

Sensor Response Modeling for Trackers (U)

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ABSTRACT

The primary objective of a sensor response model is to provide object sighting messages (OSMs) in the form of accurate position and amplitude estimates to the tracker. This paper will examine the capabilities of a sensor response model entitled "Passive Sensor Workbench (PSW)" to evaluate object sighting measurement accuracy by implementing a selected candidate sensor design and signal/image processing technique. The performance of a sensor response model is also driven by several factors external to the sensor system including the mission, threat, and environment. The mission of the sensor can vary from viewing a target from a surveillance satellite to a seeker onboard an interceptor. The threat viewed from a sensor may vary, from viewing cold targets exoatmospherically, to viewing thrusting boosters against an earth background. The environments to consider include the atmosphere, terrain, clouds, celestial bodies and nuclear effects. Each of these drivers would require a specific sensor design and signal/image processing techniques to perform within specified requirements for acquisition, detection, and track.

The Passive Sensor Workbench (PSW) is a high fidelity sensor and signal/image processing simulation tool for staring and scanning sensors. PSW is used for sensitivity analysis, algorithm evaluations, and performance assessments. It provides an algorithm testing simulation to evaluate candidate signal processing options, and implement/test the performance of algorithms proposed through objective system analysis or advanced technology programs. In addition, PSW can be used to process real world data to provide assessments of sensor performance and provide pre-flight predictions and validation with post-flight data. The simulation has been interfaced to the Synthetic Scene Generation Model (SSGM '97); a community standard target and background scene generation simulation. Through this interface sensor performance can be evaluated against realistically modeled backgrounds to evaluate filtering, detection, and false alarm performance.

The PSW is a graphically enhanced design and analysis tool. Once the targets, backgrounds, sensor design parameters, noise sources, and signal/image processing algorithms are specified and the simulation has executed; the output of the can be examined graphically (before and after) at various points in the processing chain. The user can examine data graphically by selecting a surface, image, or contour plots before and after the analog signal processor and algorithms in the time and object dependent processor. Detected target packets are extracted and processed by the pulse matching routine to perform the position and amplitude estimation prior to the generation of the OSMs. The measures of performance in generating the OSMs consist of evaluating the angular and radiometric measurement precision for various sensor designs, signal/image processing techniques, target intensities, and nominal/stressing backgrounds.

1. INTRODUCTION

The development of IR sensor response models requires the understanding of the components and processes involved in an IR sensor system. A top-level block diagram of the functional breakdown of the components and processes of a typical IR sensor system is illustrated in Figure 1. High fidelity modular development has been utilized in developing the

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PSW, providing the capability to plug-n-play modules that have a one-to-one correspondence to the functional breakdown in Figure 1. This capability allows the system designer flexibility in evaluating current systems as well as objective systems, where the goal may be to assess current performance, improvements in performance, computational processing loads, and or cost reduction.

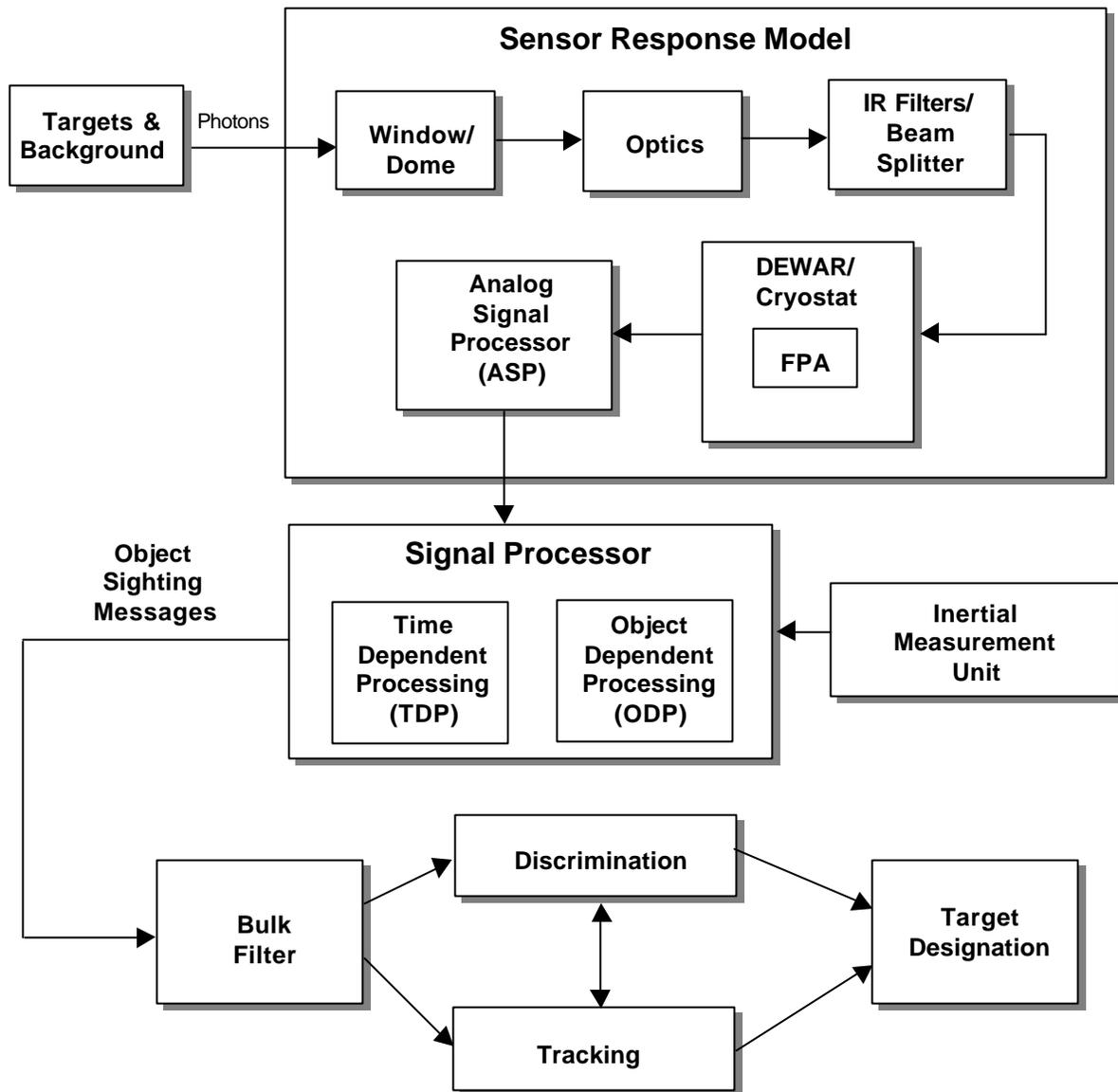


Figure 1. Block diagram depicting the top-level functional breakdown of the components and processes of a typical IR sensor system.

