

# **Laser-Based Direct Write Scene Generation Methods for Closed-Loop Focal-Plane-Array Diagnostics\***

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## **Abstract**

This paper describes recent technology development at Arnold Engineering Development Center to provide real-time closed-loop optical diagnostics for focal-plane-array and electro-optical sensor characterization and evaluation. Laser-based Direct-Write Scene Generation methods are used to simulate dynamic sensor operation and complex infrared backgrounds and target scenes. In order to provide more optimized optical simulation fidelity and to reduce computational burdens, closed-loop Direct Write Scene Generation image-synthesis methods employ image-to-object Whittaker-Shannon sampling, anisoplanatic optical convolution by quasi-isoplanatic spatial decomposition, and high-speed digital electronics for acousto-optic modulation. Optical and computational decomposition not only provide high-fidelity optical simulation for anisoplanatic optical sensors and complex infrared scenes, but also facilitates high-speed parallel-processing schemes for real-time closed-loop sensor operation. Some emphasis is devoted in this paper to describing the methodology and discussing fidelity and performance issues for closed-loop testing.

**Keywords:** anisoplanatic optics, closed-loop, direct-write scene generation, fidelity, focal-plane-array testing, laser stimulation, performance, real-time, sensor diagnostics

## **1. Introduction**

Recent technology efforts at Arnold Engineering Development Center (AEDC) provide new capabilities for laser-based Direct-Write Scene Generation (DWSG).<sup>1-8</sup> The DWSG methodology provides high-speed photonics for visible and infrared focal-plane-array (FPA) diagnostics using lasers for real-time evaluation and scene simulation. Technology developments are underway at AEDC to extend this basic DWSG capability to support real-time closed-loop DWSG (CLDWSG) operation. New photonic image-synthesis methods employ image-to-object Whittaker-Shannon sampling, anisoplanatic optical convolution by quasi-isoplanatic spatial decomposition, and high-speed digital electronics for acousto-optic modulation and deflection.

DWSG high-speed photonics processing is required for closed-loop operation and simulation of dynamic and interactive sensor commands that reposition a sensor's field of view within the field of regard. It is also required for high-fidelity simulation of optical blurring and temporal effects such as mechanical jitter and aero-optically induced image and signal perturbations resulting from high-speed flow fields over the sensor's optical elements. Real-time CLDWSG methods require that a number of operations be performed within each frame of the electro-optic focal-plane-array sensor:

- selection and transfer of the scene background field of regard,

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\*The research reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Materiel Command. Work and analysis for this research were performed by personnel of Sverdrup Technology, Inc. / AEDC Group, technical services contractor. Further reproduction is authorized to satisfy needs of the U. S. Government.

- calculation and inclusion of target intensities and positions,
- rotation and translation of the composite background and target scenes to simulate interactive sensor-pointing commands,
- simulation of sensor and satellite jitter,
- simulation of optical blurring resulting from aberrations and diffraction for broadband spectral radiation and aero-optical distortion,
- integration of the photon flux over each FPA pixel element,
- FPA pixel responsivity calibration,
- and compensation for acousto-optic (AO) cell optical-modulation and other system inefficiencies resulting from RF generation and power amplifiers.

Because of processing terabyte volumes of data, increasing bandwidth requirements, and increasing fidelity requirements for Development Test and Evaluation (DT&E) and Operational Test and Evaluation (OT&E) of electro-optical sensors, the DWSG methodology is being extended to accommodate decomposition methods to exploit highly parallel real-time image-processing schemes.

## 2. Sensor Mission and Source Radiation Issues

Testing and evaluation (T&E) and modeling and simulation (M&S) of electro-optical sensor systems to assess their operational characteristics, their performance limits, and to support engagement scenario simulations can be accomplished and understood using a top-down approach for establishing comparative models and corresponding testing criteria. Figure 1 illustrates a mission-driven approach to establish closed-loop Direct Write Scene Generation requirements using a sensor's mission and operational characteristics and related sensor T&E objectives.

As can be seen from Figure 1, identification of the mission objectives and profiles and the expected functional requirements are primary steps in designing, developing, and testing electro-optical systems. This is true whether an optical system is designed and developed for detection, discrimination, search & track, ranging, warning, or enhanced imaging, as done with traditional FLIR-type electro-optical systems. Depending on the function and mission, a sensor will generally have a particular set of important design and test parameters that characterize its operation, function, and performance. Not all parameters will be used universally for all optical systems. Also, some parameters will vary in importance depending on the mission and the function of the electro-optic sensor system. As an example, the signal-to-noise ratio in a detection or warning system is important to increase the probability of detection and decrease the probability of false alarms with little concern devoted to reproducing the exact target-signal waveforms. In contrast, imaging systems require that emphasis be placed on reproducing scene imagery with little distortion of the original object scene. The signal-to-noise ratio sometimes receives very little emphasis in some imaging systems as compared to detection- or warning-type optical systems.

Another important step is identification of the sources of radiation and related phenomenologies that will be exploited to accomplish the sensor's mission, i.e., the target and background spectral radiance, shapes, sizes, spatial extents/distributions, Wiener spectrums (spatial power-spectral densities) and temporal variations. A target's velocity and trajectory are also critical in establishing a sensor's operation (scan, step-stare, staring), field of view, and data-processing schemes employed as well as the sensor testing methods chosen for accurate and adequate measurement programs and mission simulations.

