High-Fidelity Electro-Optical Space Domain Awareness Scene Simulator

Christopher Griffith

The Aerospace Corporation

Brian Baptista, Nicholas Chapman

The Aerospace Corporation

1. ABSTRACT

Aerospace has developed a high-fidelity Space Domain Awareness (SDA) scene simulator to produce realistic space surveillance scenes for both ground- and space-based electro-optical sensors to provide stakeholders with simulated imagery during all phases of programs from concept development to operations as well as to assess mission data processing algorithms and data pipelines, among other uses. We construct scenes using sensor-target engagement scenarios that model the in-band radiometry of the scene while adding in the appropriate backgrounds, stars, targets, and noise components. The scene simulator uses stellar catalogs, including the Gaia catalog of over one billion stars, to accurately place them in the images and accurately represent their color-corrected in-band apparent brightness down to 22nd magnitude. The simulator uses other published data to model the natural sky brightness from Zodiacal light and unresolved stars in the plane of the Milky Way; additionally, elevated backgrounds due to non-rejected stray light are generated and temporal background effects such as cosmic rays are injected based on laboratory and on-orbit measurements. The simulator optionally incorporates laboratory measurements of electro-optical sensor bias structure and noise sources such as dark current, read noise, and other sources of spatial-temporal sensor noise. Aerospace can simulate scenarios with any sensor observing concept of operations (CONOPS) and the targets in the scene can be modeled at any fidelity, from simple diffuse sphere objects to high-fidelity Computer Aided Design (CAD) models rendered with realistic bidirectional reflectance distribution functions (BRDFs) and shadowing to capture complicated light curve behavior. High-fidelity scenes created by the simulator are currently used to reduce risk, guide technology development, and inform operational CONOPS on multiple programs to ensure that sensor hardware performance and data processing software will meet mission needs and requirements.

2. INTRODUCTION

Aerospace has significant heritage modeling Space Domain Awareness (SDA) programs and tactical scenarios and assisting customers in making informed acquisition and operational decisions. The core of the Aerospace SDA target, background, and electro-optical sensor modeling software TRADIX[1] dates to the 1960s and has been successfully benchmarked and validated against many operational ground- and space-based programs, including SBV, SBSS, ORS-5, GSSAP, GEODSS, and SST as well as programs in other mission areas. TRADIX offers sensor- and constellation-level analysis for ground- and space-based electro-optical sensors and calculates performance and statistical metrics such as gap time to evaluate the performance of SDA sensors. In recent years, we have built a high-fidelity SDA scene simulator based on the radiometric calculations of TRADIX to increase the fidelity of the analysis and offer customers high-fidelity SDA scenes of a modeled sensor. These scenes offer focal plane data with noise sources to test target extraction algorithms and ensure the data processing and detection thresholds meet mission needs. The scene simulator has allowed customers to fully characterize data processing pipelines during development and acquisition as well as in support of on-orbit operations. In this paper, we will discuss the modeling components that create a high-fidelity SDA scene and discuss some example products for the community to utilize.

[1] TRADIX is historically a nested acronym, but at present it is used as a name.

3. METHODOLOGY

The block diagram in Fig. 1provides an overview of the scene simulator and the following sections provide details on the methodology. Fig. 1

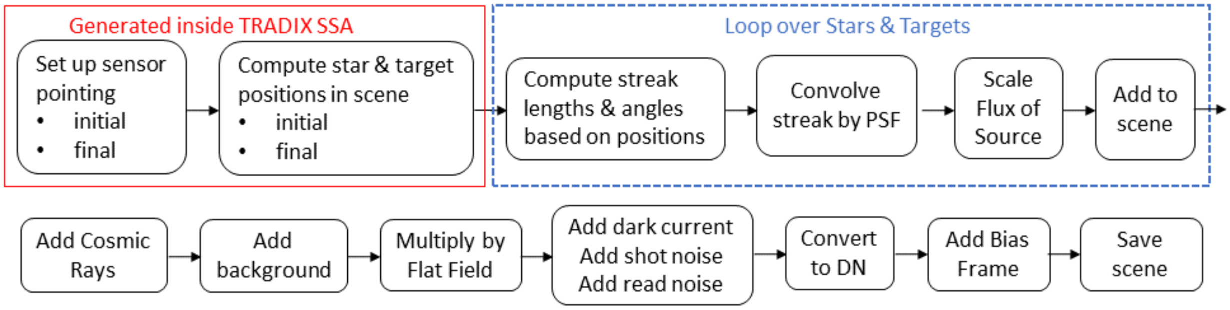

Fig. 1 Block diagram of the TRADIX Scene Simulator.