The sensor response modeling described in this paper includes sensor components and processes from the photons from targets/backgrounds through the IR sensor window/dome to the output of the Object Sighting Messages (OSMs). The OSMs are further processed by a bulk filter to remove very hot non-targets like objects from the detection stream, like stars, boosters, or post boost vehicles. The filtered extracted target data in the form of position, amplitude, and shape data is passed both to the discrimination and tracking functions. The discrimination, tracking and target designation processes will not be presented here and there is an implied feedback loop that controls the pointing of the sensor to maintain the objects of interest in the field of view. The discrimination processing extracts features from the extracted object packet, position, and amplitude data and provides feature data to both the tracking and target designation processes. The tracking process uses the object position and amplitude data along with the extracted feature data to generate, maintain, and predict tracks of the objects. The

target designation process logic utilizes the discrimination and tracking data to determine which objects in track are to be designated as targets.

The quality of the OSM data generated by an IR sensor depends upon the design, selection of sensor components, and signal/image processing techniques. The PSW simulation was developed to support this process by providing an environment for the simulation of IR sensors and signal/image processors as well as a functional analysis tool to allow the design engineer to characterize deterministic sensor and signal/image processing performance. This dual nature allows for the design, modeling, and prediction of the behavior of a sensor and signal/image processor combination and to optimize the system performance. Just as important, it allows for the processing of actual measurement data taken from the lab to perform data assessments which provides a high level of confidence in the accuracy and fidelity of the simulation.

PSW is a substantial IR sensor simulation which has been developed from experience supporting sensor design, modeling, and assessments through the following BMDO programs: FAS / AOA / AST / TAOS / DSP / GSTS / BP / BE / MSX / GBI / ASTP / DITP / SBIRS / THAAD. The PSW simulation components are implemented as modular functional models of threat and background scenes, IR sensor components, and sensor processing algorithms written in Ada and C++, consisting of approximately 60k lines of code (LOC).

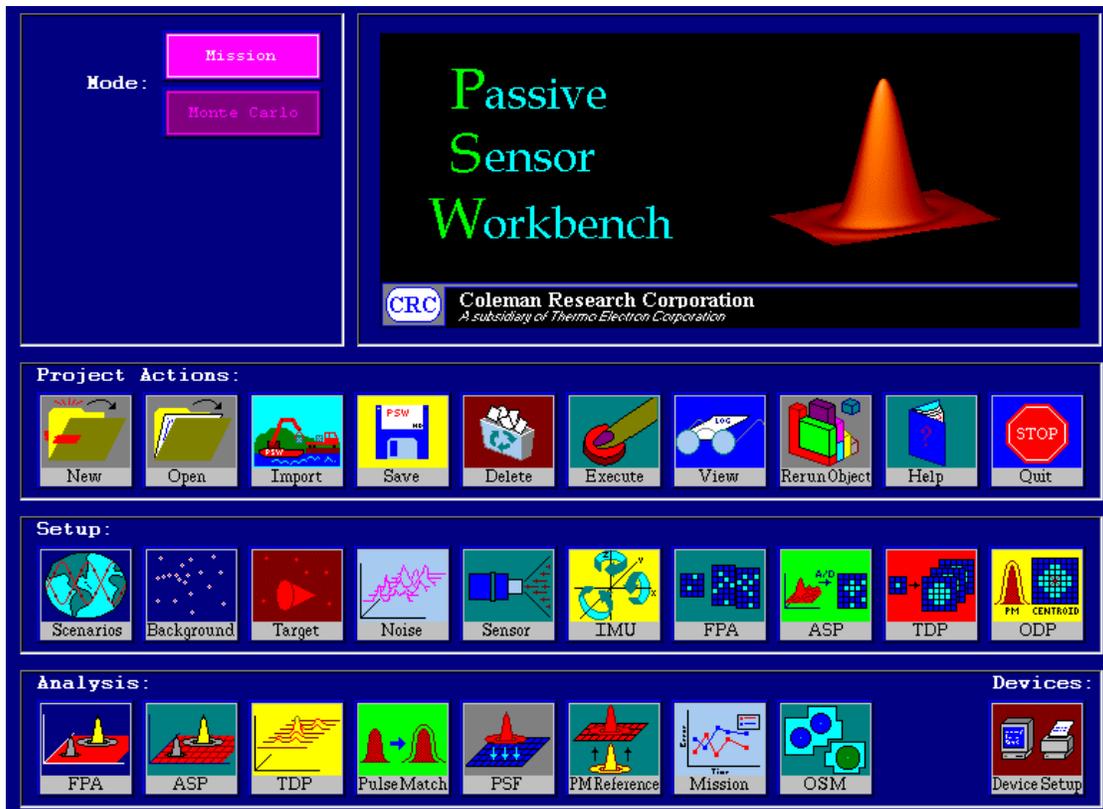


Figure 2. Passive Sensor Workbench Main GUI Window

The Graphical User Interface (GUI) shown in Figure 2 is written in PV-WAVE and is very user friendly. It controls the set up and maintains all inputs and allows data visualization at every level for simulation execution, sensor and signal processing parameter setup, and functional performance analysis. The main GUI window of the PSW (see Figure 2.) displays the project actions, setup, and analysis controls.

