An Infrared Polarized Scene Generator for Hardware-in-the-Loop (HWIL) Testing

25 March 2012

Peter S. Erbach [a]
J. Larry Pezzaniti [a]
David B. Chenault [a]

Heard Lowry [b]

Polaris Sensor Technologies
200 Westside Square, Ste 320
Huntsville, AL 35801

Abstract

Polarization signature information is becoming more useful as an added discriminant in a variety of signature analysis applications. However, there are few infrared scene projection systems that provide the capability to inject object simulation images with polarization content into an imaging sensor. In this paper, we discuss a polarization scene generator that is applicable to testing polarimetric sensor systems. The system was originally designed for operation in cryogenic-vacuum environments to test sensors subject to cold operation. However, it is also applicable to testing warm sensors that are sensitive to polarimetric signatures. This polarization scene generator is currently designed for mid-wave infrared (MWIR) operation. It includes two table-top sparse emitter arrays with individually addressable pixels, polarizers, a beam combiner, and filters to provide flexibility in spectral content. The emitter arrays are combined to generate an output with independent linearly polarized content. The current system generates S1 polarization states, S2 polarization states, or a linear combination of the two. The concept is robust because it is relatively unconstrained by the infrared (IR) scene generators used or the sensors tested.

This paper will describe the application, the scene generation system, the sparse emitter arrays, and the results of bench-top performance testing with regard to sensitivity to misalignment, radiance mismatch, and display uniformity.

Keywords: polarization, infrared scene projection, imaging polarimeter, cryogenic, vacuum, polarizer, polarimetry, electro-optic imaging sensor, polarization discrimination, space chamber, MWIR, Stokes image

1.0 Introduction

The majority of test facilities for space-based remote sensors do not have the ability to simulate extended polarized sources, or polarized point source or single pixel polarized objects. The optics in space chambers typically induce unwanted (and unknown) polarization into the projected scene through the use of beam splitters, reflective/refractive optics, filters, and coatings. These polarization artifacts can then interact with the polarization sensitivities of the sensor under test to produce responses that are unexpected and seemingly inexplicable. The primary reason for simulating polarized object signatures is

[a] Polaris Sensor Technologies
[b] Aerospace Testing Alliance.

that polarization is a candidate method for detecting differences in materials and geometries. Polarization may also prove useful for determining orientation of unresolved or only partially resolved objects.

The polarization scene generator (PSG) described in this paper is designed to enable polarized and unpolarized scene generation in space environment simulators developed to test sensors in deep space conditions (20 K background temperature).[i] The chambers operate over the visible to long-wave infrared (LWIR) portions of the spectra. The system can perform all major categories of sensor characterization providing spectrally and radiometrically calibrated signatures. The chambers include several optical test capabilities for studying space environments, hardware-in-the-loop (HWIL) testing, satellite longevity testing, and space sensor and imaging sensor calibration and characterization.[i]

This paper describes the PSG and collimator designed for the AEDC space chamber to project collimated polarized scenes into a sensor under test and the necessary polarimeter optics for verification of PSG performance.

2.0 PSG Design

The overall design for the PSG is shown in Figure 1. The PSG is composed of the PSG source block and the PSG block. The collimating optics assembly, sometimes referred to as the COA, and the relay and reduction optical (RRO) block are subsets of the PSG block.

The major requirements for the system design were as follows: (1) the primary waveband will be MWIR although the design is portable to LWIR, (2) the alignment between the reflected and transmitted sources is within 0.1 pixel of the test polarimeter, (3) the optics, polarizing elements and translation stages must be compatible with cryovacuum environments, (4) the system must be operable in an ambient laboratory environment, and (5) the PSG must generate an arbitrary S1, S2, or a combined S1/S2 image. The S1 and S2 polarization content in the combined S1/S2 image will be dependently coupled.

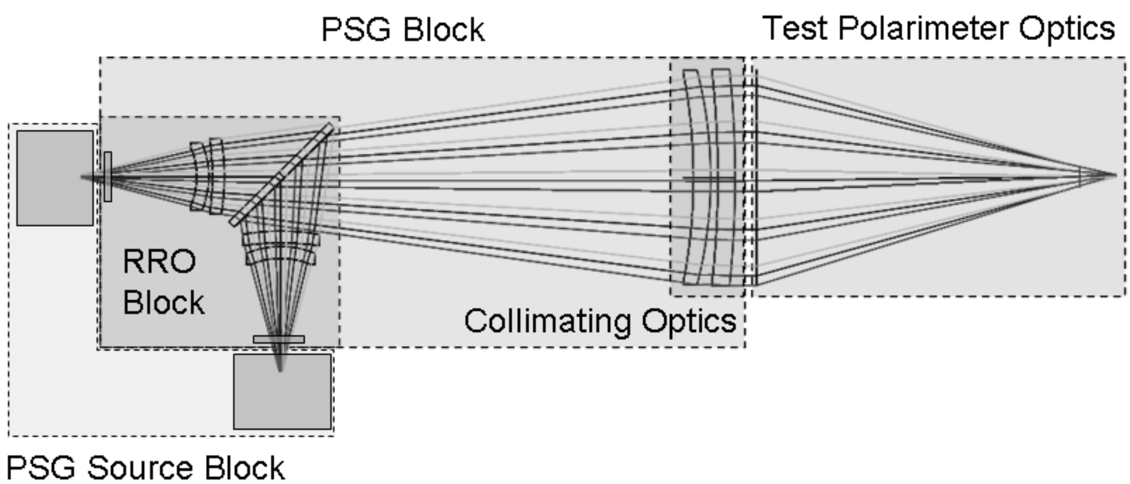

Figure 1. Basic subassemblies of the polarization scene generator

Figure 2 below shows the optical design for the PSG. The collimator is an f/6.5 collimator with a 600-mm focal length. This design was chosen to reduce price and weight for the collimator optics. There is no net effect on operation because the cold stop location/size in the polarimeter, the focal length of the collimator, and the IR source size restrict the usable clear aperture of the collimator to approximately 70 mm.

The germanium (Ge) compensator plate effectively provides the same path length in both the transmission (T) and reflection (R) legs of the PSG. In this way, the distortion and field curvature in both paths are matched as shown below (Figure 3).

The Ge beam combiner and compensator plate (BC/CP) both require anti-reflection (AR) coatings. The beam combiner requires an AR coating on only one side, whereas the compensator requires AR coatings on both sides. We examined the effect of the retardance introduced by the AR coatings on desired polarization states. We can see in Figure 3 below that there are many points along each path where the AR coatings induce nonzero relative phase shifts between the s- (vert) and p- (horiz) polarization states.

