AN INNOVATIVE, HIGH FIDELITY APPROACH TO SPACE SITUATIONAL AWARENESS (SSA) DATA SIMULATION

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ABSTRACT

Space Situational Awareness (SSA) is vital to maintaining our Space Superiority. A high fidelity, time-based simulation tool, PROXOR™ (Proximity Operations and Rendering), supports SSA by generating realistic mission scenarios including sensor frame data with corresponding truth. This is a unique and critical tool for supporting mission architecture studies, new capability (algorithm) development, current/future capability performance analysis, and mission performance prediction. PROXOR™ provides a flexible architecture for sensor and resident space object (RSO) orbital motion and attitude control that simulates SSA, rendezvous, and proximity operations scenarios. The major elements of interest are based on the ability to accurately simulate all aspects of the RSO model, viewing geometry, imaging optics, sensor detector, and environmental conditions. These capabilities enhance the realism of mission scenario models and generated mission image data.

As an input, PROXOR™ uses a library of 3-D satellite models containing 10+ satellites, including low-earth orbit (e.g., DMSP) and geostationary (e.g., Intelsat) spacecraft, where the spacecraft surface properties are those of actual materials and include Phong and Maxwell-Beard bidirectional reflectance distribution function (BRDF) coefficients for accurate radiometric modeling. We calculate the inertial attitude, the changing solar and Earth illumination angles of the satellite, and the viewing angles from the sensor as we propagate the RSO in its orbit. The synthetic satellite image is rendered at high resolution and aggregated to the focal plane resolution resulting in accurate radiometry even when the RSO is a point source.

The sensor model includes optical effects from the imaging system [point spread function (PSF) includes aberrations, obscurations, support structures, defocus], detector effects (CCD blooming, left/right bias, fixed pattern noise, image persistence, shot noise, read noise, and quantization noise), and environmental effects (radiation hits with selectable angular distributions and 4-layer atmospheric turbulence model for ground based sensors). We have developed an accurate flash Light Detection and Ranging (LIDAR) model that supports reconstruction of 3-dimensional information on the RSO. PROXOR™ contains many important imaging effects such as intra-frame smear, realized by oversampling the image in time and capturing target motion and jitter during the integration time. In addition to standalone use, PROXOR™ is also integrated into an end-to-end closed loop tracking simulation, that provides realistic behavior of the full image/track processing system. In this paper we present an overview of PROXOR™ plus simulation results of SSA missions.

INTRODUCTION

The US is increasingly dependent on its space assets for commercial, civil, DoD, and intelligence community use. For example, warfighters are extremely reliant on GPS for support of surgical strikes. Adversaries see our ever-growing dependence on space assets as a critical vulnerability to be exploited and as they look to counter US superiority in space, it will become the next battlefield. The US government has a need to catalog all objects in space, characterize them, detect uncorrelated targets and identify threats/risks to our space assets. To meet those needs, the Air Force and Intelligence Community continue to develop space-based and ground-based systems for determining and exploiting metric (location) information and resolved and non-resolved signatures of RSOs and

targets, with the long term objective of identifying objects and deriving quantitative and functional information about them[1].

Threats from foreign nations are becoming more prevalent plus the sheer number of objects in space (upwards of 22,000 objects are being tracked with >= 10 cm size and about 500,000 objects are present in space from 1-10cm size)[*] makes it increasingly difficult to maintain custody of these objects and difficult to ensure we can find new (adversarial) objects, detect changes in objects, and identify nefarious behavior in a timely manner. The growth in trackable objects is shown in Exhibit 1. The threats to our space assets in GEO are of particular concern, and additional space-based SSA platforms need to be fielded to counter this threat. A notional space-based observer searching the GEO belt is shown in Exhibit 2. There is a need to develop algorithms and perform optical system design trades in support of SSA to solve uncorrelated track (UCT) challenges: resolving conjunctions, detecting new targets, and detecting changes in target characteristics[2]. This paper covers the Ball PROXOR™ simulation tool developed to support solutions to fill these critical gaps and key shortfalls in space surveillance capabilities.