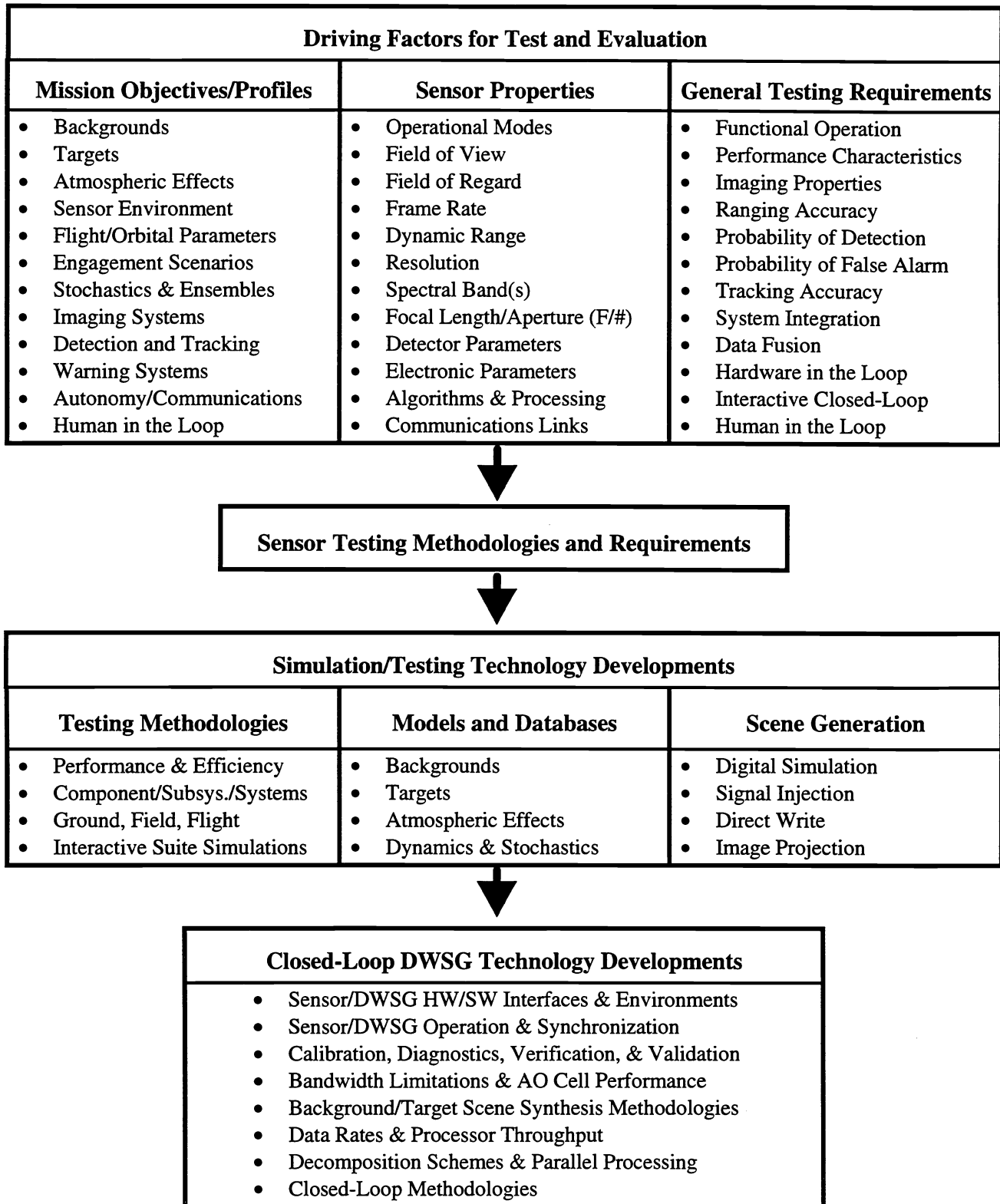


Figure 1. Sensor testing and evaluation diagram illustrating closed-loop DWSG development.

### 3. Direct Write Scene Generation Operation

The DWSG Focal Plane Array Test Capability (FPATC) includes lasers operating at 0.514, 1.06, 5.4, or 10.6  $\mu\text{m}$  and acousto-optic (AO) modulators for laser-beam control. High-speed RF electronics use Direct Digital Synthesis (DDS) to drive the AO modulators and deflectors with multifrequency input for multibeam output as illustrated in Figure 2 and Figure 3. DDS frequency modulation provides extremely accurate and independent deflection of the multibeam laser “rake”. Similarly, DDS amplitude modulation provides accurate and independent multibeam intensity control. Laser-beam scan optics focus the laser beams onto subpixel regions for pixel-to-pixel photoflux deposition with minimal stray radiation from diffraction. The laser-beam rake is then step-scanned across the FPA during each integration period.

