

# Polarimetric Space Situational Awareness using the Aero-Optical Prediction Tool

**Christopher M. Persons**

*IERUS Technologies*

**Dr. Greg A. Finney**

*IERUS Technologies*

## ABSTRACT

The Aero-Optical Prediction Tool (AerOPT) is an optical simulation tool that combines detailed scene-to-sensor effects modeling with comprehensive electro-optical/infrared (EOIR) system models. AerOPT can be used for detection and characterization analyses, parametric studies, sensitivity studies, system design, trade studies, and algorithm development. Using AerOPT, we have studied the basic applicability of polarimetric sensing for local area space situational analysis (SSA). Our first order analysis shows that polarimetric imaging provides forensic data that can be used to infer information about the state of unresolved resident space objects beyond what can be derived from radiometric data alone. For ground-based SSA, AerOPT simulates atmospheric turbulence and the backscatter potentially seen with a beacon laser. AerOPT has further use cases, including closely spaced object (CSO) studies, tracker evaluation, aero-optics and aero-thermal analyses for hypersonic vehicles, and evaluation of candidate passive and active sensing systems.

## 1. INTRODUCTION

Space-based and ground-based space situation awareness (SSA) requires a significant amount of scientific analysis, system design, and trade studies that are enabled by simulations. The Aero-Optical Prediction Tool (AerOPT) is a simulation tool that models atmospheric effects, optical effects, and various sensor architectures for answering these SSA simulation needs. Emphasis is placed on modeling accuracy, but users can reduce accuracy in favor of processing speed to enable early investigations.

This paper begins with an overview of AerOPT's capabilities as applied to both SSA and other use cases. Next, a space-based SSA scenario is presented where AerOPT is used to assess the utility of measuring the polarization state of unresolved objects. Other example outputs are given that demonstrate the applicability of AerOPT to other SSA problem areas as well as use cases that are generally outside of SSA.

## 2. AEROPT CAPABILITIES

AerOPT is an optical simulation tool that includes atmospheric, aero-optic, and aero-thermal propagation, as well as detailed active and passive EOIR system models [1]. This simulation tool has been developed over a period of 20 years on a variety of programs supporting agencies such as the Missile Defense Agency (MDA), National Reconnaissance Office (NRO), US Army Space and Missile Defense Command (SMDC), US Army Combat Capabilities Development Command Aviation & Missile Center (AvMC) and Air Force Research Laboratory (AFRL). Written in MATLAB for fast development of new features, AerOPT can produce imagery, video, and statistics and is easily integrated with custom driver scripts for more complex automated analyses.

### 2.1 Signatures

Scenes and resolved target images for AerOPT can be user generated or come from scene generators such as the Digital Imaging and Remote Sensing Image Generation (DIRSIG), Time Domain Analysis Simulation for Advanced Tracking (TASAT), Common Scene Generator (CSG), Fast Line-of-sight Imagery for Target and Exhaust Signatures (FLITES), and Infrared Modeling and Analysis (IRMA). Range images may also be supplied to enable range-dependent atmospheric calculations. Resolved target images and/or point targets are placed over optional scene backgrounds. AerOPT processes spatial, temporal, spectral, and full polarization dependence provided with any of these signatures. Reflectivity images or Mueller matrix reflectivity images may also be supplied for resolved targets to support active illumination with a laser. Lasers may be offset from the sensor, have a user-provided illumination profile, be pulsed or continuous wave (CW), and can be modeled with or without polarization. Any of

these inputs can be provided per frame or be repeated across all simulated frames. All signatures are modeled at multiple samples per sensor pixel to increase simulation fidelity.

## 2.2 Signature Modifiers

Atmospheric signature modifiers modeled in AerOPT include atmospheric transmission, path radiance, atmospheric turbulence, as well as forward scatter and backscatter due to aerosols. Either the Laser Environmental Effects Definition and Reference (LEEDR) simulation or MODerate spectral resolution atmospheric TRANsmittance (MODTRAN) can be used to supply AerOPT with path radiance, atmospheric extinction, and the turbulence refractive index structure constant,  $C_n^2$ . These are used to compute atmospheric effects that vary per sample in the scene. Fig. 1 shows an example of pixel-dependent transmission and path radiance modeled in AerOPT.