3.1 TARGET RADIOMETERY

Target brightness in visible light and near-infrared (VIS-NIR) is predominantly due to reflected sunlight.. The intrinsic brightness or radiant intensity of a target is determined by two factors: the reflectivity-area product and the lighting conditions. The reflectivity-area product is composed of the reflectance of the target, which can be modeled from a constant reflectivity to a spectral BRDF, and by the optical cross section, which is the projected area of the object as viewed by the sensor. Depending on orbit, the lighting conditions are primarily driven by the phase angles of the Sun and Earth. TRADIX computes when a target is in eclipse (in Earth's shadow) and thus not detectable in VIS-NIR bandpasses. In this section, we will discuss low- and high-fidelity methods we use to model a target.

3.1.1 SIMPLE SHAPES

The in-band radiant intensity for any diffuse convex surface can be expressed as $1/\pi$ times the reflectivity-area product times the in-band irradiance from the illumination source (e.g., the Sun) times a function of engagement geometry, which is due to target pose and phase angle to the illumination source. The radiant intensity for diffuse spheres and diffuse plates (flat one- or two-sided surfaces) can be written analytically and therefore are easy to incorporate into models. In the case of a sphere, target attitude information is not needed and assuming a reflectivity and a diameter, the radiant intensity is only a function of phase angle. The diffuse sphere is the simplest useful model that provides a phase angle dependence on the target brightness and is readily implemented in any model or simulation; this model also provides traceability to very nearly every space surveillance program back to the dawn of the Space Age when most satellites were spherical and either specular or diffuse. TRADIX's internal radiometric intensity calculator models the following simple shapes: sphere, plate, cone, cone frustum (a cone with a flat top instead of a point), cylinder, and cube. All these basic shapes are modeled as grey Lambertian sources (i.e., diffuse reflectance) and are fully parameterized by sensor bandpass, reflectivity, size parameter(s), attitude orientation with respect to the observer, and lighting conditions. Multiple simple shapes can be combined, and shapes can have time-varying orientations such as sun-, velocity-, or nadir-pointing but at this level of fidelity self-shadowing between components is not considered. The target radiant intensity is computed analytically, meaning the performance of sensors against large constellations of targets can be computed efficiently.

3.1.2 CAD MODELS

To increase the fidelity of the modeled target, the scene simulator can ingest Computer Aided Design (CAD) models. We developed an interface to a ray tracing tool that can ingest CAD models in a variety of formats. This interface allows the user to use Bidirectional Reflectance Distribution Function (BRDF) information from materials applied to the CAD model to capture both diffuse and specular features of the modeled materials. The CAD model can be oriented correctly in orbit (including articulating solar panels) to match on-orbit light curve behavior and increase fidelity when the target model is known.

3.2 POINT SPREAD FUNCTION (PSF)

The point spread function (PSF) of an electro-optical sensor is based on the optical blur due to diffraction of the optics and any relevant structures, including aperture shape, obstructions, baffle vanes, and other components. The PSF is a key figure of merit for any electro-optical sensor that determines how much signal falls onto the focal plane during an integration. When the PSF is sampled by the pixels, we now refer to pixelated point response function (PRF). The scene simulator can use a generic gaussian PSF, but in general, we use optical modeling tools such as ZEMAX to produce high-fidelity upsampled PSFs to model sensors.

The scene simulator uses a 32× upsampled PSF relative to the sensor pixel scale to accurately model the brightness of stars and satellites. The location of every star and target on the focal plane will have some sub-pixel offset (possibly zero) from the center of the peak pixel (called "phasing") that alters the resultant signal. Fig. 2 shows how three different pixel phasings of the same object will change the appearance of the PRF on the focal plane. Because the scene simulator uses a 32× upsampled PSF, we can accurately model objects within 1/32nd of a pixel in both X and Y directions, well beyond the precision usually required for centroiding algorithms