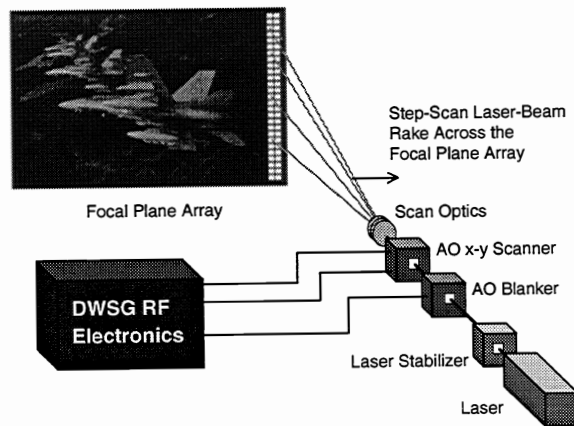


Figure 2. Direct-Write Scene Generation concept.

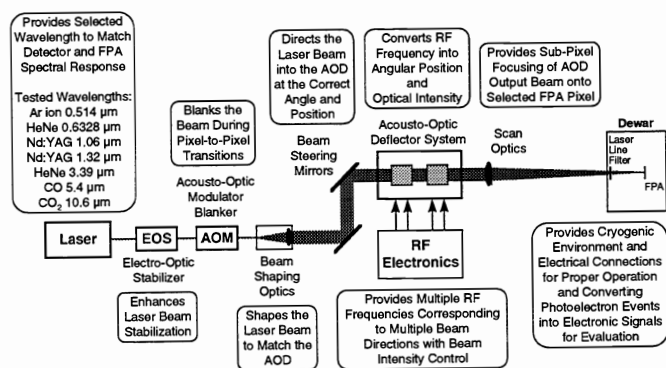


Figure 3. Direct-Write Scene Generation functions.

Acousto-optic modulation and subpixel irradiation are normally used to minimize DWSG optically-induced cross-talk signals and related signal perturbations. Modular and multiple laser-beam systems and acousto-optic photonics also help to ensure that most of the photons designated for a specific subpixel region during a given FPA frame are delivered to the desired pixel for high-fidelity scene simulation. The DWSG resolution and laser-beam spot size and separation is designed to be approximately twice the normal Rayleigh resolution criteria of most acousto-optic modulators.

### 4. Optical Simulation and Sensor Mission Concerns

FPA sensor evaluation, modeling, and simulation ultimately depend on the mission and objectives of the electro-optical FPA sensor system and the sensor’s mode of operation (as illustrated in Figure 1). To ensure high-fidelity through verification and validation, some effort is required to better understand sensor missions and objectives, background and target phenomenologies, object-to-image mappings, scene distortions resulting from 3-D to 2-D radiance mappings to FPA coordinates, temporal variations, and critical testing parameters. The “reality” or “truth” of any validation and verification effort has to be cast in the context of the intended purpose and use of the sensor being evaluated. As with any modeling and simulation effort, the DWSG FPA optical diagnostics and mission simulations will be applicable and limited to some level of verification and validation acceptable for the intended purpose.

Backgrounds and targets detected by a sensor will depend on the sensor's field of regard and the sensor's field of view, both of which can be time-dependent, semi-deterministic processes or can be stochastic processes. Sensor views for strategic and tactical missions require quite different data bases for simulation of real-world background and target engagements and related phenomena exploited for efficient detection, discrimination, and tracking. Typical flight or orbital positions will vary the field of regard that is detected by electro-optic sensor systems, and corresponding background-to-FPA and target-to-FPA mappings (as illustrated in Figure 4) have to be taken into consideration as well as differences resulting from using different wavebands for normal operations in atmospheric absorption bands or transmission windows of interest. The background and target radiance levels reaching the electro-optic sensor depends not only on the emission or scattering properties of the sources, but also on the transmission of the intervening medium such as the atmosphere and clouds. Multisensor perspectives and corresponding DWSG simulations will depend on the sensor's mission regarding multispectral detection and tracking as well as on local sensor-platform environments, other operational characteristics, and corresponding 3D-to-2D transformations.

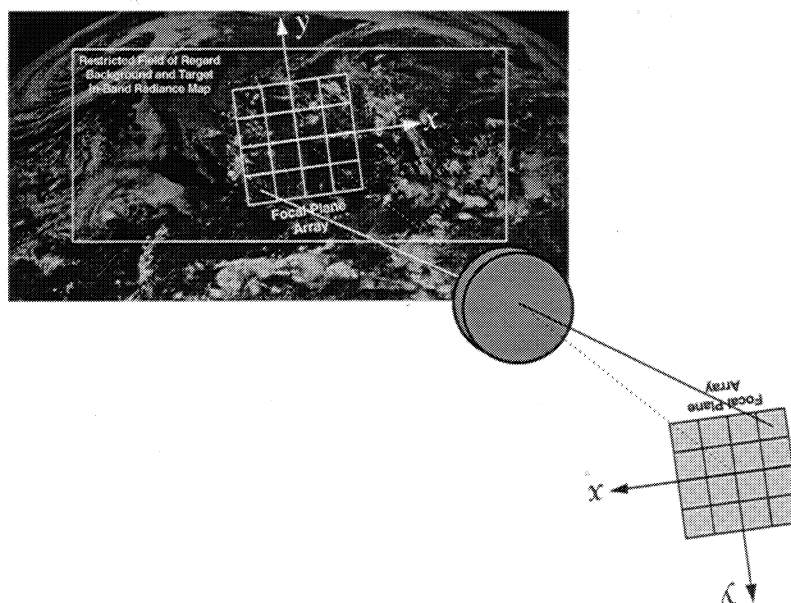


Figure 4. Conceptual illustration of a scene being mapped onto the FPA, which could be viewed as a FPA being mapped onto a 2D projection of the background and target scene.