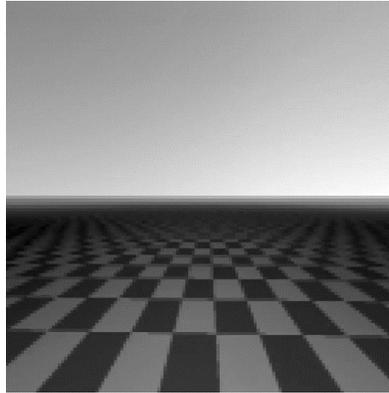


Fig. 1. AerOPT output demonstrating pixel-dependent transmission and path radiance

Atmospheric turbulence is captured and techniques are invoked to ensure the spatio-temporal correlations of turbulence are maintained even over many frames and slewing sensors. Atmospheric scattering is applied in AerOPT as forward scatter of an outbound laser, return forward scatter from reflections, forward scatter of passive signatures, and laser backscatter. The scatter model includes angular, temporal, and spatial dependencies, and can be applied for both pulsed and CW lasers.

For the hypersonics community, AerOPT is used to model the aberrations and distortions resulting from imaging through hypersonic flows as well as heated and distorted windows (Fig. 2). Techniques are used to step through a hypersonic flowfield from a computational fluid dynamic (CFD) solution, and a deformed window from a finite element analysis (FEA) to compute the phase changes to the wavefront. A three-dimensional heated window model is used to compute the transmission through and emissions from the window. Work in this area has been presented in [2].

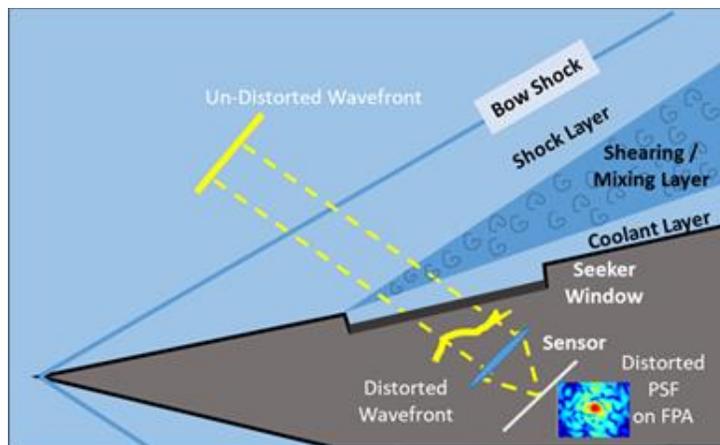


Fig. 2. Schematic of imaging through a complex flowfield and potentially distorted window

AerOPT applies Zemax-provided field-dependent and wavelength-dependent aberrations and distortion due to the lens train. Fig. 3 shows point targets in the presence of lens-induced pincushion distortion and coma, as well as a slight rotation of the sensor. AerOPT also applies uncompensated jitter; computes and applies range-dependent defocus; and computes and applies integration smear to the scene and targets, separately, as well as to moving phase screens.

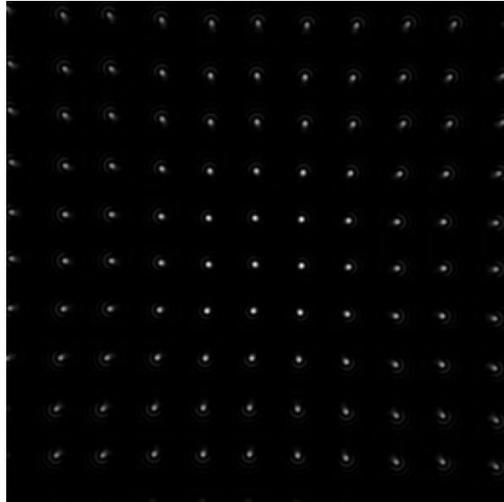


Fig. 3. Point targets in the presence of distortion, coma, and rotation

### 2.3 Sensor Models

AerOPT currently models conventional (CCD and CMOS) sensors and Geiger-mode avalanche photo-diode (GmAPD) sensors. A modeled conventional system can optionally include a Michelson interferometer, converting the sensor into an imaging Fourier-transform spectrometer (IFTS). For any of these sensor types, AerOPT can model sensor body emissions, polarimetric effects of the lens train, and Coudé train rotation. AerOPT can also model a micro-polarizer array (MPA), which filters individual pixels by linear polarizers at different orientations, arranged in a Bayer pattern. An optional optical registration array (ORA) may also be placed over the MPA to spatially register the polarimetric and radiometric signals [3].

The conventional sensor model also includes dark current, pixel-to-pixel crosstalk, and spectral quantum efficiency. Noise sources that are modeled include shot, Johnson, read, and spatial noise. Single or multiple analog-to-digital converters (ADCs) can be modeled and applied in any pattern, and the ADC conversion process can be modeled as a linear or nonlinear process. Bad pixels are applied statistically. An optional two-point nonuniformity correction (NUC) and radiometric calibration may be applied to the images.

