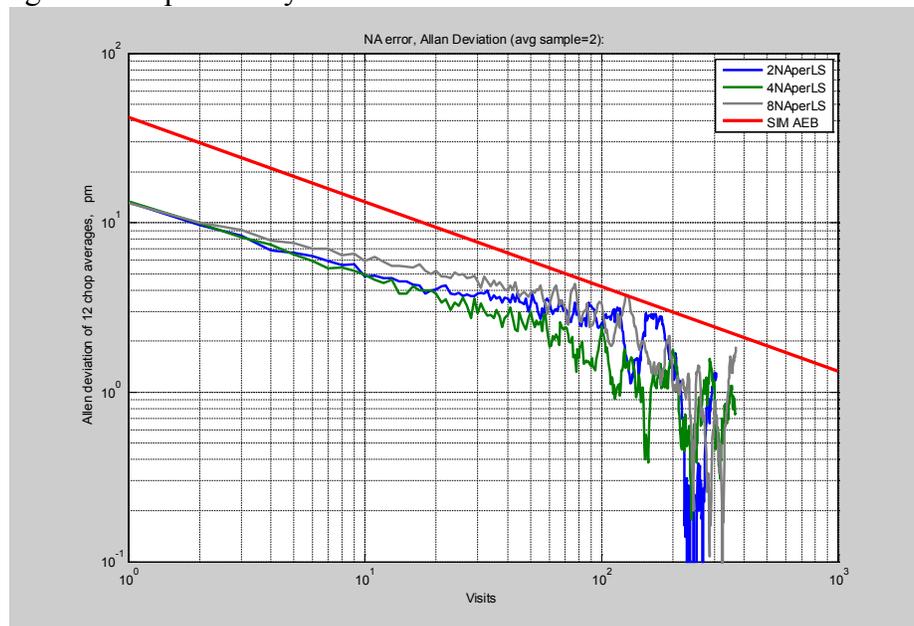


Figure 16 Sensitivity of # of NA selection on NA performance

Another interesting chart on the NA performance is Figure 17 where we plot NA performance of single filter, 8/2009 data processed with nearest LS approach, and 2/2010 data processed with random NA per daily LS pair approach. Single filter experiment is the NA error measurement by chopping the same color filter. This essentially defines the absolute testbed system noise floor. 8/2009 represents an ideal case of two color filters measurement where, for each NA visit, a LS calibration is carried out, separated by only minutes. While this observing scenario is impractical since SIM Lite can't afford such frequent instrument calibration, the result itself sets a practical noise floor on SCDU NA performance.

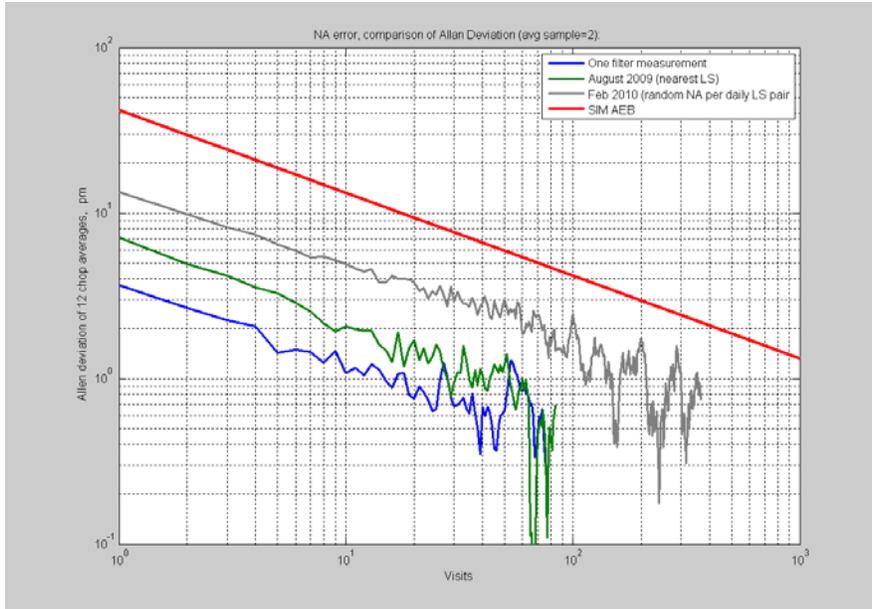


Figure 17 Comparison of testbed system noise floor (blue), NA performance floor (green), current NA performance (gray), and SIM AEB (red)