We modeled the beam combiner and compensator performance in Matlab with the AR coating retardance information provided by Dr. Muamer Zukic of Cascade Optical. Our goals were as follows:

- Determine the effects of the coatings on linear polarization
- Determine the best orientations of polarized light to inject into the system such that pure S_1 (0 to 90 deg) or S_2 (45 to -45 deg) states could be generated.

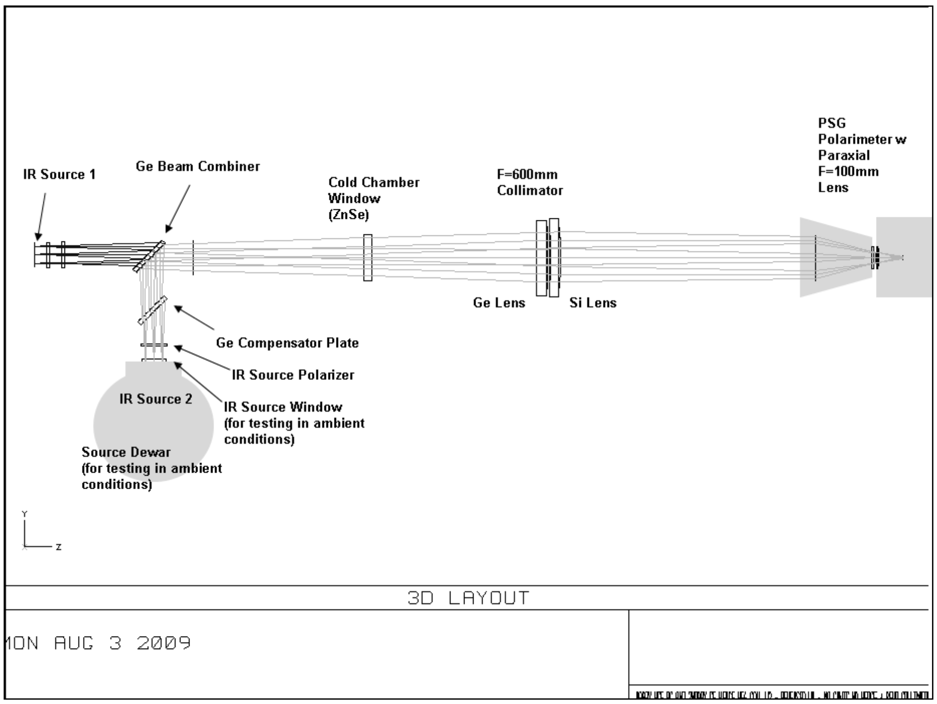

Figure 2. PSG optical design

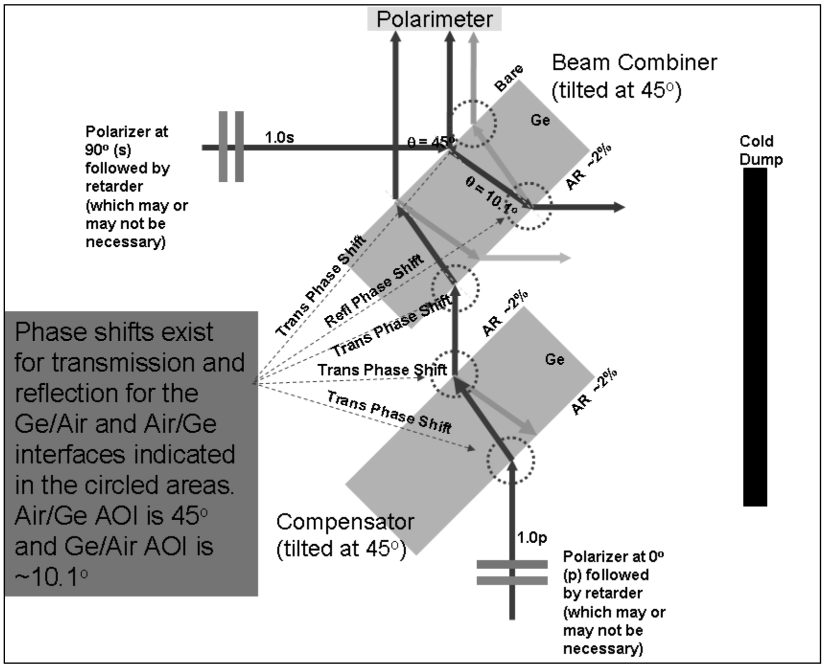

Figure 3. Locations of induced retardance

We originally took the approach of injecting a range of orientations of polarized light through the simulated reflected and transmitted legs of the optical system and then performed an optimization to arrive at the best S_1 or S_2 state. We changed our approach but still used the mathematically characterized system from the earlier effort. We started with the desired polarization states and performed an inversion operation to determine the correct input states. To generate purely 90-deg (0-deg) polarization in the reflected (transmitted) leg of the PSG we inject light linearly polarized at 90 deg (0 deg). To generate purely -45-deg (+45-deg) polarization in the reflected (transmitted) leg of the PSG we inject light linearly polarized at 54.64 deg (39.08 deg).

The results are shown in Figure 4 (for S_1) and Figure 5 (for S_2). The x-axis is injected with polarization state (+/- 0.2 deg). S_1 states are much less sensitive to errors in polarization orientation than in generating the S_2 states, and this is a result of the relative retardance induced by the AR coatings. For example, DOLP (degree of linear polarization) varies by < 0.001 in the S_2 states, and much less than that for the S_1 states. DOCP (degree of circular polarization) is noticeable, but we are only interested in injecting linear states. The modeling indicates that the 3-µm band suffers the worst effects of the retardance induced by the AR coatings. This would not pose a problem for MWIR light-emitting diodes (LEDs), but could pose a slight loss in polarization quality for S_2 generation with broadband sources at temperatures consistent with output in the 3-µm band.