## 5. Optical Simulation and Decomposition Methods

Sensor imaging of quasi-monochromatic, thermal, or blackbody sources generally depends on the theory of partial coherence. In many cases this generalization can be simplified to one of the two extreme cases of partial coherence, either totally coherent or totally incoherent. Neither of these two extremes exist completely for real sources, which are always partially coherent to some degree and partially polarized also. Thermal or blackbody sources are normally modeled using incoherent superposition assumptions for adding or integrating statistically independent object sources to obtain integrated images with very good approximations of the “real world” for many cases; each case is normally evaluated on an individual basis to ensure that the assumptions and simplifications are indeed representative of real-world engagement “reality” and “truth.”

Imaging and photodetection, as illustrated in Figure 5, follow the laws of optical diffraction, and optical components are not perfect. The images of point sources are not point sources because of the inherent wave-nature of photons and resulting diffraction and aberration effects. As a “point” source is moved within the field of view of a sensor the corresponding image of the “point” source may noticeably vary depending on the wavelength and the degree of aberrations present. Mathematically, optical systems are either spatially invariant or spatially variant. One could, however, justifiably argue that, for practical purposes, many optical systems can be considered spatially invariant and the image blur or point-spread function (PSF) does not vary as measured, and the optical system can be considered diffraction limited for a given spectral range. In other cases, there may be distortions and variations in the PSF resulting from aberrations needing to be considered for laser-based optical simulations. The optical components map the object plane onto the image plane with aberrations, blurring, distortions, and magnification, which transforms the object into the image. If one can compute this mapping transformation to some desired level of fidelity, then the image can be accurately determined and the photodetection and integrated effects of detection subsequently modeled and simulated.

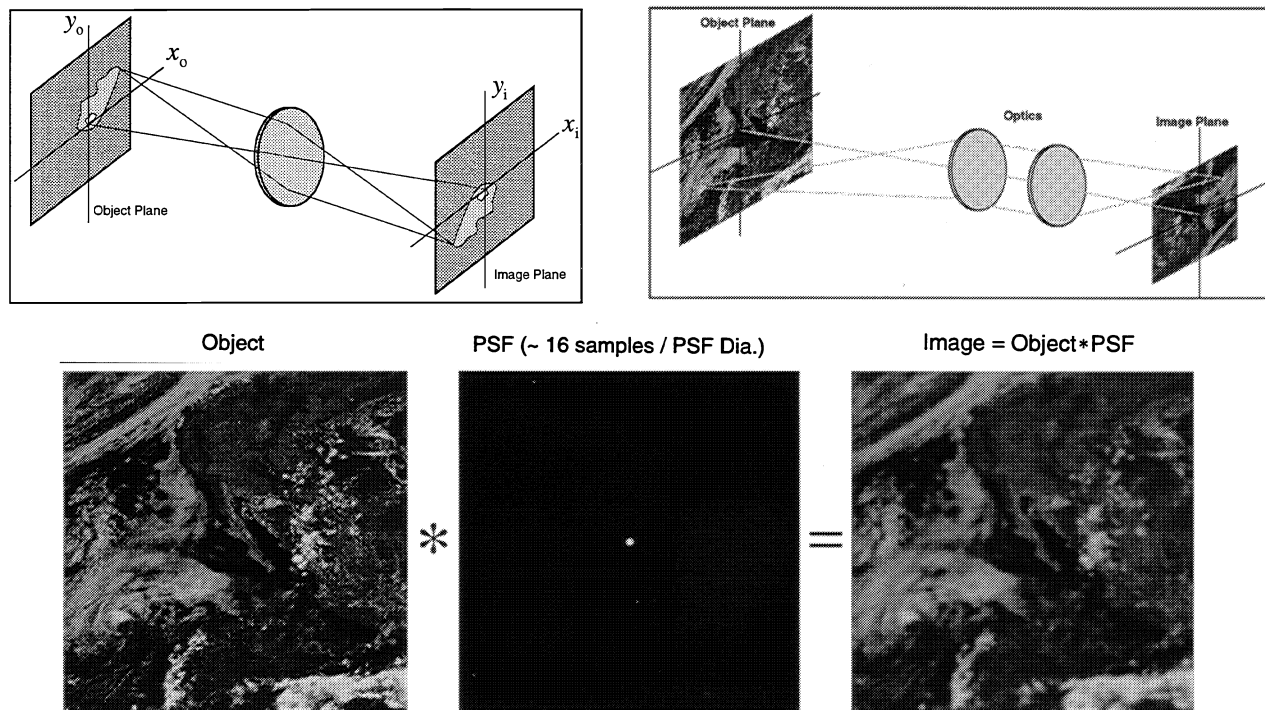


Figure 5. Illustration of the object plane being transformed to the image plane for FPA irradiation via an optical system for a simple background and target map.