Currently, a PSW C++ version is being developed that will have the same capabilities of the current Ada version. Additionally, the Ada version of the PSW because of its modular design allows for the validation, verification, and assessment of the performance of sensor flight software components written in Ada.

2. SENSOR COMPONENT AND PROCESS MODELING

2.1. Window/Dome

The selection of the window/dome material is constrained by the mission requirements of the sensor. If the mission is to perform surveillance from a space platform the sensor may not require a window but if the sensor is on an interceptor required to view objects as it is flying through the atmosphere requires a window/dome. Mission constraints affecting the window material selection include the altitude regime of operation, sensitivity of the sensor to detect targets, and the expected target signatures the sensor is required to detect. The spectral band pass, strength, costs, and possibly innovative cooling techniques are design considerations when selecting the window/dome material.

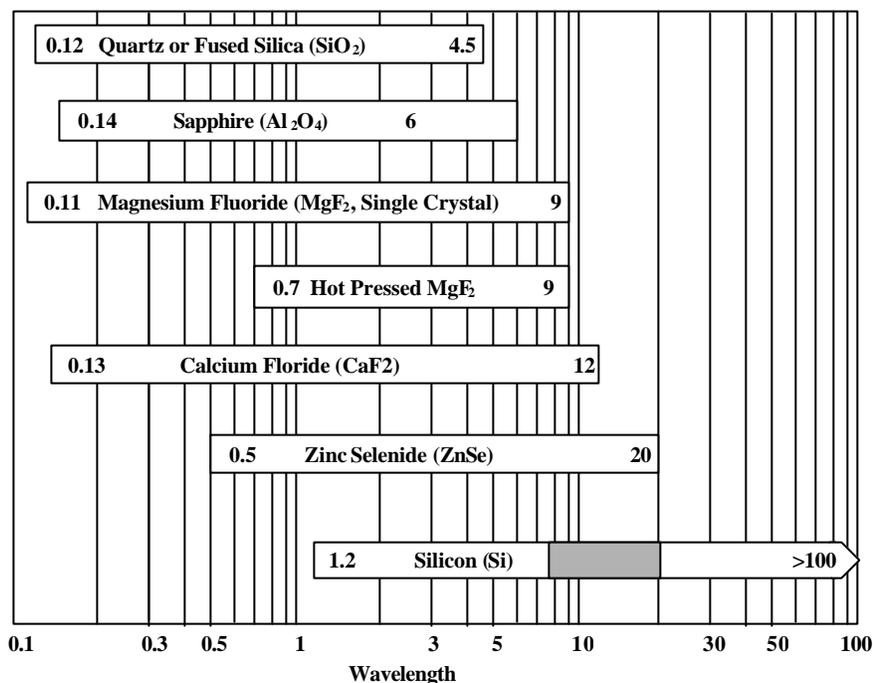


Figure 3. Transmission of Commonly Used Optical Window Materials.

The transmission limits in Figure 3 give cutoff edge, taken as the wavelength (μm) at which a 2mm thick window has 10% transmittance. Cutoff edges are only approximate and may vary with the quality of the material. Shaded regions for diamond and silicon have low transmission. The Figure 3 above is a modified representation of the data presented in the SPIE tutorial text entitled, "Infrared Window and Dome Materials", cited in the references.

The window model within PSW is currently under development and will include options for window material selection based upon the spectral band pass, transmission, emissivity, quality, size, thickness, and temperature.

2.2. Optics / Filters / Beam Splitters

The purpose of the optical system is to collect the incoming radiation from the target and background and to concentrate it upon the detector. The greater the amount of radiant energy that can be collected from the target and transmitted to the detector the greater the detector signal output, and the easier it is to extract useful information from the system. The major components of the optical system are those that focus target energy upon the detector. These elements may be refractive, reflective, or a combination of both. Mirrors employed in IR sensors are "first surface" mirrors, meaning that the reflective material is deposited upon the first surface that the radiation strikes when it reaches the mirror. Reflection takes place without the radiation traveling through the material, upon which the reflecting material is deposited, thus avoiding the

absorption and filtering effects that such material might introduce. Additional components in the optical processing chain include IR filters and beam splitters. IR filters are used to restrict the transmitted energy into the desired passband. Beam splitters (or coatings) may be employed in the optical train prior to IR filtering to split the radiant energy into two beams for example to be collected on two separate focal plane arrays (FPA).

There are four major characteristics that all optical systems have which affect the measurement being made; focal ratio or f /number, spectral transmission, resolution, and instantaneous field of view (IFOV). The sensitivity of an IR sensor depends upon the focal ratio or f /number of the optics. This is the ratio of the focal length to the diameter of the aperture. The lower the f /number the better the detectivity. The reason a short focal length is desirable is that the detectivity of all radiation detectors is inversely proportional to the square root of their area. Therefore, it is always desirable to condense the radiation collected onto the smallest detector area possible. For a given field of view, the shorter the focal length, the smaller the detector required. The spectral transmission of the reflective and refractive elements should be considered to assure the system transmits the desired wavelengths. The resolution of an optical sensor is frequently expressed as its ability to separate two closely spaced objects. The optics of an IR sensor produces an image of the scene in its focal plane. When a detector element is placed in the focal plane the only portion of the scene from which radiation is received is that portion of the scene image falling on the detector. The detector area determines the IFOV. The IFOV of the detector elements of the FPA are calculated as the detector element dimension divided by the focal length.

The design of the optical system determines the point spread function (PSF). The PSF of an optical system can be calculated by simulation such as CODE V or ZEMAX and verified by laboratory measurements and. The Fraunhofer diffraction theory proves, for an aberration free optical system, that the complex amplitude function of a point source object is the two-dimensional Fourier Transform of the aperture. The PSF of the optical system is the normalized amplitude squared function of the image of a point source object and can be defined in terms of a Bessel function. The bright and dark rings of the airy disk for a circular aperture are shown below in Figure 4.