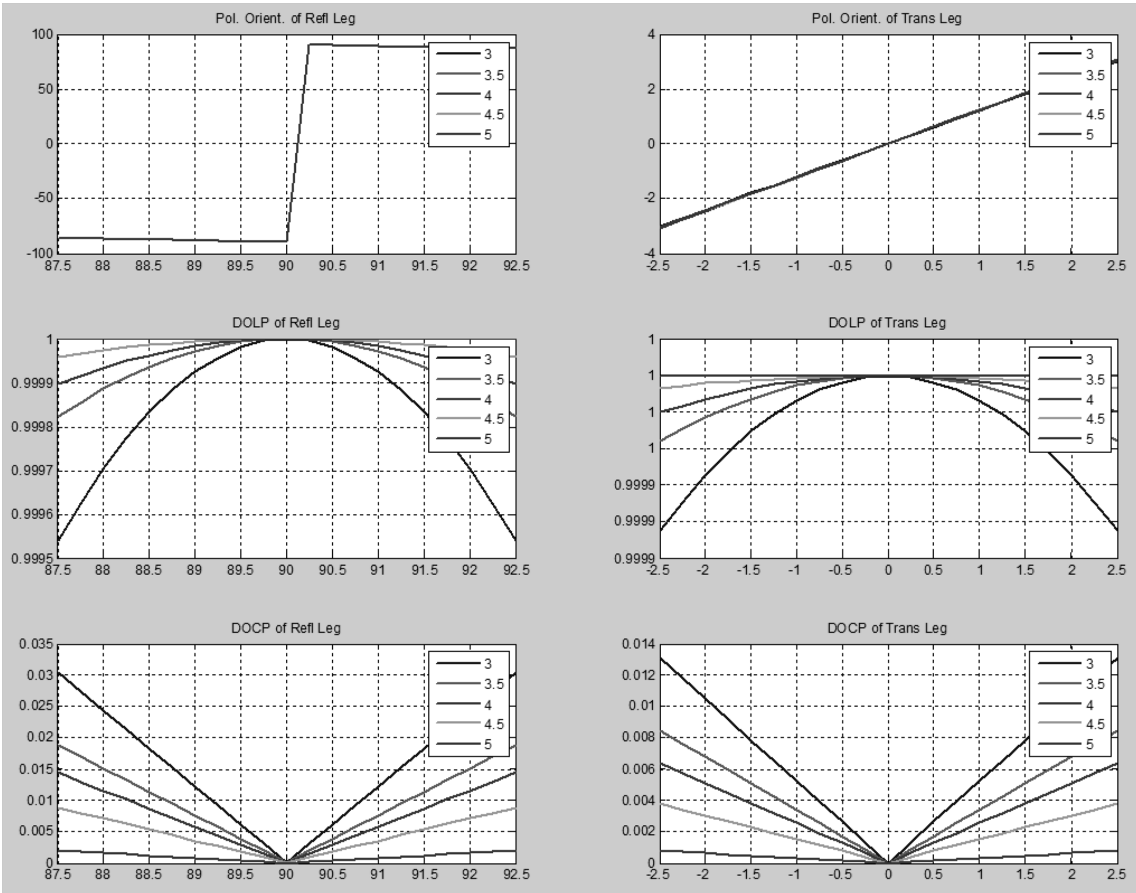

Figure 4. Modeled polarization orientation (top), DOLP (center), and DOCP (bottom) as a result of polarization (x-axis) injected into reflection (left) and transmission (right) legs of the PSG for S_1 states.

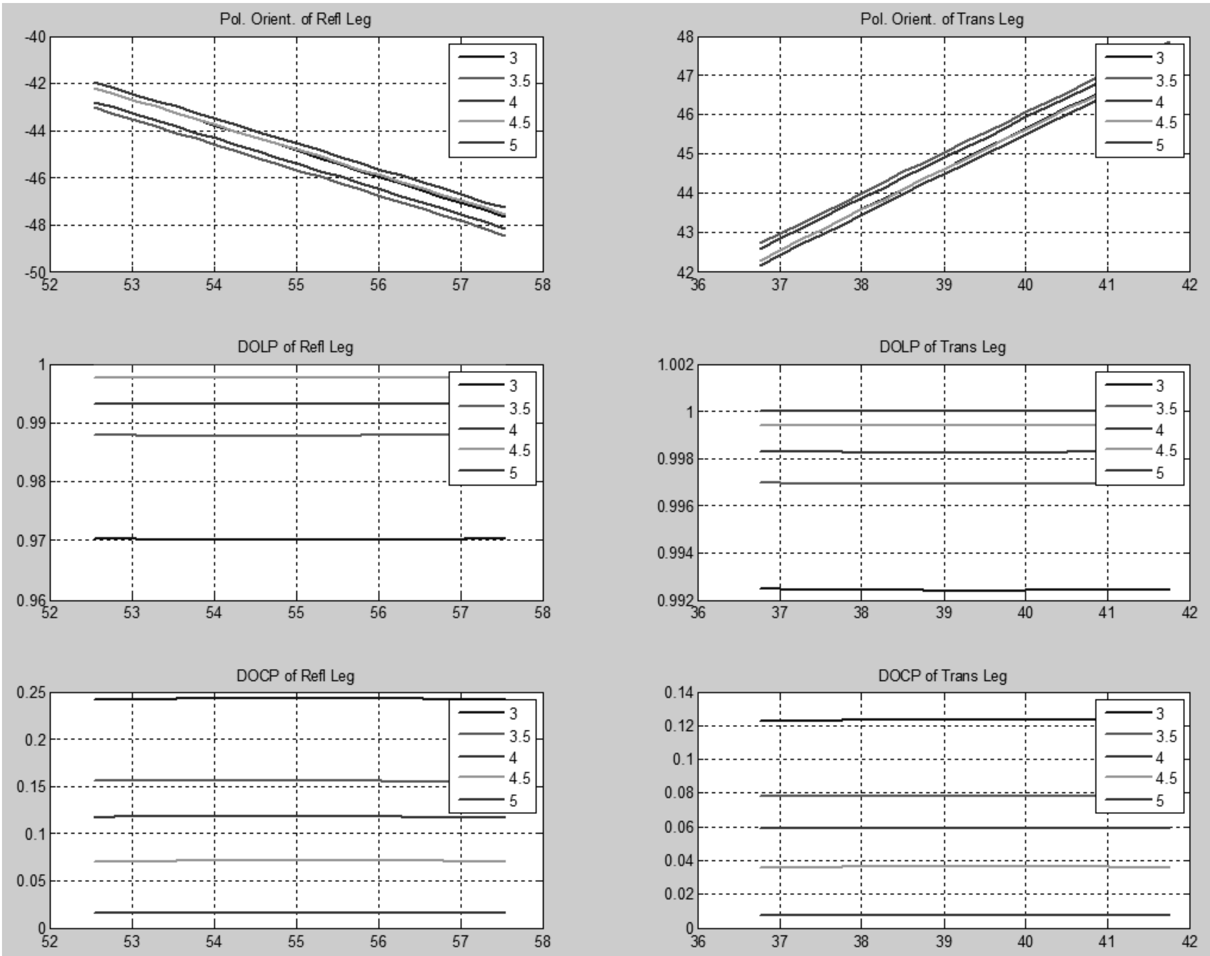

Figure 5. Modeled polarization orientation (top), DOLP (center), and DOCP (bottom) as a result of polarization (x-axis) injected into reflection (left) and transmission (right) legs of the PSG for S_2 states.