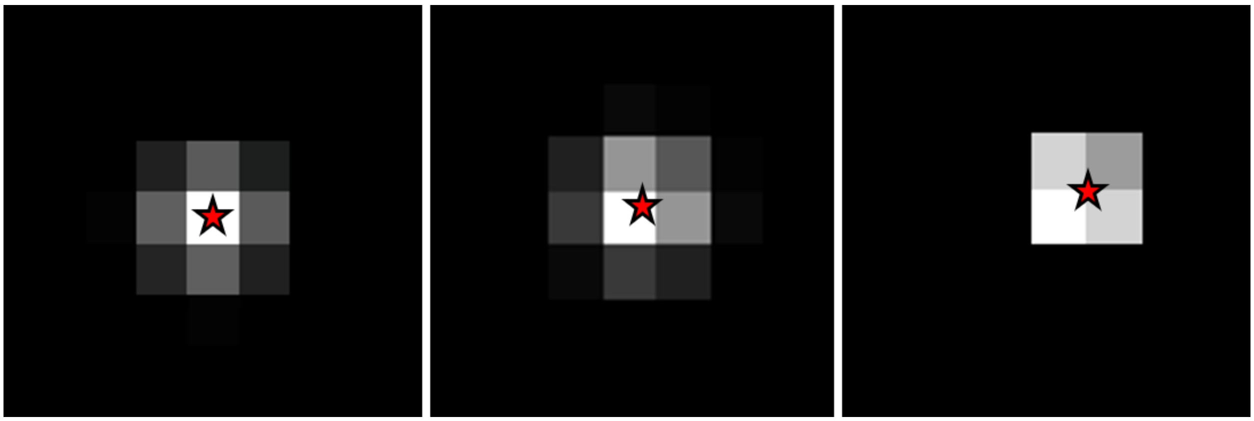

Fig. 2. Example of pixel phasing. The same point spread function, placed at three different sub-pixel locations (red star), dramatically alters an unresolved object's appearance on the focal plane. The brightest pixel is normalized in each panel, and in the far-right panel all four pixels have nearly the same value.

The scene simulator uses a single PSF across the entire focal plane; thus, field-dependent optical distortions or aberrations that alter the PSF shape at different locations on the focal plane are not presently modeled. In section 3.2.1 we use this to our advantage to speed up the image construction, specifically when adding stars to the images.

3.2.1 CONSTRUCTING THE IMAGE

Stars, satellites, or both will streak across the focal plane during an integration, depending on sensor CONOPS. The scene simulator computes the location of an object in pixel coordinates during the integration and convolves the geometric position with the PSF. This method is applied to all objects, whether it appears stationary or has apparent motion. (e.g., the stars will not streak for a sensor operating in sidereal stare mode). A single scene may potentially contain millions of stars (see section 3.4) and to increase the speed of the simulation, we assume all these stars will streak equally in the field of view (i.e., streaks will have the same angle and length). We can make this assumption because we only use a single PSF across the field of view. Each target, however, may streak differently due to range from sensor and its orbit, and therefore each target is treated individually. If a high-fidelity bus and pointing model is present for the system, we utilize this information to create non-rectilinear streaks based on the pointing model as well as jitter and drift (i.e., intra- and inter-frame boresight movement) during each image integration.

3.3 POSITIONS OF SOURCES

The positions of stars and satellites on the focal plane is not simply a matter of computing the object's Right Ascension (RA) and Declination (DEC) and placing them on the focal plane with streaking and pixel phasing. Additional effects must be applied to obtain the apparent location of the object.

3.3.1 STARS

Stars may have a proper motion associated with them. The Gaia star catalog (Section 3.4.1) contains proper motions, and the scene simulator applies these. Secondly, due to the orbit of the Earth about the Sun, star positions shift slightly due to relativistic effects. This effect is called annual aberration and is also applied by the scene simulator. Third, due to the wobble in the rotation axis of the Earth, star locations for ground-based observers are affected by precession and nutation. Finally, star positions are also affected by diurnal aberration (so named because it varies throughout the day as a ground-based observer rotates towards or away from the stars). Diurnal aberration is under consideration for inclusion in the scene simulator.

3.3.2 SATELLITES

The relative positions of satellites vary due to many effects, of which we note two. First is the light travel time from the target satellite to the sensor at a given time t the sensor sees the position of the target at time $t - \Delta t$, where Δt is the light travel time between the sensor and target satellite. A second effect is velocity aberration. Like diurnal and annual aberration for stars, this is a relativistic effect due to the apparent velocity between the sensor and target satellite. The scene simulator applies both light travel time and velocity aberration effects to satellite positions.

3.4 STAR CATALOG

The scene simulator can use any star catalog provided to it. We use a limited version of the Hubble Guide Star Catalog (GSC) to reduce simulation runtime when testing. The Gaia star catalog is used for all analysis runs. In this paper we only discuss our use of the Gaia star catalog.