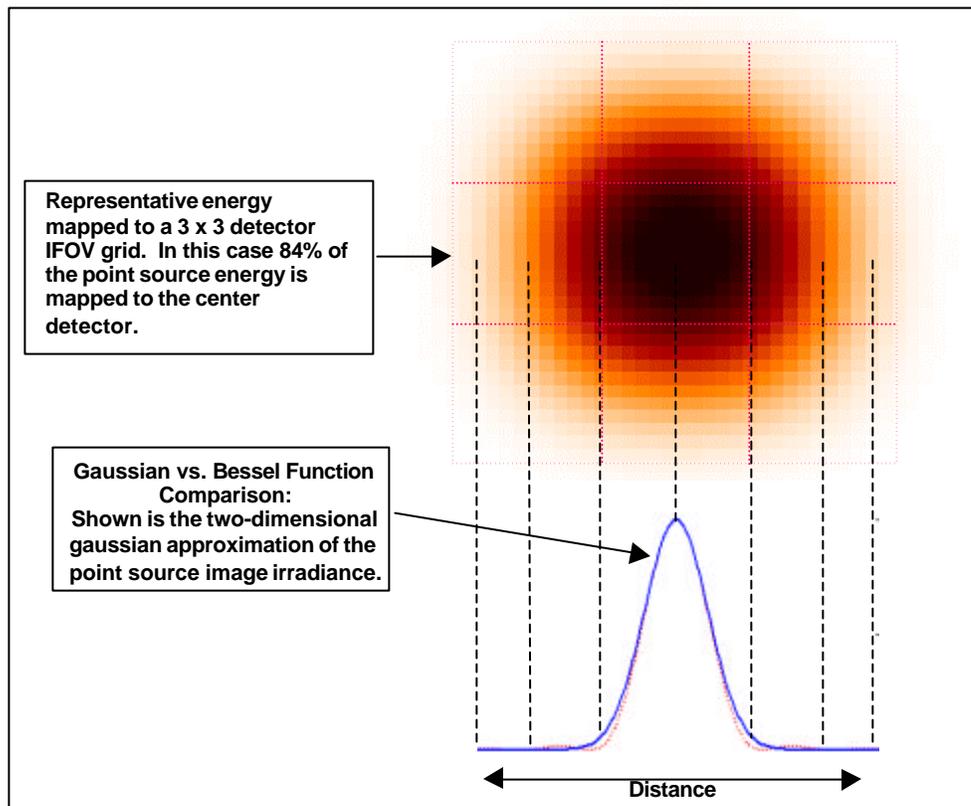


Figure 4. Bright and dark rings of the PSF of a circular aperture.

The radius and the integrated blur energy within the rings at which the Bessel function goes to zero for the first, second, and third ring, respectively, are:

$$\text{Ring 1: } \frac{1.22\lambda}{D_o} \text{ (83.8\%), Ring 2: } \frac{2.33\lambda}{D_o} \text{ (91.0\%), and Ring 3: } \frac{3.24\lambda}{D_o} \text{ (93.8\%).}$$

The fraction of the total energy contained within each circle is a function of its radius and the total radiant energy of each ring increases proportionally with the aperture area. About 84% of the energy is contained within the first ring for monochromatic light and an aberration optical system. The exact Bessel function may not describe the PSF of a circular aperture in practice because of optical aberrations and finite spectral bandwidth of the input radiation. Thus the two-dimensional Gaussian is a good approximation of the IR waveband to be modeled. Figure 4 shows the good comparison of two PSFs, one generated with two-dimensional Gaussian and the other with the Bessel function. The radius, r , of a circle of the two-dimensional Gaussian PSF which contains 84% of the total energy is approximately 1.9 sigma Gaussian. In the PSW simulation, a two-dimensional Gaussian PSF is generated by defining the σ_x , σ_y , ρ_{xy} (correlation coefficient), resolution or the number of sub-pixel PSF grid points, and the detector extent of the PSF. The next step convolves the Gaussian with the detector IFOV map to generate the detector response function. Finally, the point source energy contributions are mapped to the FPA using the PSF. For extended targets, overlapping energy contributions from multiple point sources are summed for each detector element. PSW currently can import PSFs calculated by CODE V or ZEMAX.

2.3. Dewar / Cryostat / FPA / Analog Signal Processor (ASP)

The dewar encloses the FPA and maintains a vacuum so the cryostat can cool the FPA and to maintain the FPA at a specified temperature to increase the sensitivity of the detector elements, primarily to reduce the detector dark current. The dewar has a window that allows the spectral radiation to be transmitted through to the FPA. Similarly to the selection of the window/dome material above consideration needs to be made for the dewar window material and its spectral transmission characteristics. Generally PtSi, HgCdTe, and InSb are the three most common detector materials in use today for IR FPAs. Each material has its own performance characteristics such as the spectral bandpass, quantum efficiency, linearity, non-uniformity, producibility, and reliability. The radiant energy in photons that are collected by the detector element are converted to electrons and read out by the readout electronic circuitry. The readout noise is defined as the electrons that are associated with the electronic circuitry reading the individual detector elements. The noise sources that are associated with the physical operation of the FPA detector element are non-uniformity, readout, dark current, 1/f, Johnson, and generation-recombination noise. Laboratory calibration is performed to remove the non-uniformity, to make the detector response uniform (flat fielding), and to make the detector response traceable to an absolute standard, to be able to perform target intensity estimation. Calibration can also identify and compensate the effects due to dead pixels (zero or saturated) or blinking pixels (device physics dependent), which may have output levels with bias and variation. The output of the readout electronics is digitized and sent to the analog signal processor.

In the PSW simulation, the ASP is comprised of the readout electronics and its function is to process the voltage readout from each detector element through an analog to digital (A/D) converter with the output being represented in counts. Typically 12 bit A/Ds are used and have the maximum dynamic range of 0 to $2^{12}-1$ (4095 counts) over a specified voltage range across the A/D.