Based on this testing we implemented the design concept for the PSG/RRO block development shown in Figure 6. When compared to other concepts, it has the advantages of being a more straightforward design, provides a better vacuum seal, and provides more rapid and effective cooling of source arrays and polarizer rotation mounts.

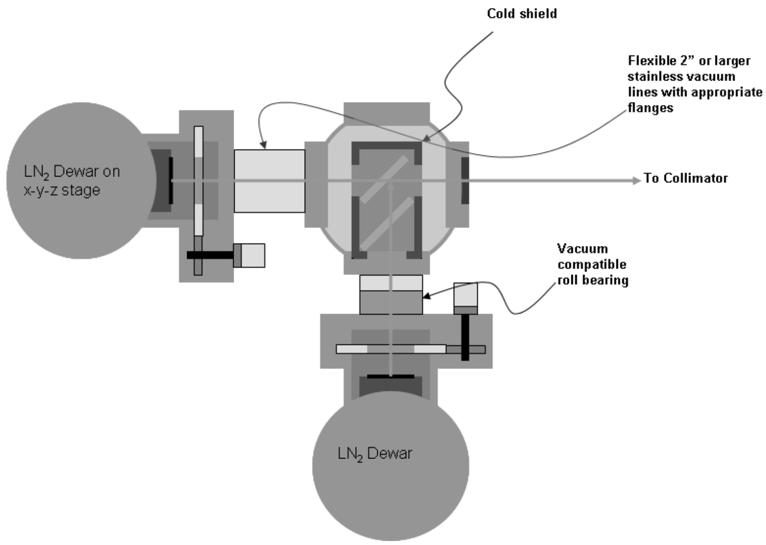

Figure 6. Design concept for the PSG/RRO block

An assembly model is shown in Figure 7 below. The dewar holding the R-leg source array is mounted on a goniometric, roll-capable stage. The T-leg source array dewar is mounted on a X-Y-Z-yaw-pitch-capable stage. The beam combiner and compensator plate are mounted on an inverted cold finger attached to a separate dewar. This mounting scheme mitigates yaw or pitch motion in the mount as the dewar cools. The vacuum chamber for this dewar serves as the mounting point for the entire dewar.

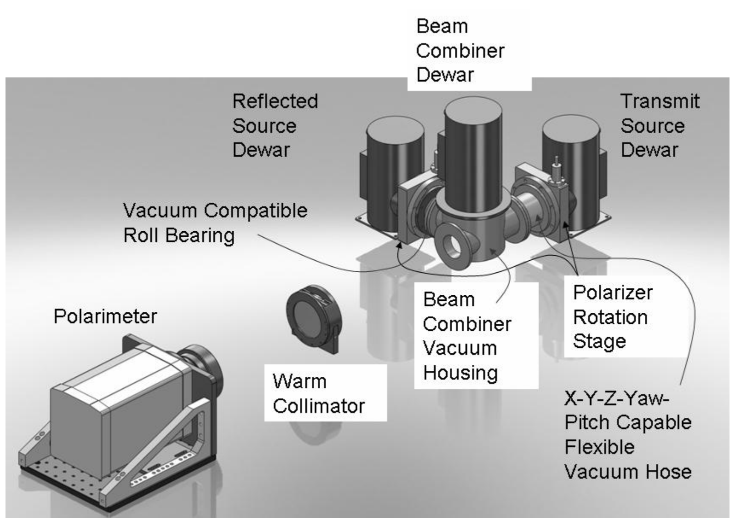

Figure 7. Generalized schematic for PSG demonstrator architecture

3.0 PSG Source Alignment

Registration is the process whereby the T and R source positions are opto-mechanically co-aligned. The goal is that the T and R point-source array point spread function (PSF) positions coincide on the polarimeter focal plane array (FPA) to within 0.1 * PSF diameter. Under ideal conditions the PSF diameter = 2.44 * λ_{cutoff} * f/#. Here λ_{cutoff} ~ 5 µm, and the f/# of the polarimeter is ~ 2.5. This yields a PSF diameter of 30.5 µm. The camera (FLIR SC6000 InSb) FPA pixel size is 25 µm. Therefore we will use 0.1 pixels for the registration criteria.

Because the PSG polarimeter has a fairly linear response from 2,000 analog-to-digital units (ADU) to 12,000 ADU (assuming the 1-msec integration time and 120+ Hz frame-rate), it is not necessary to perform the nonuniformity correction (NUC) and radiometric calibration beforehand.

The first step in the registration process is to perform a rough mechanical alignment of the PSG sources lateral to the optical axis of the PSG. In general, alignment and registration takes the following form: the user turns on only the R source array with the polarimeter polarizer set to 45 deg and the R source polarizer set to 90 deg and focuses the polarimeter on the R sources – shown schematically in Figure 8 (left).

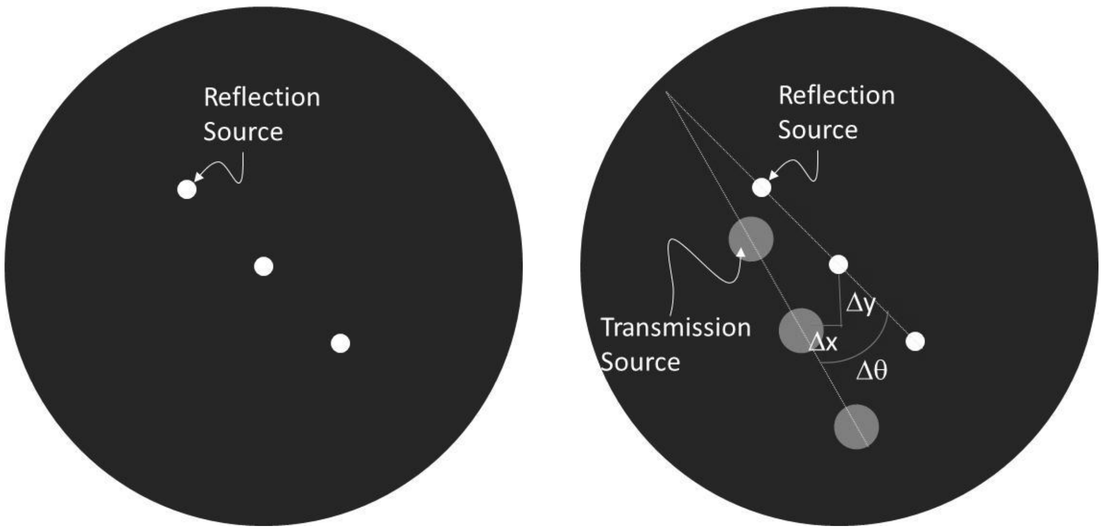

Figure 8. Source registration - locate R sources (left) and location T sources (right)