For optical scene simulations requiring real-time closed-loop operation, the sensor interactively updates the line-of-sight pointing vector relative to the sensor’s position in space and the background field of regard. To incorporate and support interactive CLDWSG operation and to accommodate simulation of anisoplanatic optical systems, the scene is decomposed into quasi-isoplanatic regions for narrow spectral bands. For this method, the scene is decomposed into segments that allow for either an application of direct convolutions or OTF methods via the convolution theorem for regions of quasi-isoplanatic patches. The spatial decomposition not only provides for improved optical fidelity in simulating anisoplanatic sensor optics, but also provides a method to decompose and compute the scene

in parallel for each segment and be synthesized for laser-based DWSG FPA projection. We can also use these methods to examine the effects of spatial decomposition and to mitigate edge effects and diffraction loss, while at the same time provide anisoplanatic simulation for comparative analysis.

FOV/spatial decomposition, computation, and synthesis of the object/image scene provides a useful method that facilitates multiple PSFs to be used to determine and directly simulate an anisoplanatic optical system using laser-based scene simulation. Although spatial decomposition and computational methods can lead to anomalous computational artifacts resulting from optical diffraction, sampling, and other windowing effects, various methods have been investigated to improve the optical simulation and to mitigate computational artifacts. As illustrated in Figure 6, using extended computational domains helps to improve the simulation fidelity and subsequently improve experimental results.

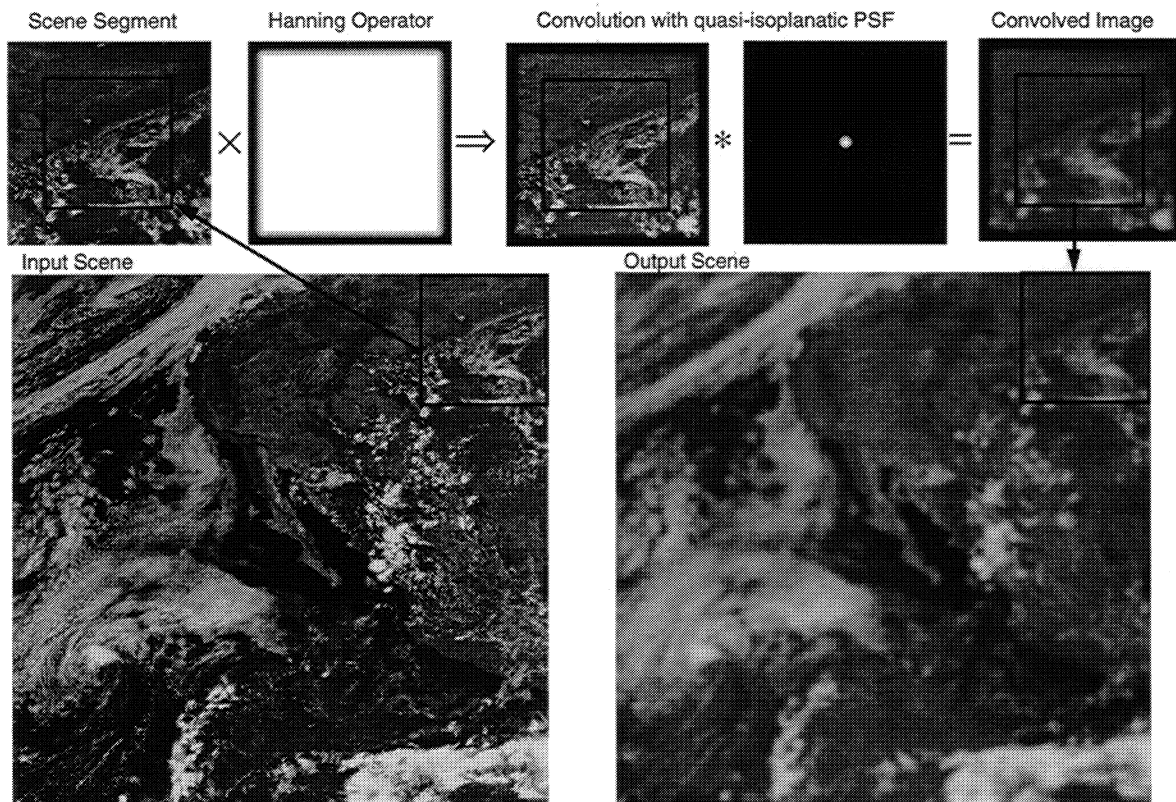


Figure 6. Methodology for using extended computational regions to not only support anisoplanatic decomposition for better fidelity and optical simulation, but to also support highly parallel processing schemes for real-time closed-loop DWSG/sensor operation.

There are a number of methods for establishing a sensor's PSF or its corresponding optical transfer function (OTF). A sensor's image and the FPA's integrated photoflux can then be determined by basic integration methods. For near spatially invariant FOV regions, direct convolution methods or the convolution theorem plus OTF methods can be used as illustrated in Figure 7. The method chosen depends on the desired fidelity as well as the computational performance desired. As with any computational/scientific model, these methods have inherent assumptions and simplifications and have to be understood to provide a quantitative method to account for and potentially accommodate for any resulting errors within the context of an intended purpose and verification and validation procedure.