The GmAPD sensor model includes either a linear or nonlinear dark count rate, the gate delay, photon detection efficiency, and cascade-induced crosstalk.

### 2.4 Outputs

AerOPT produces high-resolution images of point spread functions (PSFs) due to individual and combined effects. An example output PSF is shown in Fig. 4 along with how it appears in an output image. Computed PSF statistics include Strehl ratio, contained energy diameters (CEDs), and boresight error. For conventional sensor systems, AerOPT outputs noise and “noise equivalent” statistics, as well as images in electrons, counts, and radiance. An example radiance image of an Air Force resolution target is shown in Fig. 5. For MPA systems, the polarimetric products are also produced. IFTS systems produce these products as a function of wavelength. The outputs for GmAPD systems include probability of trigger images and range images.

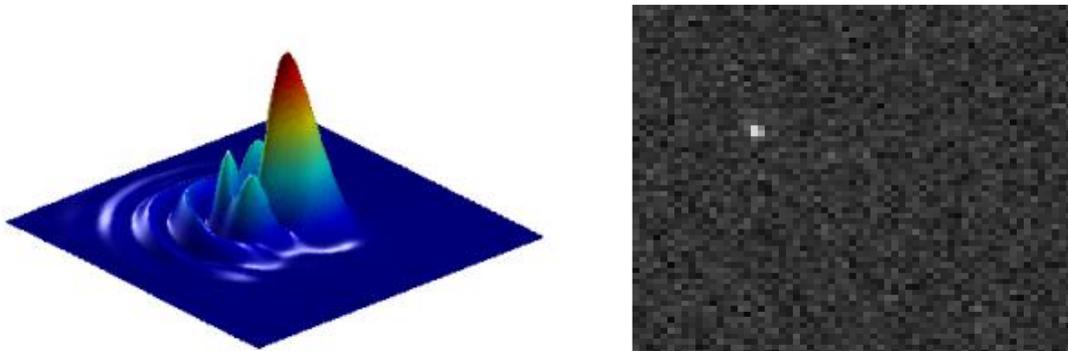


Fig. 4. (left) Point spread function with significant coma and astigmatism (right) Resulting scene containing point source with significant noise and coma

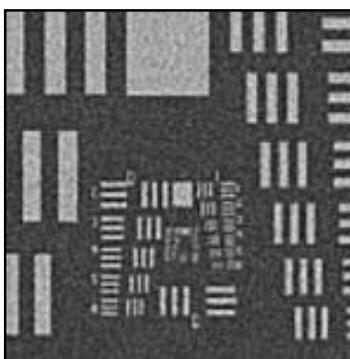


Fig. 5. Air Force bar target

### 3. AEROPT APPLIED TO SPACE-BASED SSA

AerOPT was used to assess the utility of polarization in a space-based SSA scenario. First, a simple cubical satellite was postulated and modeled in TASAT; only the exterior surfaces shown in Fig. 6 were included in the model. The geometry of the scenario is shown in Fig. 7. The radiometric and polarimetric signatures of the unresolved target were produced by TASAT and input into AerOPT.