Next the user would set the T source polarizer to 0 deg and turn on the T sources as shown in Figure 8 (right). Figure 8 shows that the R and T sources are misaligned laterally (X and Y translation), and in roll (θ). The T source PSFs are much larger than the R source PSFs due to defocus of the T source relative to the R source. This is the Z (longitudinal) misalignment. There are multiple paths from this point: the user can correct for roll, defocus, or translation. Figure 9 shows that the translation error and defocus error has been corrected first (left) then the roll error has been corrected (right). Note that differences in output for the R and T point sources can also cause differences in the size of the PSFs at the polarimeter FPA. For example, suppose that after propagation through all the optics in the PSG, the T sources are illuminating the FPA with more energy than the R sources. Suppose also that both sources are equivalently focused and equivalently aberrated and distorted. Then after a certain drive voltage the T source will have a larger lateral size than the R sources due to additional power in the outer pixels. Therefore, not only must the defocus be removed during registration and before polarimetric operations, but also the T and R source power must be reasonably balanced before polarimetric operations can commence.

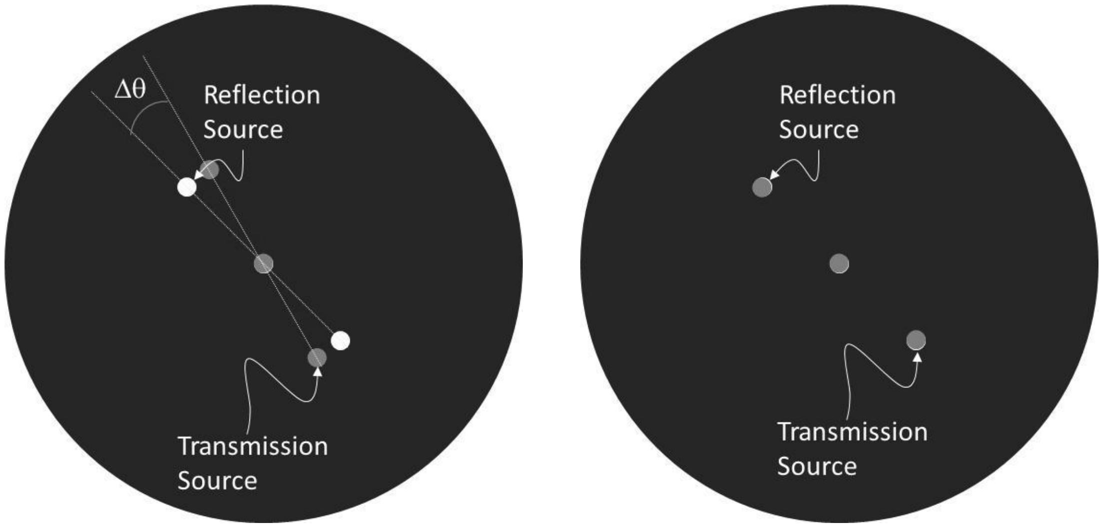

Figure 9. Source registration - align T and R sources in X, Y, and Z (left) and in roll (θ) (right)

The PSG software (SW) provides registration tools to assist the user in the alignment process. A description of the general procedure was acquired while the T and R source dewars and the BC/CP dewar, the PSG, were placed in cryovac conditions. The PSG was evacuated to less than 10^{-4} mbar, and the dewars were continually filled with liquid nitrogen until the T and R source dewars stabilized at 78 K and the BC/CP dewar stabilized at 97 K.

It is important to properly balance the T and R source power at the FPA to achieve good alignment, and it is also important to properly align the sources to achieve good power balance. Thus, the registration and alignment process is iterative. First, the polarimeter polarizer is set to 45 deg and the T and R source polarizers are set to 0 and 90 deg, respectively. When properly power balanced and registered, polarimetric measurements should yield a S_1 value of 0 in this condition. These settings also allow both sources to be viewed simultaneously without nulling one or the other. The T and R source polarizers will be set to 51 and 35 deg, respectively, while the polarimeter polarizer is set to 90 for S_2 operation. This slight rotation in the source polarizers can cause beam wander due to out-of-plane tilts of the polarizers and may require that the procedure need to be repeated.

Prior to using the PSG registration SW, a coarse optomechanical alignment should be performed with the T and R sources powered on to a voltage of 1.5 V – 2 V, and the polarimeter should image the sources at a polarizer position of 45 deg. This provides sufficient source signal strength without saturation. It is not difficult to set the Z position of the R sources near the focus of the FPA via adjustment of the focus barrel on the objective lens. If necessary, a region of interest (ROI) can be drawn around the source and the max and mean value of the box can be observed as the focus is adjusted. After maximizing the R source value at the focus position, the user must afterwards lock the focus barrel on the objective as this sets the focus through the collimator. When both the max and mean are maximized, the R source is in focus. While under vacuum, the Z position can be set using the collar and offset screws in concert with the Z-axis position with the XYZ stage supporting the T source. Once the Z position is "reasonably" set, the X and Y positioners can be adjusted to remove most of the translational error. Then the roll error can be coarsely adjusted by loosening the screws on the R source dewar base that connect it to the optical posts. The R source dewar base can then be rotated until the roll error is minimized and the screws are tightened slightly.

4.0 PSG Calibration

The PSG system is ready for polarimetric measurements after T and R source registration has been completed and after NUC and radiometric calibration has been performed (not described here). It is a good idea to perform some balancing of the T and R source outputs for a given desired polarimetric output. There are several sources of inaccuracies in achieving the desired polarimetric output from the PSG:

- Inaccuracies (resolution) in the source power output adjustment
- Vibrations in the PSG or the polarimeter that can cause the sources to drift on the FPA, resulting in drifts in power detected per pixel
- Variations in blackbody uniformity due to convection currents in front of the blackbody aperture
- Variations in the heating cycle for the micro-blackbody source in the T and R source
- Inaccuracies in determination of the polarimetric constants in the PSG and PSG polarimeter (polarizer band-pass, polarizer diattenuation, polarizer positioning repeatability, etc.)
- Slight mismatches in optical distortion, aberration, and magnification between the T-leg and R-leg of the PSG
- Variation in the cooling and heating of different components in the T-leg and R-leg of the PSG
- Spatial variation in the polarimetric and illumination performance of the optics in the PSG and PSG polarimeter

Prior to source balancing, the user should locate the source points using the software ROI tool to draw boxes around each source point. The boxes should be of sufficient size that they capture the majority of the energy in the spot – such as 11 x 11 or 9 x 9 pixels centered on the centroid. The sources should then be turned off and statistics of the pixels in the boxes recorded (see Figure 10). The T and R source polarizers should be set at 0 and 90 deg, respectively, and the polarimeter polarizer should be set at 45 deg. If the transmission through all of the optics in the T-leg and R-leg of the PSG were matched, having the polarimeter polarizer at 45 deg would balance the output for similar source outputs. However, the power output for each source is not the same. The spatial output from each source is not uniform and behaves similar to the top of a Gaussian illumination pattern that has been clipped by a square. Inaccuracies in locating the micro-blackbody sources in their mounts due to machining errors will result in the pinholes sampling a slightly different region of the source illumination. Furthermore, differences in AR coatings from run to run and Fresnel effects from the Germanium beam combiner optics result in subtle differences between the expected power outputs and the desired power outputs. Regardless, PSG calibration and operation are primarily determined by the power from each source that propagates to the FPA of the polarimeter, not the desired power.