3.4.1 GAIA STAR CATALOG

Gaia is a European Space Agency (ESA) satellite mission designed to make the most precise three-dimensional map of the Galaxy by taking photometric and astrometric data of approximately 1% of the Galaxy's stars. It was launched in 2013 and is expected to operate until 2025. The Data Release 2 (DR2) catalog contains 1.6 billion stars with positions, magnitudes in a panchromatic CCD band dubbed 'G', and two narrower bands G_B (Gaia Blue) and G_R (Gaia Red) to allow spectral typing. The catalog is a complete sky survey between 3rd and 22nd magnitude in the G band. Note, there are ~250 stars missing from the catalog that are brighter than 3rd magnitude in the G band. The Gaia catalog positions provide precise astrometric positions with Right Ascension (RA) and Declination (DEC) based on J2015.5 with proper motions in RA and DEC also provided [1].

The scene simulator by default uses the entire DR2 catalog. While there are some bright stars missing, these are not the driving confusers to SSA detection and tracking algorithms, as the bright stars are significantly brighter than the typical SSA target. Bright stars are under consideration for inclusion in a future version of the scene simulator. At the faint end, 22nd magnitude is deep enough to model most SSA sensors and CONOPs and the extent of the catalog ensures that our star placement in simulated scenes is complete down to or below the typical detection threshold while still allowing fainter stars to be found when stacking frames. The faint stars also add some additional confusion noise to realistically evaluate detection algorithms.

3.4.2 COLOR-COLOR CORRECTIONS

The Gaia mission provides a zero-point magnitude that can be used to convert Gaia G band magnitudes into photoelectrons *in the Gaia bandpass*. Because the scene simulator is used to generate imagery for arbitrary filters, we cannot use the Gaia star catalog magnitudes as-is to compute their fluxes. Instead, we must compute a color-color correction curve for the specific filter to convert the Gaia magnitudes into the magnitudes of the filter band of interest. Fig. 3 shows how this process works. The left panel shows the stellar spectra for various star spectral types: O5V, A0V, G2V, and M0V. These spectral types represent stars with a range of surface temperatures from very hot (O5V) to cool (M0V). The Sun has a spectral type of G2V. We use the stellar spectral flux library by A.J. Pickles to compute the flux observed through different bandpass filters [2]. Overlaid on the stellar spectra are the filter responses for Gaia, Johnson V, and a Teledyne HiViSI filter [3]. Note that different spectral types have different amounts of flux at different wavelengths, and thus each filter will measure different fluxes for the same stellar type. Failing to account for these filter responses will lead to inaccurate stellar fluxes in simulated data.

Fortunately, the Gaia star catalog provides two narrower bandpass magnitudes, Gaia Blue (G_B) and Gaia Red (G_R), which can be used to fit color corrections. We use these G_B and G_R bandpasses to compute observed fluxes and perform a polynomial fit to convert between Gaia G band magnitudes and magnitudes in the filter band. Magnitudes are normalized such that each color is set to zero for A0V, and the bandpass zero point is set based on the A0V spectrum. The right panel in Fig. 3 shows these polynomial fits for several pairs of filters. ZR1_Cam is a generic name we have assigned to a 2k×2k focal plane in the Aerospace focal plane lab. The polynomial fits can be performed once for each filter and saved. The scene simulator reads the fit and applies it to every star in the field of view to accurately compute the photometry of each star.

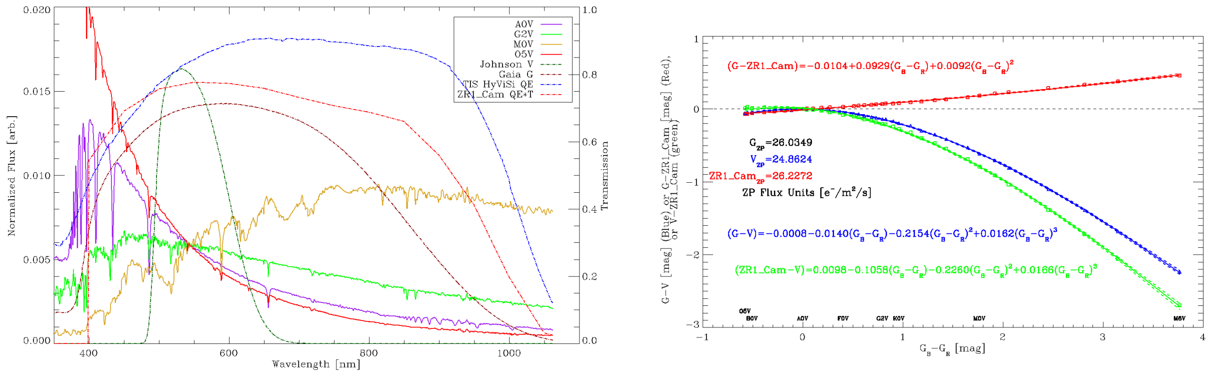

Fig. 3. Left panel – Star spectra and several filter bandpasses. Right panel – Color-color correction required to convert from Gaia G band to the band of interest.