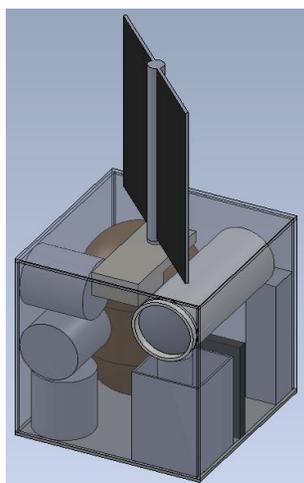


Fig. 6. Postulated cubical satellite modeled in TASAT

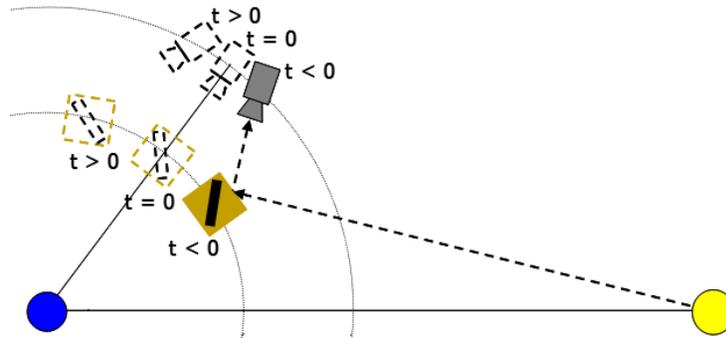


Fig. 7. Geometry of simulated scenario

The AerOPT sensor included both an ORA and MPA. Figs. 8 through 10 show AerOPT results, in green, with error bars indicating standard deviations in the signatures. A separate database was developed that modeled anticipated signatures for simple surfaces of different orientations and sizes; these are shown as blue curves in the figures. Fig. 8 shows the result when the database model includes the correct materials, orientations, and sizes. Note that the blue database shows general agreement with the signatures modeled by AerOPT. The database model was modified so that size and orientations were correct, but the materials were incorrect. The results, shown in Fig. 9, show that a standard sensor would likely predict this as a candidate model. However, the polarization signature indicates it is incorrect. The next database model, shown in Fig. 10, has the correct materials, but the size is too large. Here, the polarimetric signature agrees, but the radiance is incorrect.

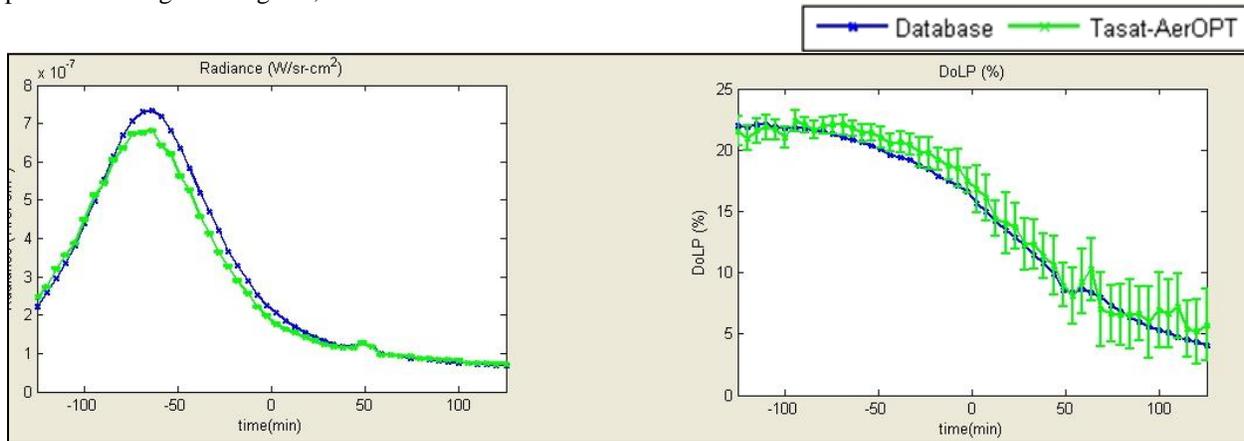


Fig. 8. Database model with correct materials, orientations, and sizes

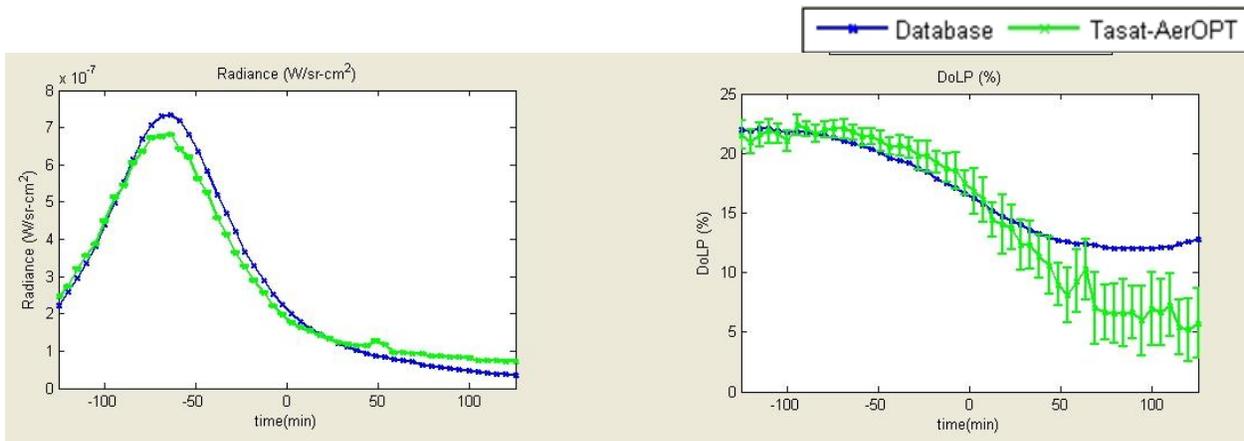


Fig. 9. Database model with correct orientations and sizes, but incorrect materials