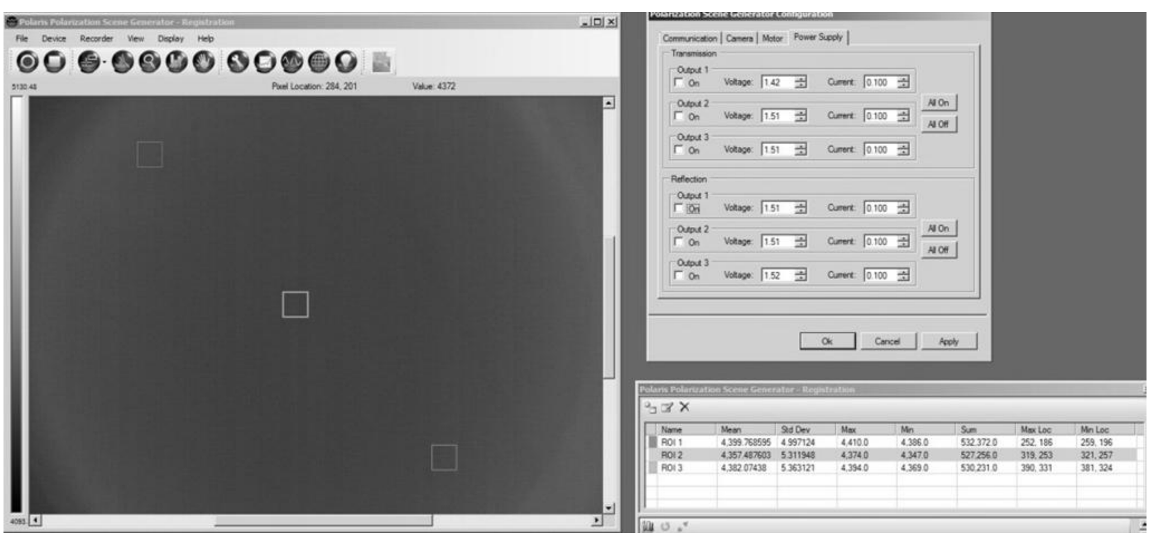

Figure 10. Using ROIs to capture background statistics

Understanding the background statistics is required so that the user can determine which will be the most appropriate method for calculating and comparing the source output for each T and R source. In the first case, we use the standard deviation (sigma, σ) of the pixel values in the box. The T or R source is turned on and the power output is adjusted until the standard deviation is the same (or very nearly the same) for each box. This is shown in Figure 11 and Figure 12, in which case the sigma chosen was 200 ADU. This method ignores the fact that the peak of the PSF may not fall on the center of a pixel. If this happens, the maximum pixel values in the boxes can easily differ by 1,000 ADU. In addition, the standard deviation ignores the mean value and thus approximately removes the constant background in the box. To some extent it also ignores some of the variances mentioned in the previous paragraph – e.g., spatial variations in illumination. Note that the mean value, standard deviation, max value, min value, sum, and source locations were all almost exactly the same, with the exception of the lower right spot.

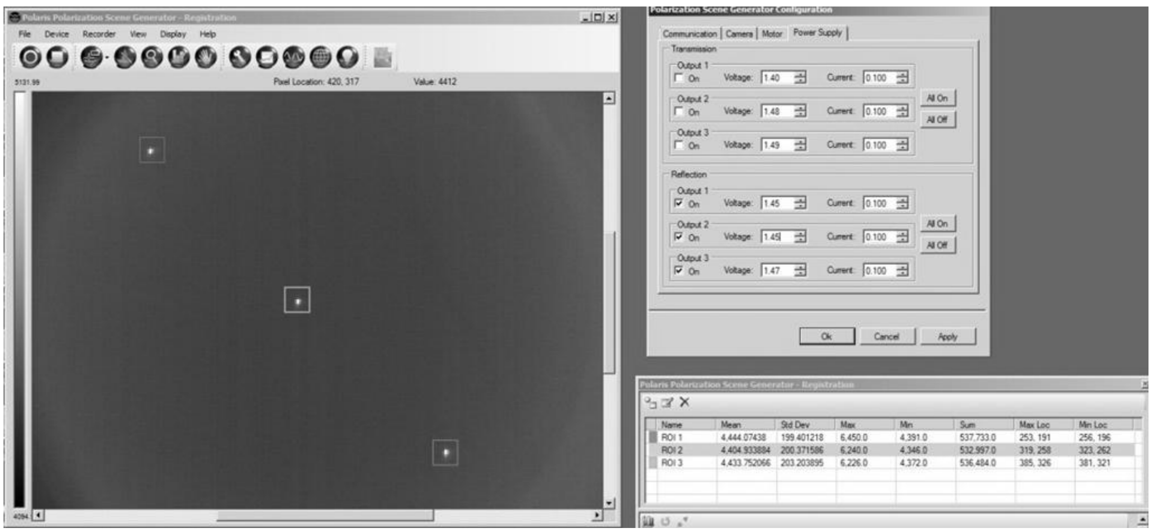

Figure 11. R source balancing using the standard deviation method for σ = 200 ADU