3.5 SKY BACKGROUND SOURCES

In addition to stars and targets, a scene will contain background radiance and temporal effects from various sources. These background components add flux to the scene and make it more difficult to detect targets. The scene simulator inherits the background modeling performed by TRADIX. In TRADIX, six background components are modeled: zodiacal dust, galactic diffuse gas, galactic diffuse integrated starlight, stray light from the Sun, stray light from the Earth, and stray light from the Moon. The scene simulator uses TRADIX to compute the background at the four corners of the focal plane. If the four values differ by less than 50%, then the average value is used as a uniform background throughout the scene; otherwise, the background is computed on a grid pattern across the focal plane, and bilinear interpolation is used to compute the background. This latter method allows the scene simulator to capture background gradients, which can be dramatic when looking close to the Sun, Moon, or Earth. The background is added to the image pixel-by-pixel.

TRADIX uses published brightness data of the zodiacal dust and galactic diffuse integrated starlight & gas for backgrounds [4]. The zodiacal dust arises from particles in the solar system and is brightest in the ecliptic plane. Note that Gegenschein is also present in the model. The galactic model has two components; one is for the diffuse gas, the second is for unresolved integrated starlight. Both components are brightest in the galactic plane.

TRADIX models stray light using a point source transmission (PST) curve, which relates the stray light caused at the focal plane due to the flux at the entrance aperture of a point source target as a function of angle off boresight. Optical analysts can generate a curve from a model or measured lab data. We model the Sun and Moon as effective point sources for stray light modeling but use a more sophisticated model to compute stray light from the Earth.

3.6 SENSOR PARAMETERS AND CONOPS

The scene simulator can model any visible to near-infrared telescope system by using key figures of merit for the sensor design and/or by using lab-measured data. This flexibility allows us to model systems in early stages of development as well as when the design or hardware are well characterized. We can parametrically alter the CONOPS of the sensors to determine the optimal CONOPS against different classes of targets.

3.6.1 SENSOR HARDWARE

Key figures of merit for sensors include: entrance pupil diameter, focal length, pixel pitch and fill factor, focal plane array size, pixel instantaneous field of view (IFOV), optical transmission, quantum efficiency, bandpass, analog-to-digital Converter (ADC) bit depth, and full well capacity (FWC). The user can specify detector noise and dark current parameters by either single numbers or as images from measured data that capture noisy/hot pixels in 2-D noise and dark spatial distributions. Noise and lab measured data will be discussed further in section 3.8.

3.6.2 SCENARIO DEVELOPMENT AND CONOPS

The CONOPS of an electro-optical sensor includes parameters such as integration time(s), number of frames taken per dwell, and the selected tracking method (i.e., target rate mode, sidereal stare, or some other rate when drift scanning). These parameters are key in the evaluation of the system as it determines how the target appears against background stars (streaking vs. non streaking, as shown in Fig. 4) and how to properly analyze the data. We build scenarios to test specific missions for sensors such as using a large resident space object catalog to determine sensor capacity metrics (whether cued or serendipitous) and sensor- and constellation-level hardware and detection and tracking algorithm performance.

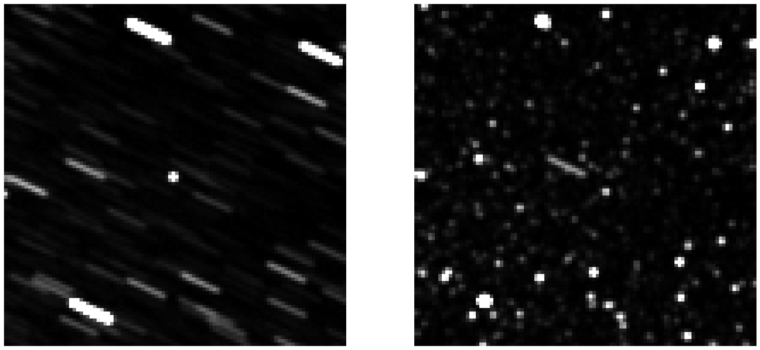

Fig. 4 – Left: Sensor is tracking the target therefore the target is held in one position on the focal plane while the stars are streaked. Right: The sensor is operating in sidereal stare mode, so the stars are held fixed and the target streaks on the focal plane.

3.7 COSMIC RAYS

Cosmic rays can optionally be added to a scene as an additional temporal noise source and tracking algorithm confuser that a processing algorithm needs to reject correctly. The scene simulator cosmic rays are derived from lab measurements and scaled to known on-orbit cosmic ray rates from operational sensors, rather than attempting to build a cosmic ray model. We used a focal plane in Aerospace's labs (see Section 3.8.1) to collect approximately 24 hours of data with the shutter closed. After processing the data, the cosmic rays in each frame (if any) were assigned an ID number of that frame. Fig. 5 is a combined map of all the cosmic rays collected.