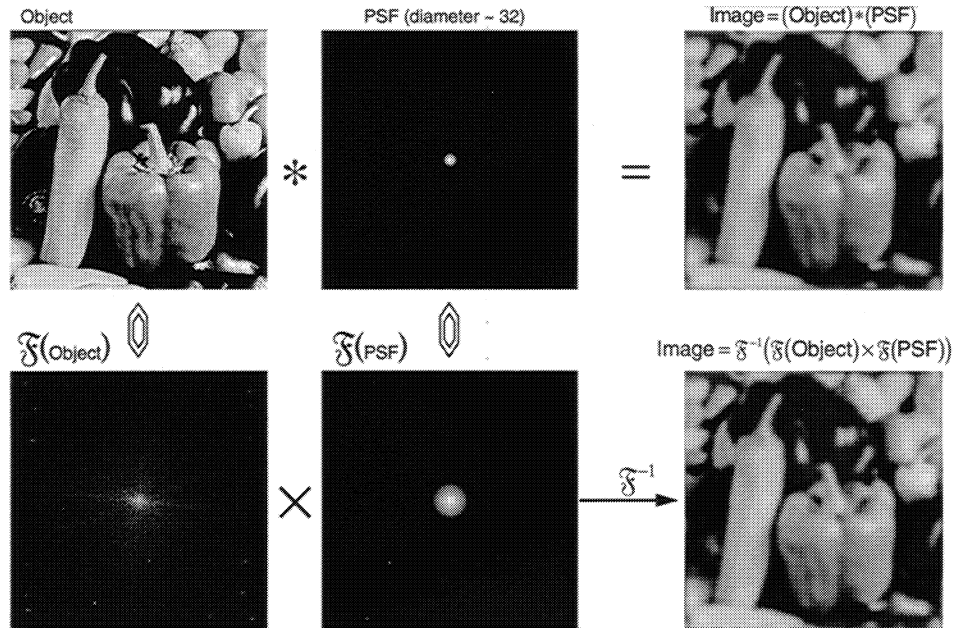


Figure 7. Optical convolutions accomplished by either direct methods or indirect FFT methods using the convolution theorem and the OTF of the sensor.

In Fourier optics, the object and PSF convolution can be viewed as a filtering process. With this perspective, the object is viewed in the frequency domain and the OTF filters attenuate the high-frequency components (amplitude and phase) of the object scene resulting in a low-frequency image. When we observe spatial variations in the object, the spatial variations or modulation in the image are attenuated for higher spatial frequencies. For incoherent imaging and when the geometrical image's spatial frequency is on the order of magnitude of the reciprocal of half the PSF dimension, then the contrast or modulation reduces to zero and the image details or information is lost. Any spatial frequency beyond the cut-off frequency of the optical system will be attenuated in the image plane and will be of little concern when using laser-based FPA image simulation. When viewed from the frequency domain, we see that spatial frequencies larger than the cut-off frequency are filtered out and not present in the image scene. That is to say that high frequency details are filtered out by the optical sensor's low-pass, spatial-frequency OTF.

With the high-frequency content stripped off, the image does not have sharp edges or discontinuous spatial features. In these cases, a small radiation source's diffracted image is essentially the same as the system's PSF, which is also the same as that produced by a small circular source; they can be indistinguishable. The bandwidth-limited image provides some guidance to implement the Whittaker-Shannon sampling theorem<sup>9</sup> in image space. However, object space is not necessarily bandwidth-limited and the Whittaker-Shannon sampling theorem does not apply. If the sampling function is projected back into object space and the average radiance within the small region is used then fairly good results are obtained. When using the Whittaker-Shannon sampling theory (illustrated in Figure 8), we can use an array of sources that generates a similar irradiance pattern if the array of source intensities are properly selected for OTF-filtered, bandwidth-limited optical images. Under some circumstances, one can then conceivably simulate images with sources that are distinctly different yet yield the same effective image as detected by the FPA, where slight differences are averaged out over the detector's integration region.

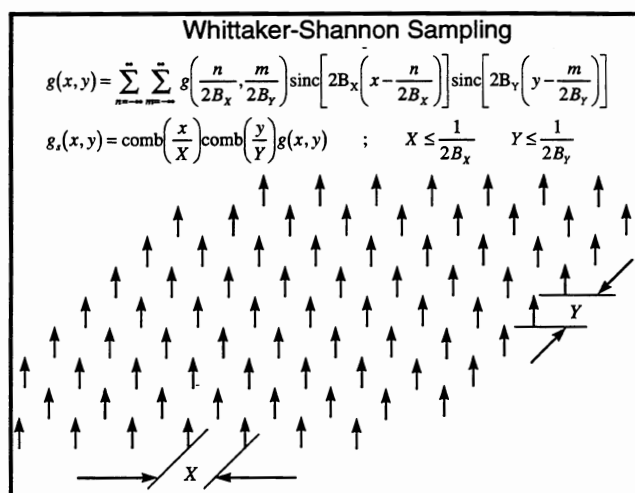


Figure 8. Two-dimensional Whittaker-Shannon sampling method to reduce computational burdens. (The sampling interval is approximately 1/5 the PSF diameter for the shortest inband wavelength.)