2.4. Inertial Measurement Unit

The gyroscopic and accelerometer data are used to compute the linear and angular position, velocity and acceleration estimates of the transformation matrices used to compute the sensor bore sight and line-of-sight. The IMU data is input to the signal processor to be able to perform FPA frame-to-frame registration in the case of multi-frame processing. The PSW IMU model generates specified azimuth and elevation profiles to simulate a drifting or dithering sensor. PSW can also import IMU data from a test flight or laboratory test to support data reduction and performance assessments.

2.5. Signal Processor: Time/Object Dependent Processing

The signal processor is conventionally comprised of the time dependent processor (TDP) and the object dependent processor (ODP). IR sensor observational data output from the ASP consists of a virtual array of data (in count space) representative of the environmental phenomena viewed by the sensor. The primary functions of the TDP are to perform noise reduction, signal/image enhancement, thresholding, extraction of object detection packets, segmentation, and object parameter estimation.

Noise reduction can be performed by applying filters in either the spatial, temporal, or frequency domain. Noise removed by multi-frame integration, where multiple frames of virtual FPA data are registered and then co-added which yields an effective square root of the number of frames co-added reduction in the noise sigma. Multi-frame processing for staring array (mosaic) sensors may require additional processing such as deconvolution to remove any blurring of the collected data due to sensor motion.

Signal/image enhancing can also be performed in the spatial, temporal, or frequency domain. Typically, the filtering techniques employed are dependent upon the objects the sensor is designed to detect. Types of filters used in the PSW consist of laplacian, matched, morphological, sobel, deconvolution, and background estimation filters. Once the virtual array of FPA data has been conditioned to reduce the noise and enhance the image, thresholding algorithms are used to further isolate regions that may contain objects of interest.

Thresholding can again be performed in either the spatial, temporal, or frequency domain. Typically, thresholding levels can be set by estimating the background noise sigma across the entire virtual FPA data field (excluding the targets if possible) or adaptively in sub-regional areas similarly to a convolution process with a mask of size $N \times N$. Once thresholding is complete, data above the threshold value are tagged as exceedances and then segmented by tagging the associated data surrounding the data exceeding the threshold value. The segmented data above threshold, identified as the extracted object packet data, are then extracted and sent to the ODP.

The job of the ODP is to process the extracted object packet data and produce position and amplitude estimate data called Object Sighting Messages (OSMs). The conventional methods for amplitude estimation include centroiding and pulse matching. In the centroiding case, the centroid and first moment of the extracted object packet data is determined. The centroid is essentially the position of the object relative to the FPA and the moment is the estimate of the energy mapped to the FPA due to the object plus noise. The amplitude of the object can be estimated because the detector response function (energy mapped to the FPA by the PSF) that is used to map the energy to the FPA is known. The other method of amplitude estimation is pulse matching and is performed with a two-dimensional nonlinear least squares regression fit of the extracted packet data and the detector response function. The detector response function used in pulse matching should be consistent with the PSF whether it comes from the two-dimensional gaussian, CODE V, ZEMAX, or is modified to account for motion the sensor went through during the integration period.

2.6. Object Sighting Messages

Conventionally, the OSMs consist of the extracted object packet data, position and amplitude estimates of the objects detected per frame or multi-frame processing. The OSM data is output to the bulk filter that removes very hot non-targets like objects from the detection stream, like stars, boosters, or post boost vehicles. The resultant data is passed to the discrimination and tracking functions and then processed by the target designation function to determine the target(s) of interest in the field of view. The quality of the resultant OSM data depends greatly upon the design of the sensor components and the signal/image processing techniques used.

3. FUNCTIONAL PERFORMANCE ANALYSIS

3.1. Design Trade Space

Within the PSW environment trade studies can be performed to optimize the system to meet specified mission requirements. The design trade space depicted in Figure 5 below shows the design trades and component/process trade space possible within PSW that should be considered when implementing sensor designs and signal/image processing techniques. For example when a requirement for the Radiometric Measurement Precision (RMP) and Angular Measurement Precision (AMP) are specified all of the components and processes need to be considered to calculate the performance.