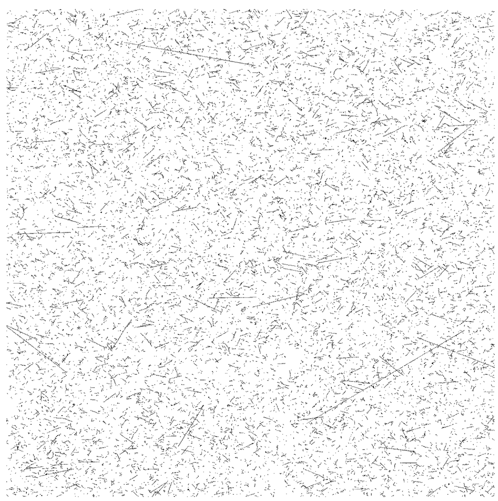

Fig. 5 – Combined image of all cosmic rays detected in our lab measurements. We use this data to add real cosmic rays to simulated scenes.

To use this data in the scene simulator, the user scales the desired cosmic ray rates relative to the lab measurements. This rate is adjusted based on the integration time of the simulated scene and lab data to compute the total number of cosmic ray frames to add to a scene. The scene simulator will then randomly select cosmic ray samples to inject into the simulated scene, but since not all lab-collected frames contained cosmic rays, the total number of cosmic rays added may be lower than the rate chosen by the user. This feature simulates the random arrival time of cosmic rays.

When we simulate a smaller focal plane than the tested 2k×2k focal plane, a sub-portion of the focal plane is cutout from the center. If the simulated focal plane is larger than 2k×2k, then the cosmic ray image is tiled across the focal plane. Note that when tiling, the same cosmic ray will appear at multiple locations in the image.

3.8 NOISE & INSTRUMENT ARTIFACTS

After the generation of a simulated image with stars, targets, background flux, and cosmic rays, the final steps in scene simulation involve the addition of various noise sources and adding image artifacts to arrive at a simulated raw image in Digital Number (DN). These noise and artifacts are added stepwise in the order listed below.

- **Multiply by Flat Field** – A flat field may optionally be defined for the scene (if not defined it is unity everywhere). The flat field is the non-uniform response across the focal plane to a uniform brightness source, due to both optical effects such as vignetting as well as pixel-to-pixel non-uniformity, if measured or estimated.
- **Add Dark Current** – Dark current is the number of electrons per second per pixel even in the absence of light due to thermal effects within the detector. Dark current can be added to each pixel as a single rate, or if it has been measured in the lab, a (scaled) dark current image is applied to each pixel.
- **Model Photon Noise** – Photon noise arises from the random natural of the arrival time of photons. It is modeled on a Poisson distribution, which is computed for each pixel using that pixel value as the input to the Poisson distribution. A distribution is created for each pixel and a value is chosen for the modeled image.
- **Add Read Noise** – Read noise arises when transferring charge from the pixels. It is defined as a standard deviation in a Gaussian distribution centered at zero. A single read noise can be used, in which case it uses the same standard deviation for each pixel. Alternatively, read noise can be computed from laboratory measurements and supplied as an image, in which case each pixel will have a different read noise standard deviation.
- **Convert to DN** – The image in electrons is divided by the gain, electrons per Digital Number or DN.
- **Add Bias** – A measured image might have a bias applied to it so that low DN pixels will not be close to zero. Bias is either zero or supplied as an input image to be added to each pixel.
- **Digitize by ADC** – The maximum signal in a pixel is capped at $2^N - 1$, where N is the Analog to Digital Converter (ADC) bit depth. The scene simulator can support up to bit depth of 63. Also, to capture any bad pixels from previous inputs, any value less than zero is set to zero.

3.8.1 LAB MEASUREMENTS

Aerospace has multiple Focal Plane Array (FPA) characterization labs that measure various characteristics of focal planes including read noise, dark current, and uniformity to provide as-measured data for various applications. The scene simulator can ingest these measured noise data of focal planes to provide high-fidelity noise characteristics in the simulated data. These high-fidelity noise features in the simulated scenes allows the end-user to verify proper image processing and reduction of the noise sources and ensure the source extraction algorithms are effective on noisy data. Fig. 6 shows examples of the data that can be added to a scene.