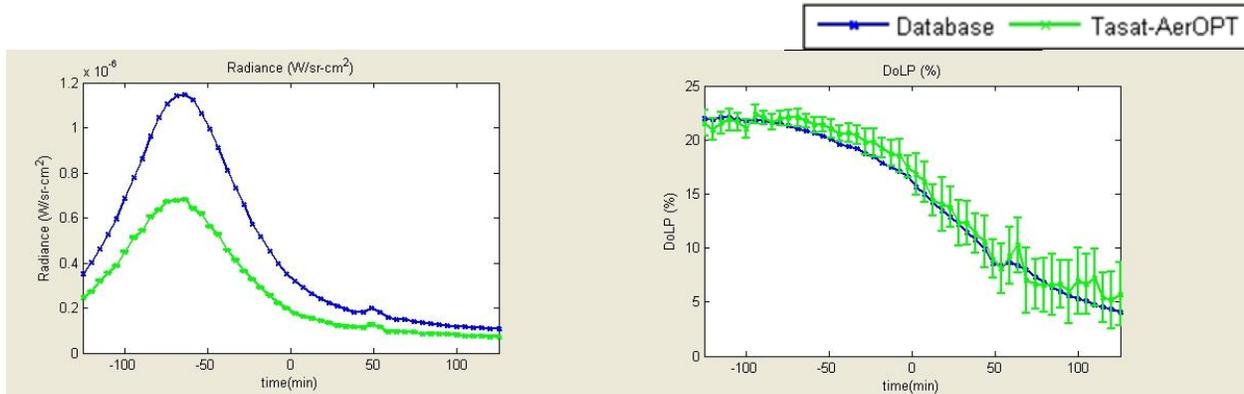


Fig 10. Database model with correct materials and orientations, but incorrect sizes

The problem with broadband radiometric sensor measurement of unresolved targets is that material reflectivity and size are inseparable. However, this TASAT-AerOPT study shows that a polarimetric sensor can improve material classification, which can in turn be used to assess target size.

#### 4. OTHER AEROPT USE CASES

AerOPT has many other use cases, some of which intersect with the needs of the SSA community, including the atmospheric turbulence and beacon backscatter potentially seen in ground-based applications. The following is a sampling of AerOPT use cases.

##### 4.1 Turbulence

AerOPT can be used to simulate field-dependent aberrations and distortions due to atmospheric turbulence. In the figures below, the sensor is pointing horizontally and imaging a checkerboard scene. The bottom edge is near the ground. Turbulence worsens (the Fried parameter decreases) closer to the ground. Seven phase screens are modeled and each move vertically with time in this example. The top row of Fig. 11 shows radiometrically calibrated images from AerOPT for frames 1, 2, 3, and 10, all on the same scale. To show the time evolution of the turbulence, the second row shows the difference between these images and the first image, all on the same scale. Fig. 12 shows the difference images for all ten frames in an area corresponding to the red rectangle in the top left image of Fig. 11. The vertical motion of the evolving turbules demonstrates the spatio-temporal correlation in the turbulence. AerOPT's turbulence model has been compared favorably against results in [4].

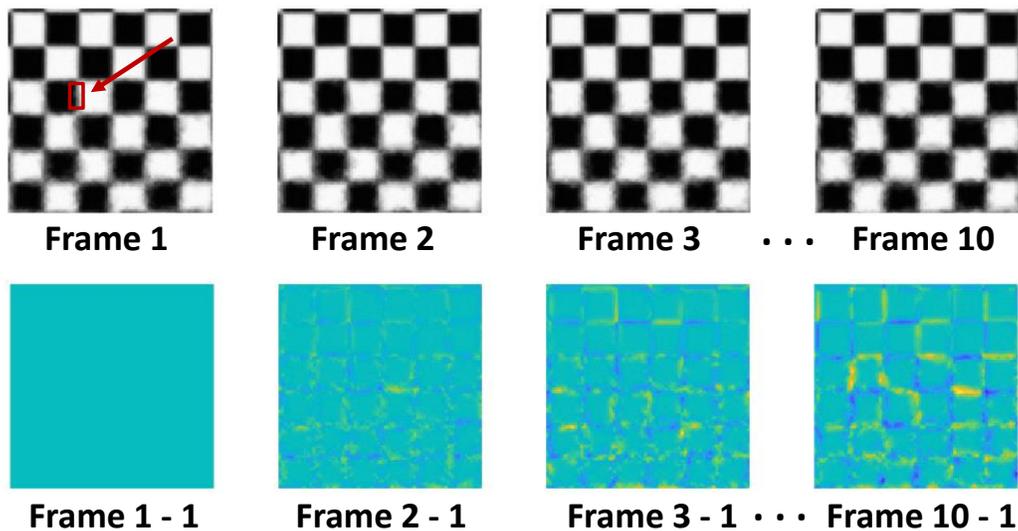


Fig 11. Output frames (top) and difference frames (bottom) of turbulence simulation