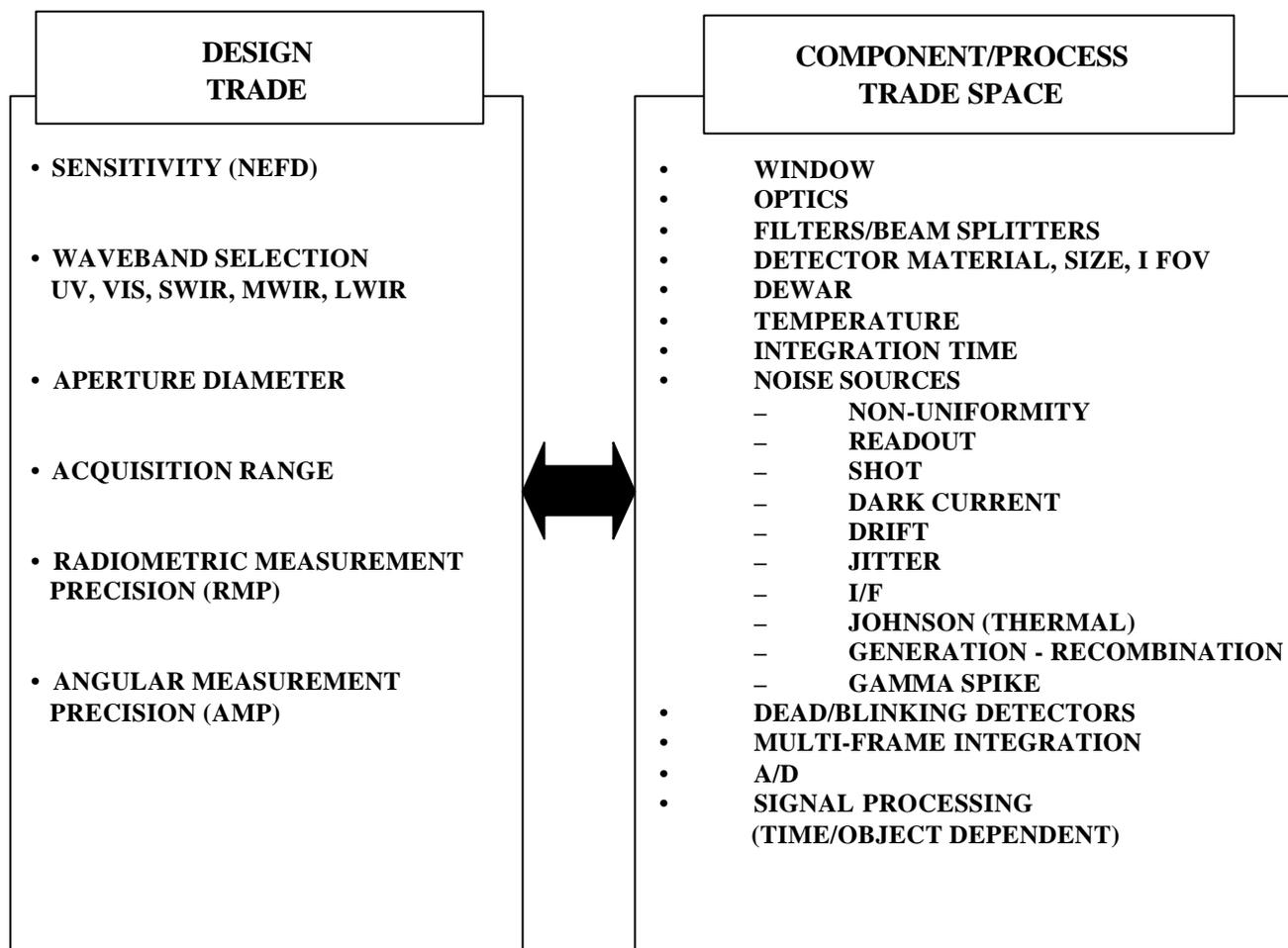


Figure 5. Design and Component/Process Trade Space

3.2. Sensor Response Modeling Analysis Example

The examples that follow were generated using the PSW simulation. The environmental background phenomena was imported using the Synthetic Scene Generation Model (SSGM '97), developed by the Naval Research Laboratory, consisting of a background scene that is viewed from a satellite surveillance sensor viewing below the horizon at a scene containing terrain and clouds. In this example, the sensor waveband is set to 4.2 – 4.45 (CO² band) and is viewing four point source targets that are moving across the scene, where two of the targets are closely spaced objects (CSOs). The sensor realized scene with the embedded targets without noise contributions is shown after being processed through the ASP in Figure 6.

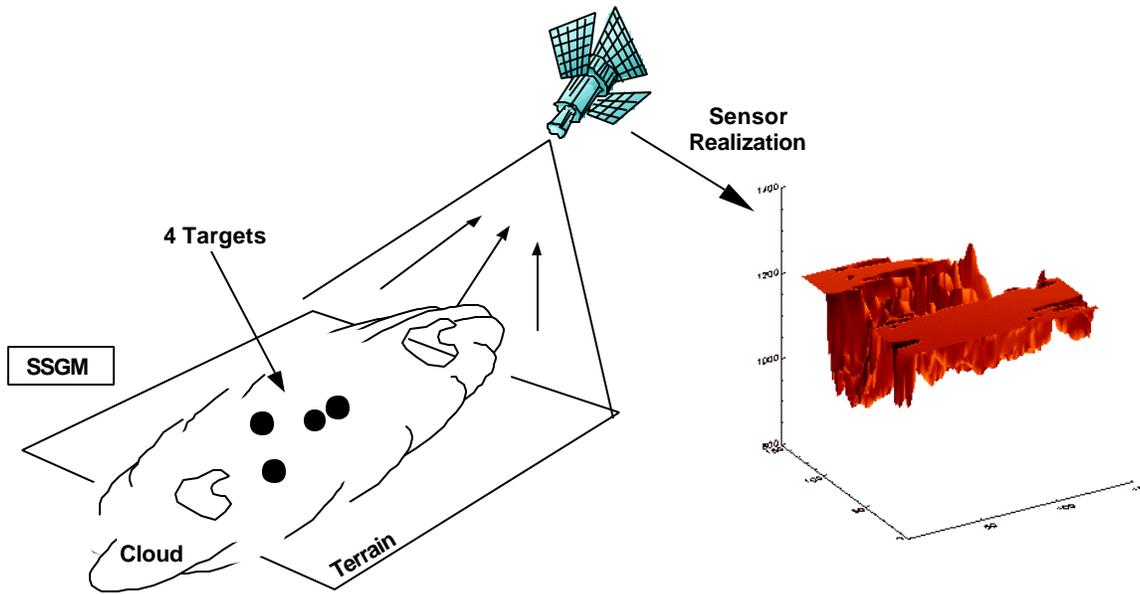


Figure 6. SSGM Scene with desert terrain and clouds viewed by the PSW IR Sensor Model. The sensor realization (no noise) is shown on the right after the ASP.

Characterization of the sensor response of the background scene is important to understand the data trends (mean, sigma, distribution (probability density and cumulative probability), 2-D FFT, PSD ...) to attempt to optimize the noise reduction and image enhancing signal processing techniques. Typically trade studies are performed for various terrain, cloud, solar (diffuse or specular) conditions to assess various design constraints for best, nominal and stressing conditions. Figure 7 shows the probability density and cumulative probability of the SSGM terrain/cloud scene with diffuse solar illumination. In this waveband (CO₂) the clouds (H₂O) attenuate the radiant energy radiating from the terrain (CO₂) creating a very cluttered return. From the distribution of the data it can be seen from the minima around the mean that a simple thresholding schema will not be acceptable in extracting targets, where an adaptive approach should be employed to search within sub-regional areas. The same sensor realization with noise contributions including 1/f, shot, dead pixels, blinking pixels (varying 20%), and nonuniformity is shown in Figure 8.