PROXOR™ simulates the observer(s) platform and sensor pointing, trajectory(ies), and sensors [electro-optical (EO) and LIDAR sensor(s)]. We include high fidelity detector models, artifacts, RSO trajectories, star fields (including viewing artifacts such as the galactic core), and environmental effects (scattered light, radiation hits, and atmospheric turbulence for ground based sensors). The sensors can be space-based or ground-based. PROXOR™ is radiometrically accurate, and generates realistic high fidelity images over time that are used to i) assess and compare the performance of potential mission architectures (e.g., GEO constellations vs. GEO/LEO constellations for SSA), ii) provide image frames over time to support SSA algorithm development and verify algorithm performance (e.g., Pd vs. SNR/visual magnitude performance, metric accuracy, etc.), and iii) support mission planning by accurately predicting mission performance. Because PROXOR™ provides realistic data for development or assessment[†], it can be used to develop improved mission architecture (constellation) designs, develop and assess payload systems, and develop/verify algorithms that work well in the real world "right out of the chute". This in turn improves the probability of successful mission execution, whether the mission is to find threats as part of Indications & Warning (I&W), avoid collisions, perform RSO characterization, or execute other Space Protection missions.
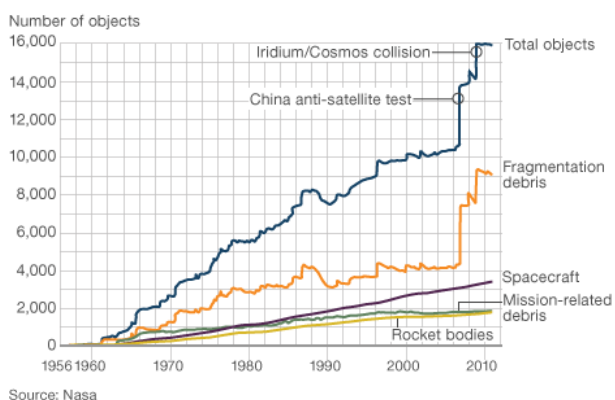

Exhibit 1. The growth of orbital objects has increased significantly over the last 50 years with large spikes due to debris caused by intentional (Chinese ASAT test) and unintentional collisions (Iridium/Cosmos).

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[*] See, e.g., http://www.bbc.co.uk/news/science-environment-14763668
[†] Based on a) targets correctly modeled via BRDFs, b) many detector noise characteristics and artifacts modeled, c) optical system including aberrations and obscurations are modeled, d) environmental characteristics modeled, and e) actual star fields modeled.
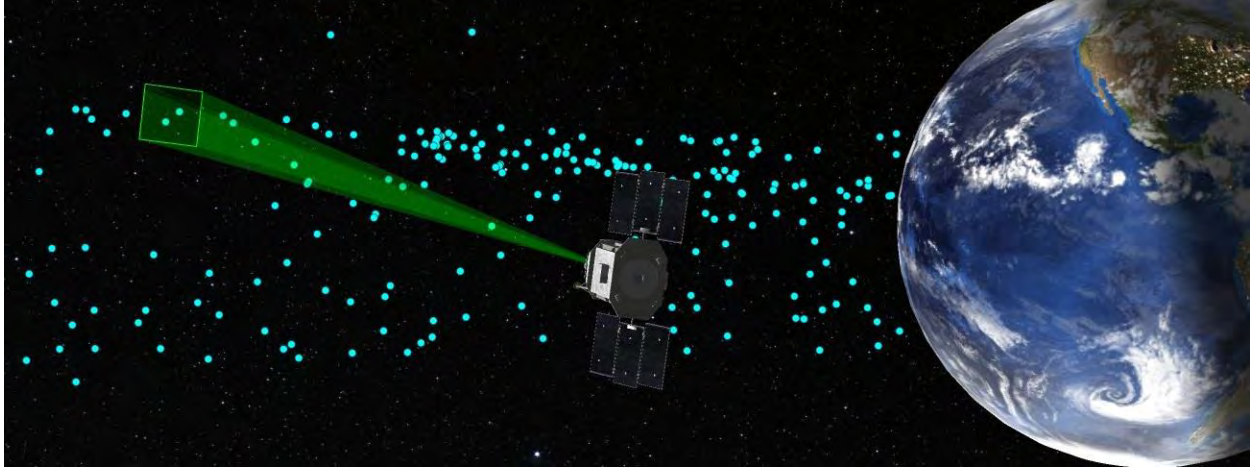
Exhibit 2. Example mission scenario showing geometry of observer in Search mode viewing RSOs and stars in its Field of Regard (FOR).‡