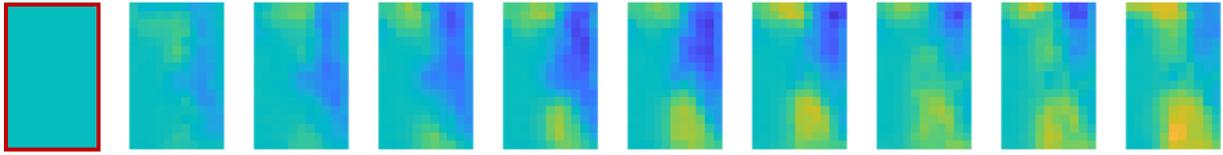


Fig 12. Subimage of difference images (red rectangle shown in frame 1 of Fig 11.)

#### 4.2 Atmospheric scatter

AerOPT can also model the impacts of scattering when imaging through aerosols. Fig. 13 shows active illumination of an unmanned aerial system (UAS) through fog. The illuminating laser is offset slightly from the sensor, resulting in an offset backscatter pattern. Also included in this simulation are the scatter of the outbound laser and the scatter of the return.



Fig. 13. Active illumination of a UAS through aerosols

#### 4.3 Closely Spaced Objects

Pixels can be modeled with many samples in each dimension, resulting in very high-resolution representations of unresolved targets. This enables studying the relationships between target spacing and sensor response. Though not shown, the effects of optical aberrations and distortions can also be studied. Fig. 14 shows the high resolution PSFs on a focal plane array (FPA) and the resulting image in counts and radiance.

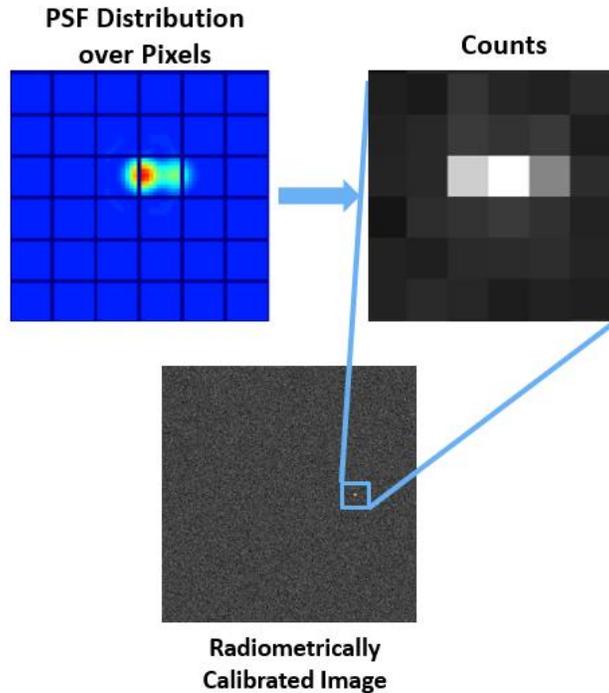


Fig. 14. High resolution PSFs on a focal plane array and resulting measured images in counts and radiance

#### 4.4 Sensor and Algorithm Evaluation

Since AerOPT is designed with both simulation fidelity and reasonable runtimes in mind, it can be used to evaluate sensor designs as well as detection and tracking algorithms. Fig. 15 shows the comparison of two candidate systems for tracking a mortar. The two systems are identical except for the selection of FPA. The system on the right enables a longer integration time which lowers noise. Since the sensors are tracking the target, the longer integration time also increases integration smear of the background scene.