The shifting of NA error mean between 3 batches over 5 months is about 10pm level, and can be explained by the fact that we changed white light source twice in between. Figure 18 show the spectrum curves of two color filters at each batch. Clearly these are 3 different color filter sets. And we have learned that³, with the current spectral calibration algorithm, different color filter sets will have different NA error mean.

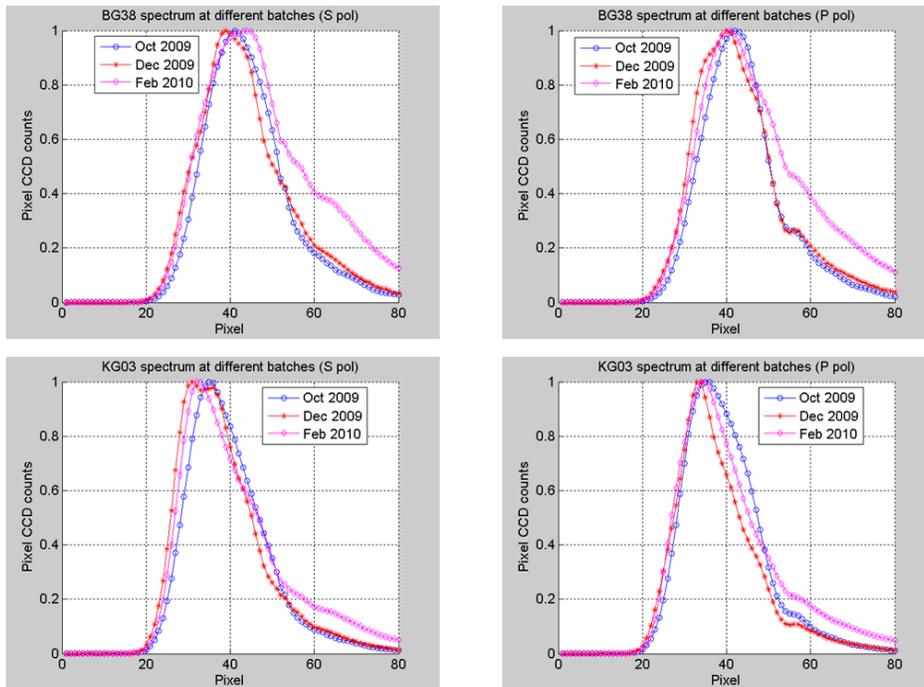


Figure 18 Correlation of differential PS and shifting of the NA error mean

4. SUMMARY

SCDU is designed to show that the chromatic effect encountered by SIM-Lite (Space Interferometer Mission) in the search for nearby Earth-like exoplanet can be calibrated to the sub-microarcsecond level. Over the course of SCDU development⁸, here are some highlights:

1. We have demonstrated the feasibility of achieving 1pm Allan deviation after 200 visit of SIM narrow angle observation.
2. We have found and explored 3 major contributors to improve NA performance: pointing sensitivity, CDCS, and FTC-ATC registration.
3. We have discovered a strong correlation between the system alignment and the thermal environment. This discovery deepened our understanding of the system, and directly triggered the implementation of FTC fringe placement control loop which greatly reduced the drifting of the NA error.
4. We have quantified the FTC centroid placement sensitivity on NA performance is about 8pm/40nrad in differential mode, and 2pm/40nrad in common mode.
5. We have developed a full set of measurement on various system alignment status. This characterization capability not only enables us to align the system to its optimal, but also greatly helps us to understand the measured NA performance.

ACKNOWLEDGEMENT

The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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