PROXOR™ OVERVIEW

Ball's PROXOR™ tool, shown in Exhibit 3, provides a **high-fidelity** and **innovative** simulation architecture for modeling the orbital motion, attitude control, radiometry and focal plane images of a sensor or multiple sensors and multiple RSOs in realistic SSA, rendezvous, and proximity operation scenarios. PROXOR™ **enables** the simulation of real SSA mission scenarios, including resolved and unresolved space objects, using actual-validated satellite data (i.e., real DMSP and Intelsat spacecraft surface properties). PROXOR™ has a Graphical User Interface that facilitates setting up mission scenario and sensor modeling parameters, as well as selecting satellite(s) of interest from an expandable library of satellite models. PROXOR™ is also integrated into an end-to-end (ETE) image processing/tracking (open and closed loop) simulation, where the entire image/track processing algorithm chain, sensor models and gimbal models are included. In this case, PROXOR™ acts as the image generator, using a command-line mode.
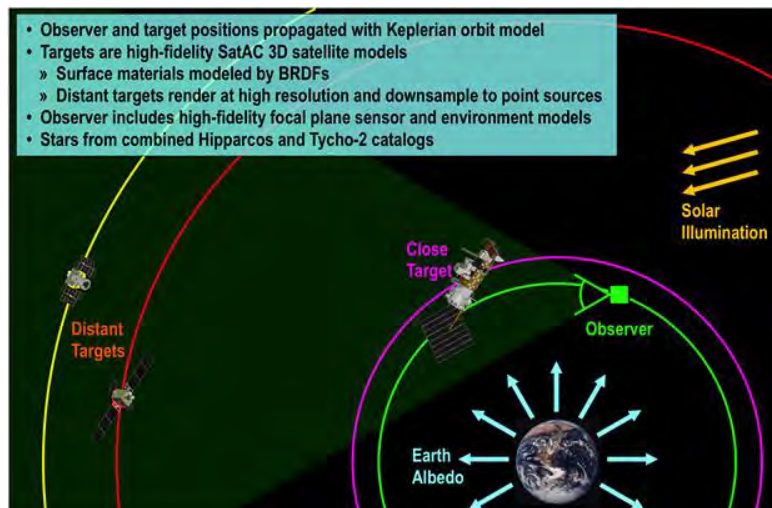

Exhibit 3. PROXOR™ Modeling & Simulation tool is used to model mission scenarios, support SSA algorithm development and verification, support analyses using generated data and SSA algorithms that inform optical system design trades [focal plane Field of View (FOV) / Instantaneous FOV, aperture size, PSF, noise, etc.]

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‡ Note that high fidelity PROXOR™ images are shown below in Exhibits 5–9.

The ability of PROXOR™ to generate a complete range of exquisite imagery and non-resolved light curves is invaluable in evaluating and predicting mission performance and developing successful algorithms for SSA mission analysis, RSO detection and tracking, and RSO characterization for all objects including high interest objects. For space-based scenarios, PROXOR™ independently propagates the positions of the observer and one or more target satellites using Keplerian orbit parameters and accounts for secular perturbations. For ground-based sensors, we follow the same process, fixing the observer position on the ground and rotating with the Earth. The viewing and illumination angles for each target are calculated as a function of time, and 2-D images of each target are rendered for each frame. Ball leverages the high fidelity government-approved satellite models from the AFRL Satellite Assessment Center (SatAC) that include surface material specifications. A material database contains both Phong and Maxwell-Beard BRDF coefficients for modeling the surfaces.