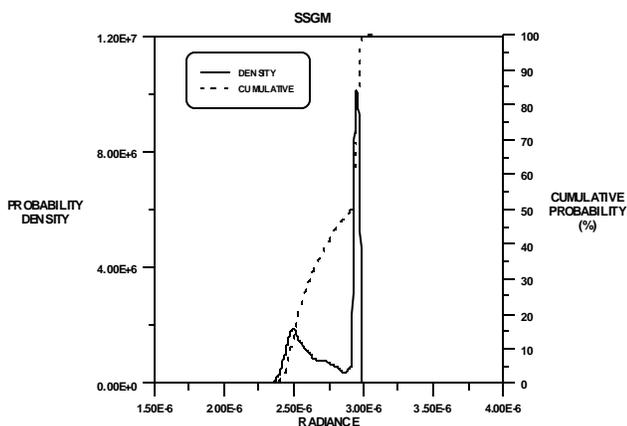


Figure 7. Background Scene Data Analysis SSGM Scene (Terrain/Cloud), Probability Density & Cumulative Probability Vs Radiance.

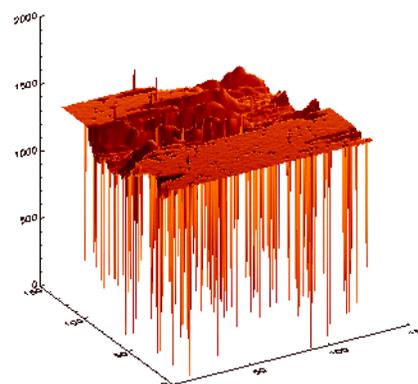


Figure 8. ASP Output: (single frame) SSGM Scene (Terrain/Cloud) Noise: 1/f, shot, dead / blinking pixel, non-uniformity, 4 targets

The effects of gamma spike noise are shown in Figure 9. Further processing of the scene with targets and noise by multi-frame integration and noise suppression is shown in Figure 10. Applying the morphological filter to further enhance the separability of the targets from the background is shown in Figure 11. Adaptive thresholding (sub-regional thresholding) is applied to the data and the resultant output is displayed in Figure 12.

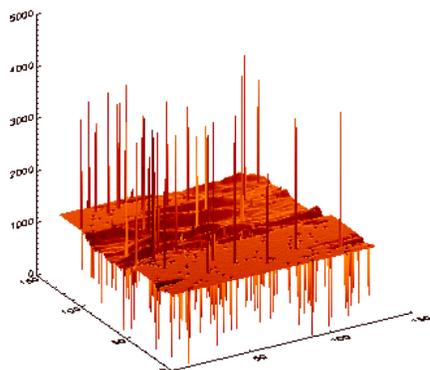


FIGURE 9. ASP Output: (single frame)
SSGM Scene (Terrain/Cloud),
Noise: 1/f, shot, dead / blinking pixel,
non-uniformity, gamma spike, 4 targets,

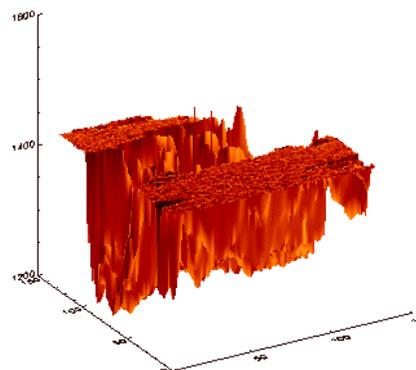


FIGURE 10. TDP Output:
SSGM Scene (Terrain/Cloud)
Noise: 1/f, shot, dead / blinking pixel,
non-uniformity, gamma spike, 4 targets,
multi-frame integration (10 frames)

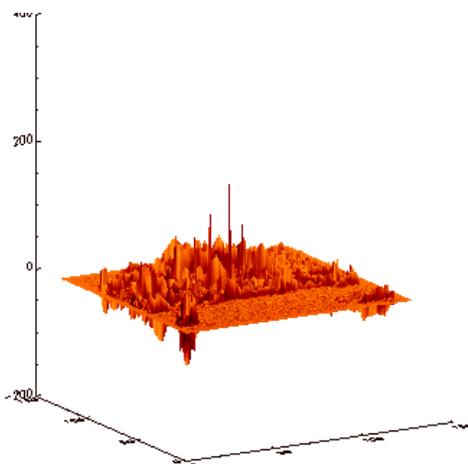


FIGURE 11. TDP Output:
After Morphological Filtering,
SSGM Scene (Terrain/Cloud),
Noise: 1/f, shot, dead / blinking pixel,
non-uniformity, gamma spike, 4 targets,
multi-frame integration (10 frames)

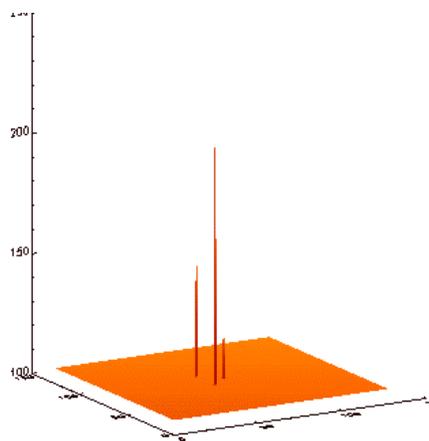


FIGURE 12. TDP Output:
After Adaptive Thresholding,
SSGM Scene (Terrain/Cloud),
Noise: 1/f, shot, dead / blinking pixel,
non-uniformity, gamma spike, 4 targets,
multi-frame integration (10 frames)

The extracted data after being processed by the pulse matcher is shown in Figure 13, which determines the parameter estimates for the position (azimuth and elevation relative to the FPA) and amplitude of the objects of interest. Finally, the OSM output depicting graphically (see Figure 14) the results of the data that is passed to the discrimination and tracking functions. Plotted within the OSM output display window are the extracted object packet data along with the truth and estimated target positions.