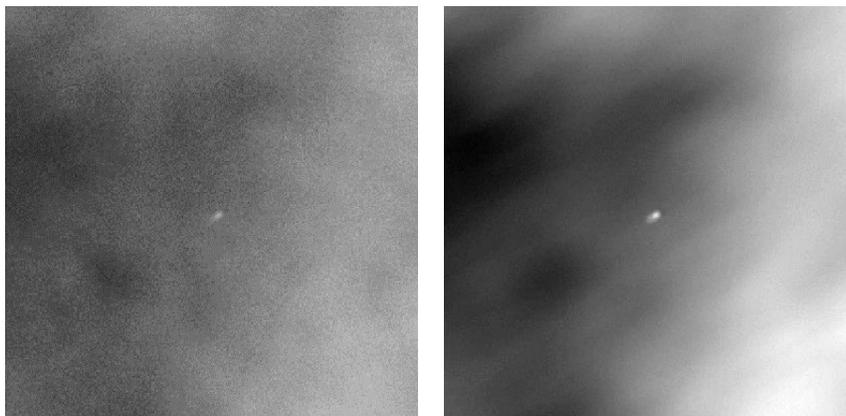


Fig. 15. Two candidate sensor systems for tracking a mortar

#### 4.5 Aero-Optics and Aero-Thermal

AerOPT began as an aero-optic propagation tool for the hypersonics community. AerOPT's aero-optic and aero-thermal modules compute the net PSF resulting from imaging through a hypersonic flowfield and a window deformed by thermal and pressure loads. The PSF shown in Fig. 16 is a representative result from such an analysis.

AerOPT computes important statistics from the PSFs such as boresight error, Strehl ratio and contained energy diameters.

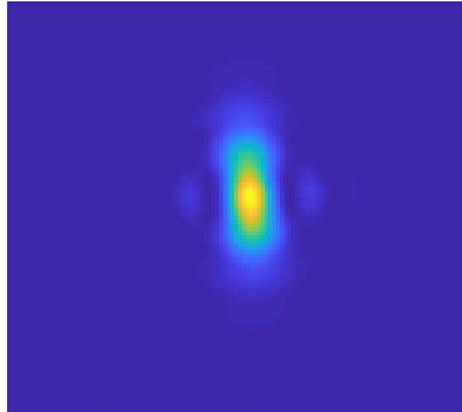


Fig. 16. Representative PSF from aero-optic/aero-thermal analysis

#### 4.6 Lidar Imaging

Lidar systems image the three-dimensional (3D) content of scenes by measuring the return times of laser pulses across a detector array. AerOPT simulates 3D imaging with a detailed model of a GmAPD lidar system with a pulsed laser.

Figs. 17 – 19 show AerOPT results when simulating 3D imaging of a sphere in the presence of atmospheric turbulence. Fig. 17 shows the average detection events at four timepoints during the laser return from the sphere. Fig. 18 shows the resulting range images of the sphere with (left) a clear background and (right) a cloud background. Dark gray pixels are not triggered during the pulse. A coincidence processing step filters out returns that have insufficient spatio-temporal coincidence, which is typical of passive signatures and pixels dominated by dark counts. Fig. 19 shows the coincidence processed range results with (left) a clear background and (right) a cloud background. Light gray pixels are those that are removed by coincidence processing.

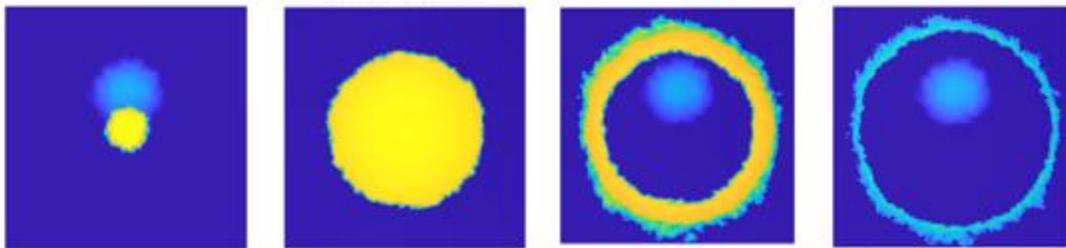


Fig. 17. Average detection events at four timepoints during the laser return from a sphere when imaging through atmospheric turbulence

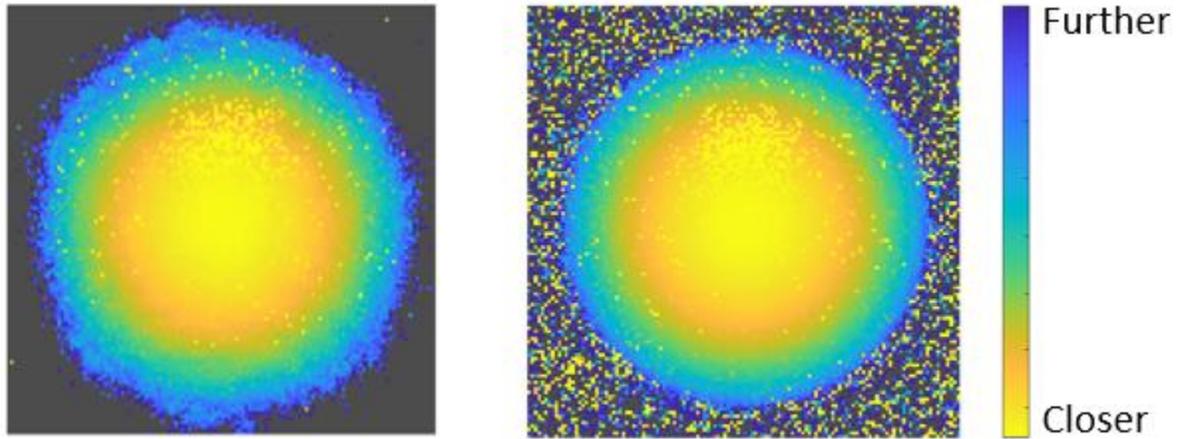


Fig. 18. Range image of a sphere with (left) a clear background and (right) a cloud background