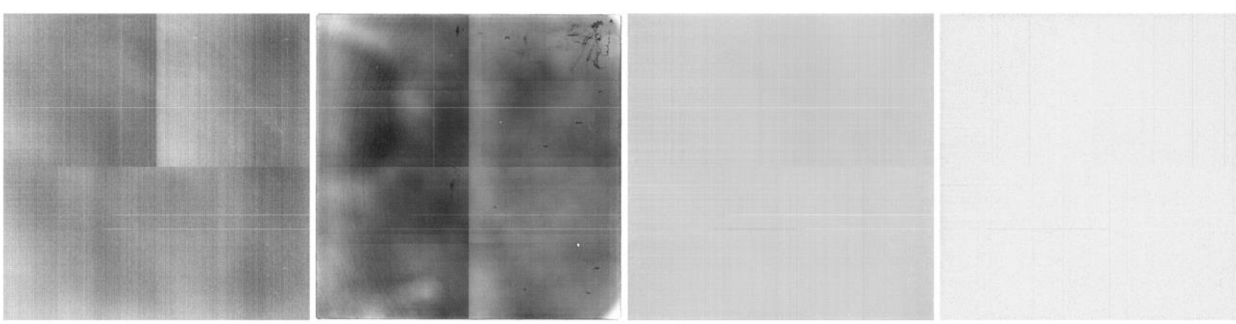

Fig. 6 – Examples of images that can be read into and used in the scene simulator to simulate the most realistic imagery possible. From left to right: bias image, flat field image, dark current image, and read noise image.

4. EXAMPLE SIMULATED IMAGE

Fig. 7 shows an example simulated image from the scene simulator after processing (subtract off bias + dark image, divide by flat field). This image shows examples of targets (green circles), cosmic rays (cyan ellipsoids), bad pixels and rows, and stray light from the Earth (background gradient on the right side of the image). This image combines all the features discussed in the previous sections to provide a high-fidelity SDA scene for target extraction algorithms. Given the CONOPS of a sensor and its mission objectives, we can provide any number of scenes to stress the system with different lighting conditions and scenarios to ensure the sensor hardware and image processing software meet requirements. The time required to create a single scene is highly dependent on factors such as field of view size, length of streaks due to integration time, and stellar density. However, an image like the one in Fig. 7 was created in a few minutes and multiple images can be created in parallel. The scene simulator does not yet run in "real time" for hardware in the loop applications.