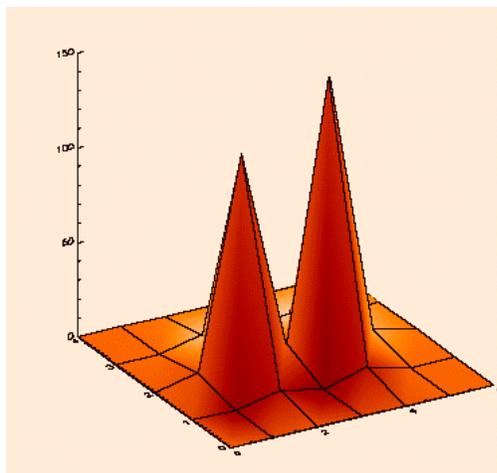


Figure 13. Pulse Matcher Output:
2 CSO objects resolved, position, and amplitude

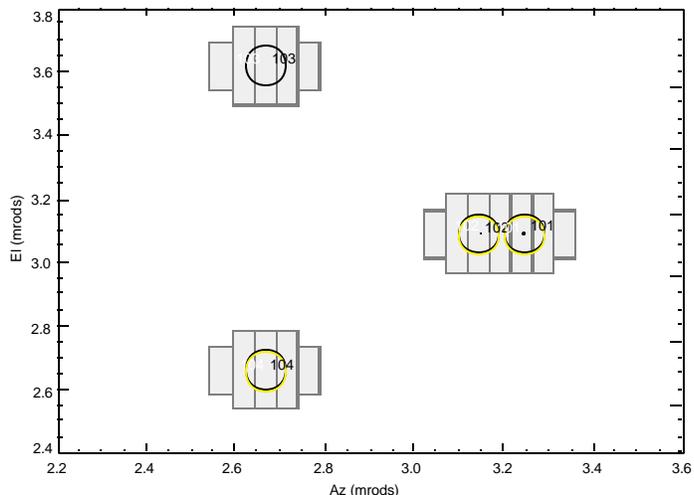


Figure 14. OSM Output:
Extracted object packet data, truth position, pulse matcher estimated position

Design trades can be performed with the PSW simulation. The NEFD versus the optics temperature trade shown in Figure 15 depicts the sensitivity of the sensor to varying temperature and non-uniformity. The analysis shows that for this example at temperatures greater than 280K the sensor is shot noise limited, but by reducing the optics temperature (possibly with considerable costs) below 280K the sensitivity becomes readout noise limited. The NEFD versus Readout Noise trade shown in Figure 16 illustrates the effects of varying the A/D (12 or 14 bits) and the readout noise levels. For this case, the sensitivity improves by a factor of two by just going from a 12 bit A/D to a 14 bit A/D. Additional trade studies highlighted in Figure 5 can be performed with the PSW.

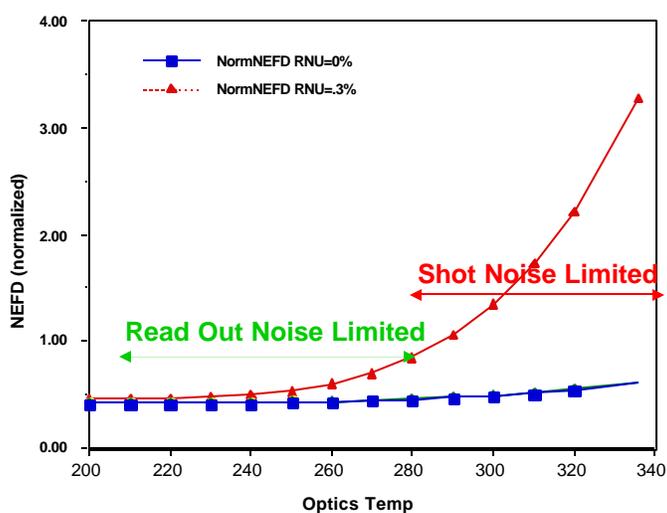


FIGURE 15. NEFD Vs Optics Temperature Trade
Not much benefit by cooling below 280k

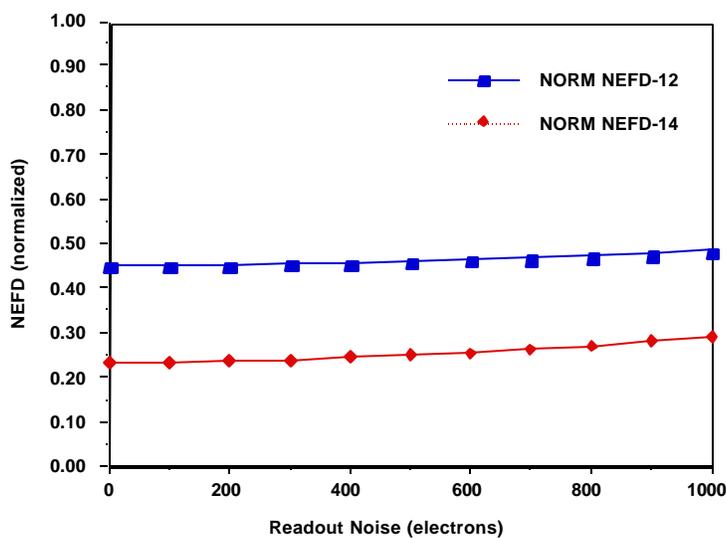


FIGURE 16. NEFD Vs Readout Noise
Improving mux noise reduces NEFD

4. SUMMARY

This paper is intended to highlight IR sensor physics and IR sensor response modeling and to show some of the capabilities of the PSW. The PSW has been carefully designed to fulfill its roles as a high fidelity IR sensor response model and signal/image processing environment and data analysis tool. Enhancements to the PSW simulation are in progress and include: fidelity enhancements to the sensor response component modeling, addition of new/innovative signal processing techniques, automatic target recognition, and aimpoint selection algorithms, interface to the tactical scene generation model "Paint the Night" (NVESD), and automated design trade analysis options.

The PSW simulation is built modularly to allow the design engineer to test out and optimize the sensor components, design, and signal/image processing algorithms. PSW allows the design engineer to implement and evaluate existing, alternative, and new technology advances of sensor designs and signal/image processing algorithm options.

The PSW has been used to analyze IR sensor test / flight data and simulated data for actual and proposed optical systems. Its output has been carefully compared to laboratory data and was found to agree within the uncertainties of the laboratory setup.

5. ACKNOWLEDGEMENTS

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