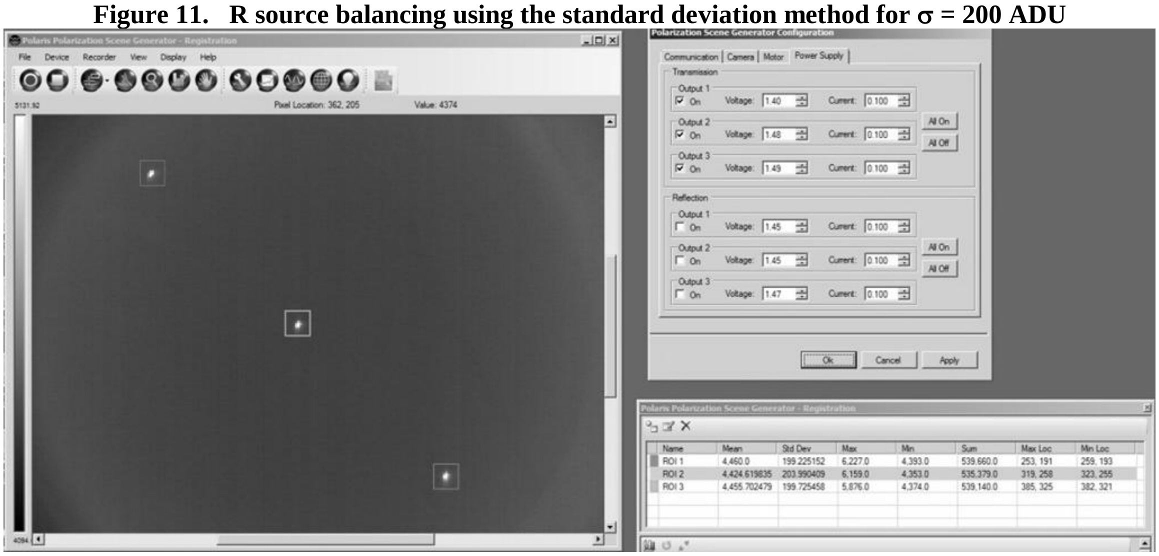

Figure 12. T source balancing using the standard deviation method for σ = 200 ADU

This discussion of the balancing method provides the reader with some insight into the complexities of balancing the power between the two sources. In order to use and test the operation of the PSG, there are a few measurements that yield the most informative data sets for the user:

- Bright objects with strong polarization signatures
- Bright objects with low polarization signatures
- Dim objects with strong polarization signatures
- Dim objects with low polarization signatures
- Verifying these four cases for both S_1 and S_2 objects

Generation of a polarization state with arbitrary S_1 component using 0- and 90-deg polarization states can be described by:

$$S_{out} = S_{\text{Transmission}} + S_{\text{Reflection}} = \begin{pmatrix} S_{10} \\ S_{11} \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} S_{20} \\ S_{21} \\ 0 \\ 0 \end{pmatrix} = Src_1 \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix} + Src_2 \begin{pmatrix} 1 \\ -1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} Src_1 \\ Src_1 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} Src_2 \\ Src_2 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} Src_1 + Src_2 \\ Src_1 - Src_2 \\ 0 \\ 0 \end{pmatrix}$$

Equation 1. Generation of arbitrary S_1 state

Although the Stokes vector is shown with four components, the fourth component is ignored for a system (such as the PSG polarimeter) that only measures linear polarization. In the case of the PSG, Src_1 is the T source (0 deg) and Src_2 is the R source (90 deg). Generation of a polarization state with arbitrary S_2 component using 45-deg and -45-deg (135-deg) polarization states can be described by:

$$S_{out} = S_{\text{Transmission}} + S_{\text{Reflection}} = \begin{pmatrix} S_{10} \\ 0 \\ S_{12} \\ 0 \end{pmatrix} + \begin{pmatrix} S_{20} \\ 0 \\ S_{22} \\ 0 \end{pmatrix} = Src_1 \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix} + Src_2 \begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix} = \begin{pmatrix} Src_1 \\ 0 \\ Src_1 \\ 0 \end{pmatrix} + \begin{pmatrix} Src_2 \\ 0 \\ Src_2 \\ 0 \end{pmatrix} = \begin{pmatrix} Src_1 + Src_2 \\ 0 \\ Src_1 - Src_2 \\ 0 \end{pmatrix}$$

Equation 2. Generation of arbitrary S_2 state

If the transmitted polarization state is equivalent to the reflected polarization state (for either S1 or S2), the result is unpolarized – i.e., no S_1 or S_2 components.

$$If\ S_{\text{Transmission}} = S_{\text{Reflection}},\ S_{out} = \begin{pmatrix} 2 \cdot S_{\text{Transmission}} \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 2 \cdot S_{\text{Reflection}} \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Equation 3. Generation of arbitrary S_0-only state

In theory, the concept is simple. However, as shown in Figure 13, the arbitrary S_2 component generation is not as straightforward as the S_1 component generation. Mueller calculus must be used to derive the desired input states for the generation of 45- and -45-deg polarization states. This necessitates an input T source polarization state of 51 deg to achieve 45-deg polarized output. Likewise, an input R source polarization state of 35 deg is required to generate a -45-deg polarized output.

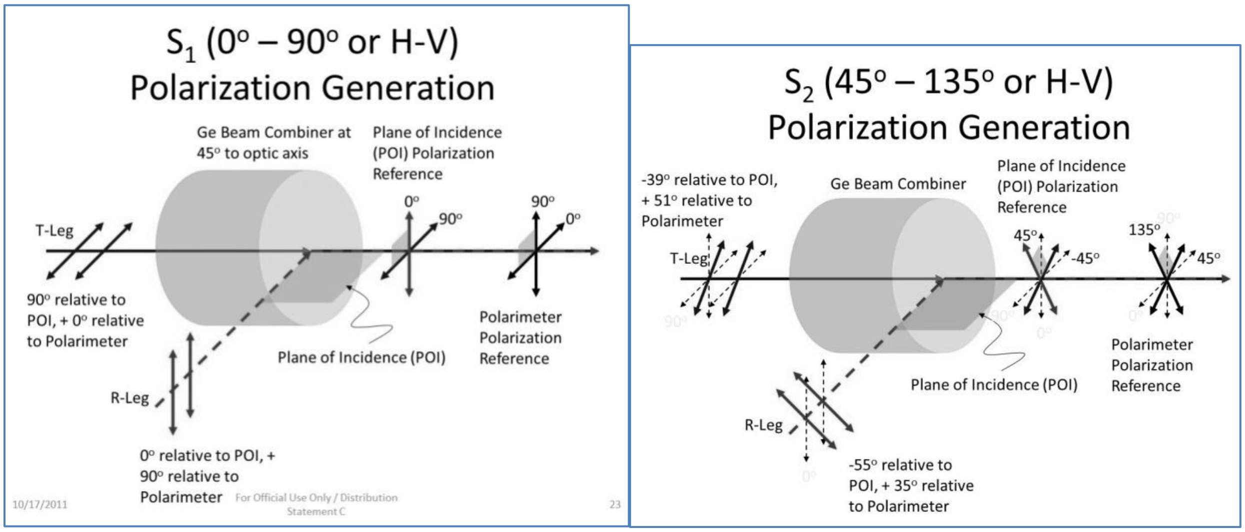

Figure 13. Inputs required to generate arbitrary S_1 or S_2 components

The PSG polarimeter and accompanying PSG software measure the polarization state and polarization state components in the following manner:

- The polarimeter acquires an image at each of four polarimeter polarizer orientations: 0, 45, 90 and 135 deg (-45 deg)
- The images are NUC'ed and converted to radiance (radiometric notation is L with units [W/sr/m^2]) via the Planck equation which linearizes the response
- The three linear Stokes vector components are calculated using
  - $S_0 = 1/2\,(L_{0^o} + L_{45^o} + L_{90^o} + L_{135^o})$
  - $S_1 = (L_{0^o} - L_{90^o})$
  - $S_2 = (L_{45^o} - L_{135})$
- The normalized Stokes vector components are calculated using
  - $Normalized\ S_1 = S_1/S_0$
  - $Normalized\ S_2 = S_2/S_0$
- The derived polarimetric quantities are calculated using:
  - $Degree\ of\ Linear\ Polarization,\ DOLP = \sqrt{(Normalized\ S_1)^2 + (Normalized\ S_2)^2}$
  - $Orientation\ of\ Polarization = 1/2\,tan^{-1}(S_2/S_1)$

Figure 14 shows the PSG polarization generation and analysis screen. The screen shows the user the image of the sources acquired at each polarizer orientation. The streaks in the images are due to the AR coating having partially peeled off the polarizers after dicing (cutting apart). They do not appear to overlap the point-source locations to any appreciable degree.

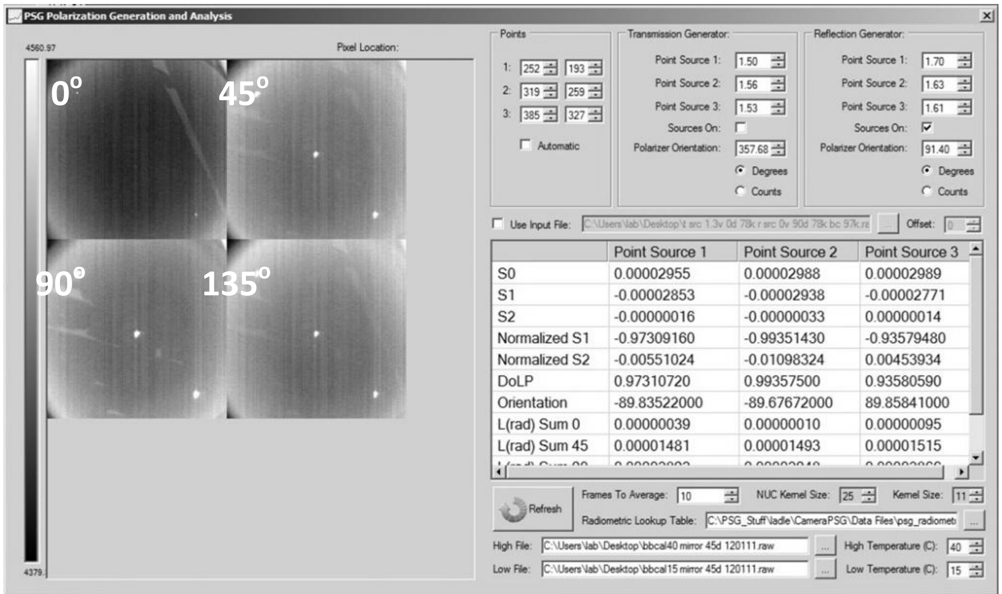

Figure 14. PSG Polarization Generation and Analysis screen

The screen allows the user to automatically or manually enter the location of the centroids of the source PSFs – manual entry is necessary for dim objects. It allows the user to manually adjust each T and R source voltage and adjust the T and R source polarization orientations. The software derived voltage setting resolution is 0.01 V, but the power supply used has a resolution of 0.001 V. The user can either calculate polarimetric quantities from an imported polarimeter data set using "Use Input File" or use live updating. The user can determine the number of frames to average as well as the size of the NUC kernel and polarimetric kernel (see Figure 15).

Polarimetric measurements are not carried out over the full 640 x 512 pixel polarimeter camera image; instead, a 200 x 200 pixel area in the center of the FOV is displayed to the user. The software NUCs radiometrically calibrate the data inside an M x M pixel box centered on the PSF centroid. The SW uses the high- and low-temperature blackbody calibration files and the system response curve to generate a 2-point linear fit of the recorded data at a given polarimeter polarizer orientation and convert the data to a linearized radiance value. This operation also removes fixed pattern noise (FPN). The SW uses a 1-point corrected image for bad pixel replacement. This operation is performed on all data in the M x M pixel box.

The software removes the background in an N x N pixel box centered on the PSF centroid and then sums the data in the box for each polarimeter polarizer orientation. It then calculates the polarimetric quantities in each N x N box and displays that data to the user. The reason for this particular operation is as follows: during polarimeter polarizer rotation, the PSF revolves in a circle on the FPA with a radius of 0.25 to 0.3 pixels due to wedge or tilt in the polarizer. A pixel-by-pixel subtraction of the 0- and 90-deg images to obtain S_1 would then result in undesirable artifacts. It is assumed that the user has aligned and registered the T and R source PSFs to within 0.1 pixels via the PSG source registration screen. The entire PSF energy can then be captured over all pixels in the N x N box and subtracted. This mitigates the artifacts due to misregistration.

Note that as indicated earlier, it is more accurate for dim objects to use a low-temperature blackbody setting that provides a response similar to the background.

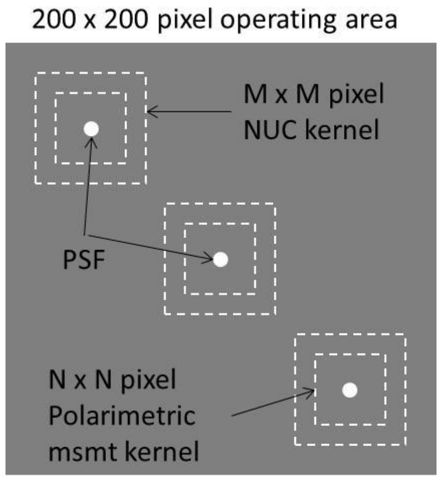

Figure 15. Polarimetric measurement area

5.0 Summary

Polaris demonstrated an approach that allowed the PSF from two separate point sources to be polarimetrically and radiometrically controlled. Most remarkable was that the PSFs were from two different arrays of sources, and Polaris achieved very good overlay of each point within each array. The system components are cryogenically cooled. Control of the system is provided through Windows software for ease of control. The performance of the entire system was characterized.

---

[i] Lowry, H. S., et al., "Expanding AEDC's Space Sensor Test Infrastructure to Meet Future Test and Evaluation Requirements," Presented at 2010 U.S. Air Force T&E Days, Nashville, TN, 2 Feb 2010.