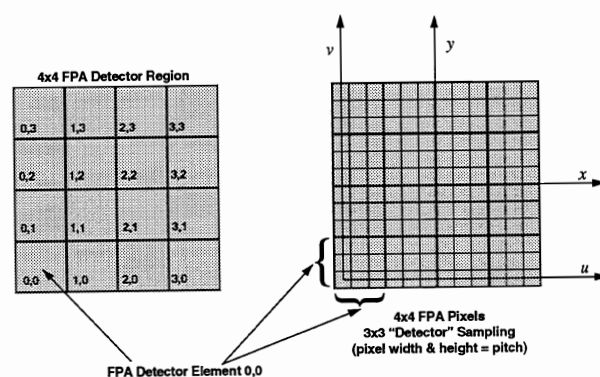


Figure 9. Background, target, and FPA sampling provide efficient and flexible computational schemes for scene extraction and image convolution by employing near Whittaker-Shannon sampling.

To simulate anisoplanatic optical systems and to better support real-time DWSG photonics optical processing, the scene and FPA are quantized into small grid-sampled regions, as illustrated in Figure 9, to perform the integrated image/detector photoflux computations. The degree or level of sampling needed for a scene and FPA combination generally depends on several parameters for a desired fidelity. Figure 9 illustrates a 3x3 sampling region of each detector. When the PSF for the shortest inband wavelength is approximately equal to each detector's width, then a 5x5 detector sampling would correspond to Whittaker-Shannon sampling (about 1/5 of the PSF dimension). Efforts are being made to extend this methodology by using effective PSFs to include optical aberrations and jitter.

The spatial decomposition scheme illustrated in Figure 6 can be generalized to allow the extended computational domain to be a width equal to one or more PSF dimensions or any fraction of a PSF width. The width of the extended computational domain and the corresponding number of grid-points within each computational region can then be selected for optimized fidelity. The number of grid points within each extended computational region can be arbitrary and not necessarily an integer power of two. To accommodate this arbitrariness, Winograd FFT (WFFT) methods can be used. The WFFT method is based on integer prime-factor decomposition, and the computational speed is related to the sum of the prime factors of the grid size used for the WFFT as illustrated in Figure 10 and Figure 11. The Winograd method provides an algorithm for FFTs that does not require integer powers of two for the computational regions as normally used with the Cooley-Tukey method and padding.

An extended computational region's dimension is chosen using the set of integers whose prime-factor sums provides the best WFFT performance (lower bound illustrated in Figure 12) for a desired region dimension. The performance gain by using the optimum set of dimensions for an NxN region is illustrated in Figure 13. The performance gain ranges from about one up to about 50. The computational region does not have to be square and can be some MxN region where M and N are individually selected from the optimum set. By supporting arbitrary dimensions, the extended-domain computational scheme facilitates considerable flexibility to support anisoplanatic simulation and parallel processing.

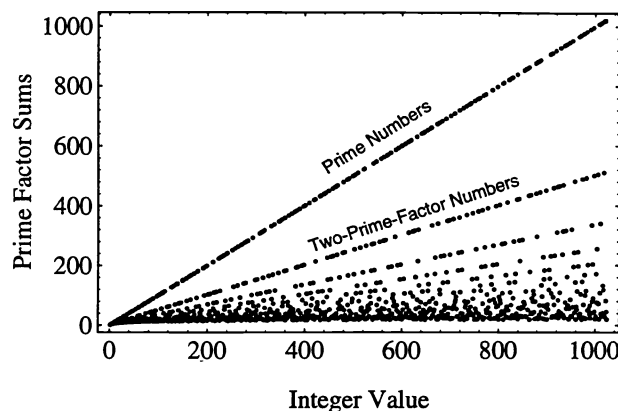


Figure 10. Integer prime-factor decomposition and prime-factor sums.

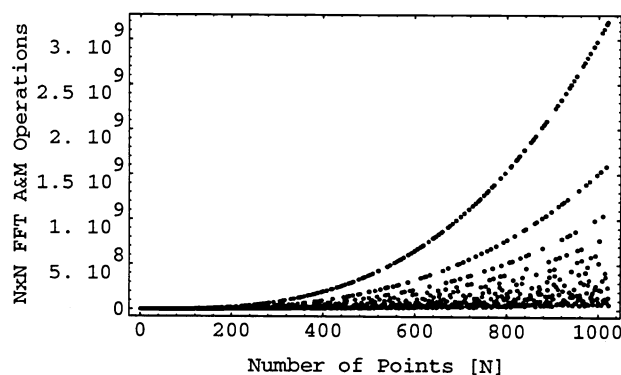


Figure 11. Arithmetic operations for NxN Winograd FFT algorithms.

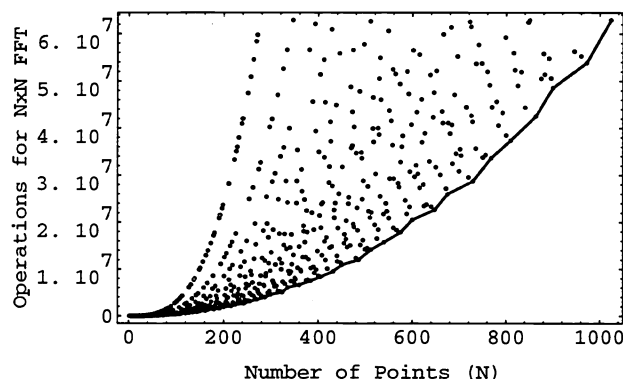


Figure 12. Lower bound optimum set for selecting grid size dimension for Winograd FFT algorithms.