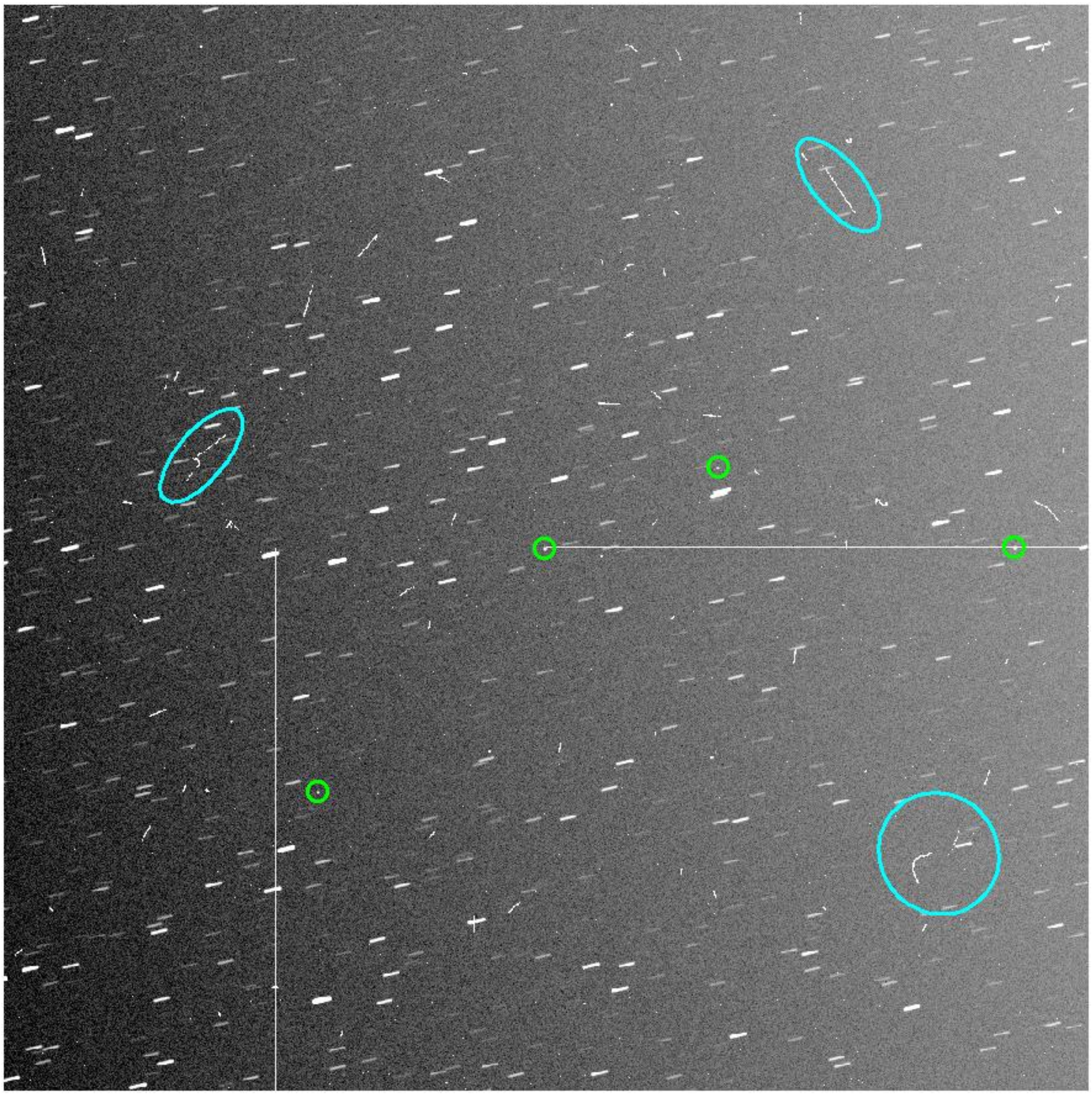

Fig. 7 – Example image from the scene simulator. There are four satellites in the field (green circles). In addition, several examples of cosmic rays have been circled (cyan). The sensor rate tracks the target at the center of the FOV and as a result, the stars streak across the image. The look angle is ~30 degrees away from the Earth, which results in a background gradient across the image due to stray light from the Earth. Finally, some notional "bad pixels" have been added to the scene as both randomly distributed hot pixels and two thin lines in a row or column.

5. CONCLUSION

Aerospace has successfully developed a high-fidelity SDA scene simulator that can used for a variety of applications and studies. The scene simulator includes sensor lab-measured performance, target radiometry, stellar color corrections, elevated backgrounds due to non-rejected stray light and the natural sky background, all other relevant phenomenological effects, and sensor CONOPS to assess sensor hardware performance and mission data processing pipelines. These simulated images help ensure that algorithms extract targets correctly and that electro-optical sensors and mission data processing meet mission requirements. The flexibility of the tool allows the user to create specific scenarios to stress systems and determine the correct CONOPS for the mission needs. The TRADIX scene simulator provides the SDA community a capability for testing ground or onboard mission processing algorithms and pipelines to a high fidelity and helps reduce risk on systems at any point in the lifecycles of sensor hardware and mission data processing software, from concept development to operations.

6. REFERENCES

[1] "eSA Gaia Science Community - Gaia - Cosmos," [Online]. Available: https://www.cosmos.esa.int/web/gaia.

[2] A. Pickles, "A Stellar Spectral Flux Library: 1150-25000 Angstroms," *The Publications of the Astronomical Society of the Pacific,* vol. 110, no. 749, pp. 863-878, 1998.

[3] Y. Bai, W. Tennant, S. Anglin, A. Wong, M. Farris, M. Xu, E. Holland, D. Cooper, J. Hosack, K. Ho, T. Sprafke, R. Kopp, B. Starr, R. Blank and J. Beletic, "4K×4K Format, 10 μm Pixel Pitch H4RG-10 Hybrid CMOS Silicon Visible Focal Plane Array for Space Astronomy," *Proc. of SPIE,* vol. 8453, 2012.

[4] C. Leinert, S. Bowyer, L. Haikala, M. Hanner, M. Hauser, A.-C. Levasseur-Regourd, I. Mann, K. Mattila, W. Reach, W. Schlosser, H. Staude, G. Toller, J. Weiland, J. Weinberg and A. Witt, "The 1997 reference of diffuse night sky brightness," *Astronomy & Astrophysics Supplement Series,* vol. 129, pp. 1-99, 1998.

7. ACKNOWLEDGEMENTS

The authors would like to thank the many Aerospace employees that have developed and validated TRADIX SDA modeling over the past six decades. These people include Jason Fields, Matthew Britton, Dave Lawrie, John Hamilton, and Breann Sitarski, among others. The TRADIX scene simulator is built on top of their great work and would not have been possible without their knowledge and guidance.