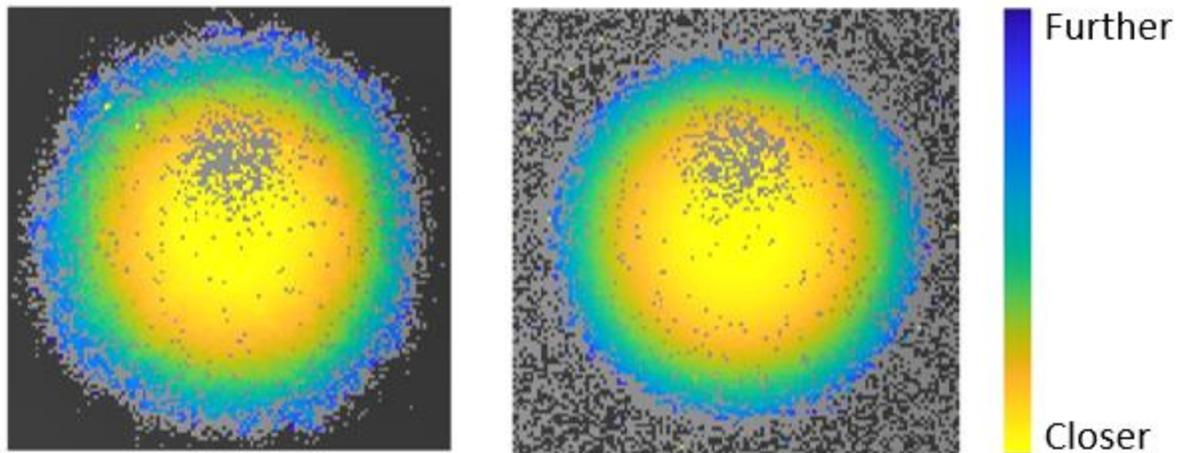


Fig. 19. Coincidence processed range image of a sphere with (left) a clear background and (right) a cloud background

## 5. CONCLUSION

AerOPT is a powerful tool used across many disciplines for high fidelity simulations. The tool simulates passive and active signatures of targets and background scenes; models various signature modifiers including atmospheric, aero-optic, aero-thermal, and lens aberrations and distortions; and includes high fidelity conventional, IFTS, and GmAPD sensor models. AerOPT captures the spatial, temporal, spectral, and polarization variability required for detailed analyses. Results from AerOPT can be used in detection and characterization analyses, parametric studies, sensitivity studies, system design, trade studies, and algorithm development.

The simulation tool was used to assess the forensic benefit of polarization measurements in a space-based SSA scenario when the sensor is equipped with an ORA and MPA. The analysis indicates that polarization may be used to classify materials, enabling improved size estimation using the radiometric signature. AerOPT is well positioned for further analyses important to both space-based and ground-based SSA applications.

## REFERENCES

- [1] C. Persons, A. Dorsett, M. Jones, K. Spradley, M. Gulley, "Modeling polarimetric imagers using the Aero-Optical Prediction Tool (AerOPT)," DoD Optical Polarimetric Sensing and Effects Workshop, GTRI, Atlanta, GA, Dec. 2006.

- [2] A. Dorsett, G. Finney, A. Little, C. Persons, "AerOPT Simulation of Optical Effects of Window Heating in Flight," 17th DoD Electromagnetic Windows Symposium, Short Proceedings Paper, 2020.
- [3] G. Finney, C. Persons, D. Phillips, "Performance of a microgrid polarizer array employing a micro-optic registration element", Proc. SPIE 10655, Polarization: Measurement, Analysis, and Remote Sensing XIII, 106550D, 2018.
- [4] Voelz, David, Hanyu Zhan, and Erandi Wijerathna. "Wave and Ray Optics Simulations of Short Exposure Incoherent Imaging in Atmospheric Turbulence." Propagation Through and Characterization of Atmospheric and Oceanic Phenomena. Optical Society of America, 2018.