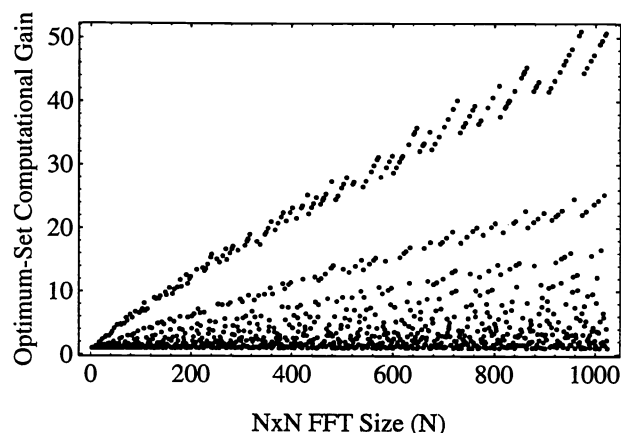


Figure 13. Potential computational gain for using optimum set for selecting the dimension of NxN Winograd FFTs.

It is very desirable that the methodology developed scales easily for high-speed parallel-processing methods. Table 1 illustrates the potential performance that can be obtained from parallel processing methods that employ the WFFT methods and using C30-type processors. As expected, the potential performance will decrease as the detector sampling increases from 1x1 to some larger over-sampling that may be needed to maintain adequate fidelity. Table 1 indicates that for a 3x3 detector-element sampling, a 60 Hz frame rate is possible for a 128x128 FPA. The actual performance obtained will depend on the architecture chosen and other processing overhead.

When the detector's dimension is large compared to the PSF, then one also has to consider the integration effects of the detector elements to help establish the grid-sampling method chosen. The choice of using either small-kernel direct convolution methods or OTF frequency-domain methods with WFFTs depends on the desired fidelity needed and the performance needed to support high-speed FPA applications. In either case, the PSF/OTF is restricted to a finite domain for optical simulation and provides a limited simulation that can be acceptable for some intended purpose.

Table 1. Potential frame rates for parallel-processing using a C30-processor baseline.

| <b>FPA Pixels</b>                                                                                                                                                                    | <b>Grid/Pixel</b> | <b>MFLOP<sup>1</sup></b> | <b>Frames/s</b> | <b>MBytes/s</b> |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------|--------------------------|-----------------|-----------------|
| 128x128                                                                                                                                                                              | 1x1               | 1.19                     | 535.10          | 8.7             |
| 128x128                                                                                                                                                                              | 3x3               | 9.54                     | 67.05           | 9.8             |
| 128x128                                                                                                                                                                              | 5x5               | 27.74                    | 23.06           | 9.4             |
| 256x256                                                                                                                                                                              | 1x1               | 5.17                     | 123.61          | 8.1             |
| 256x256                                                                                                                                                                              | 3x3               | 41.71                    | 15.34           | 9.0             |
| 256x256                                                                                                                                                                              | 5x5               | 120.80                   | 5.29            | 8.6             |
| 512x512                                                                                                                                                                              | 1x1               | 22.28                    | 28.72           | 7.5             |
| 512x512                                                                                                                                                                              | 3x3               | 181.03                   | 3.53            | 8.3             |
| 512x512                                                                                                                                                                              | 5x5               | 522.52                   | 1.22            | 7.9             |
| <sup>1</sup> Million Floating Point Operations (MFLOP)<br>Assumes available bandwidth of C30s @ 20 MFLOP/s, a baseline of 32 C30s ~ 640 MFLOP/s,<br>and one Byte/Pixel for transfers |                   |                          |                 |                 |

## 6. Concluding Remarks

New DWSG photonic image-synthesis methods are being developed and incorporated to provide more realistic optical simulations with either realistic or synthetic scenes. These photonic image synthesis methods can more accurately generate and represent temporal power-spectral densities and Wiener spectrums for complex background/target scene simulations that are more representative of scenes and optically convolved FPA images anticipated, and typical of real-world FPA sensor operation.

Although extended computational domains help to reduce computational artifacts, the extended computational domains seem to primarily resolve the errors and effects due to diffraction onto adjacent computational regions. Whether one uses either modified Hanning operators or even extended decomposition ultimately depends on the desired speed and resulting fidelity. The choice of either direct small-kernel convolution methods or OTF frequency-domain methods also depends on the desired fidelity and performance needed. In both cases, the PSF and the OTF are restricted to a finite domain for optical simulation.

Optical and computational decomposition will not only provide high-fidelity optical simulation for anisoplanatic optical sensors and complex infrared scenes, but also facilitates high-speed parallel-processing schemes for real-time closed-loop DWSG/sensor operation. This technology effort is providing new optical diagnostics for cost-effective and systematic DT&E and OT&E of large FPA sensors using parametric and statistical methods not amenable to more costly field or flight testing methods.

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