To create images from these high fidelity satellite models, PROXOR™ calls one of two renderers: the Solid Modeling Tool (SMT) rendering engine (a software based ray tracer from SatAC), or Ball's Real-Time Scene Simulator (RTSS) - an OpenSceneGraph based renderer that leverages a GPU for faster rendering. In both cases, a 2-D view of the 3-D CAD model[§] of the target satellite is rendered using ray-tracing based on the BRDF of the satellite materials. We also optionally include a Ball-developed foil-model to more accurately represent surfaces covered in multi-layer insulation (MLI). PROXOR™ includes both solar illumination and earthshine. PROXOR™ focuses on visible wavelength imagery, but can also render at short, medium, and long infrared wavelengths. The sensor model (discussed in the following section) is used to determine the sampling of the targets based on pixel IFOV (which is oversampled) and the range to the target. PROXOR™ automatically includes additional oversampling if a minimum number of points are not placed across the target. After high-resolution rendering, the target image is aggregated back to the sensor model sampling. This "exquisite" imaging approach guarantees radiometric accuracy even for point source targets. For GEO applications PROXOR™ can simulate articulation of satellite solar panels. Since solar panels move with the sun, or are offset from the sun (typical of newer spacecraft that have more efficient solar panels), including this articulation capability improves the image generation fidelity and light curve generation radiometric accuracy. These PROXOR™-generated light curves provide much higher realism than "typical" light curves generated by using Lambertian spheres. However, PROXOR™ also includes an analytic Lambertian sphere renderer to enable modeling target satellites where radiometric accuracy requirements are relaxed or for comparison with typical Lambertian-sphere-based analyses. Exhibit 4 shows a PROXOR™ functional block diagram.

[§] CAD model formats include standard .osgb or custom SMT .nsm. PROXOR™ includes a converter from .nsm to .osgb.
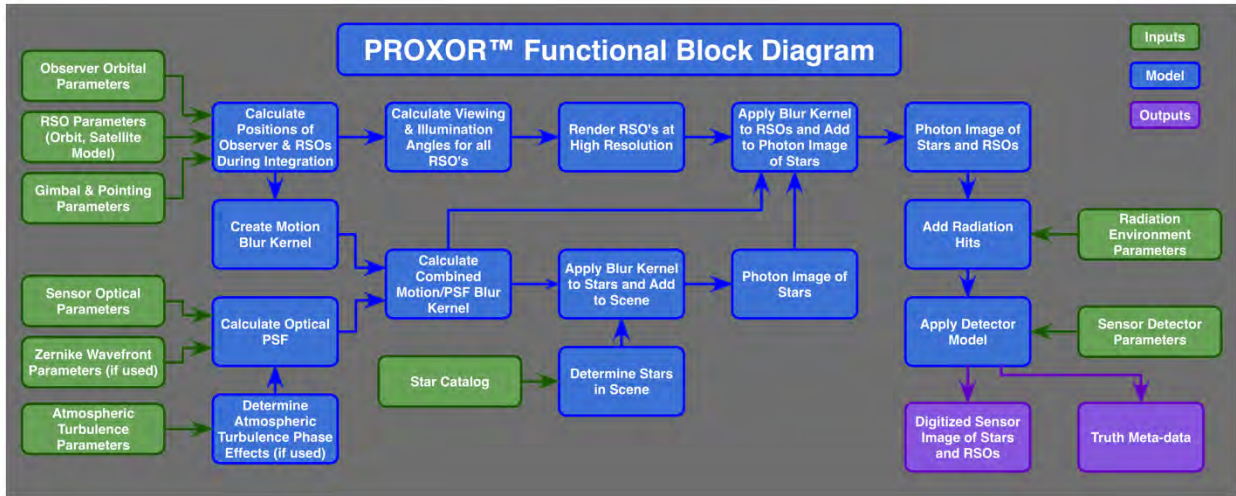
Exhibit 4. PROXOR™ Block Diagram showing the production of a single image frame of digitized sensor data.

SENSOR POINTING MODEL, MOTION, AND OPTICAL SYSTEM EFFECTS

PROXOR™ assumes the sensor is mounted on a 2-axis gimbal in determining the orientation of the sensor. The user controls gimbal pointing and can choose between 2 preset orientations (nadir or Sun) or can specify the gimbal orientation with external data. With the gimbal orientation specified, the user can select the boresight pointing mode, choosing from rate mode (locked onto a specified target), sidereal mode (locked onto a particular vector on the celestial sphere), or user specified gimbal angles. This pointing model implementation accurately controls sensor orientation when observing a target including image rotation around the line of sight due to the gimbal motion when tracking a target or the stars. Examples of PROXOR™ images in rate mode and sidereal mode are shown in Exhibit 5.
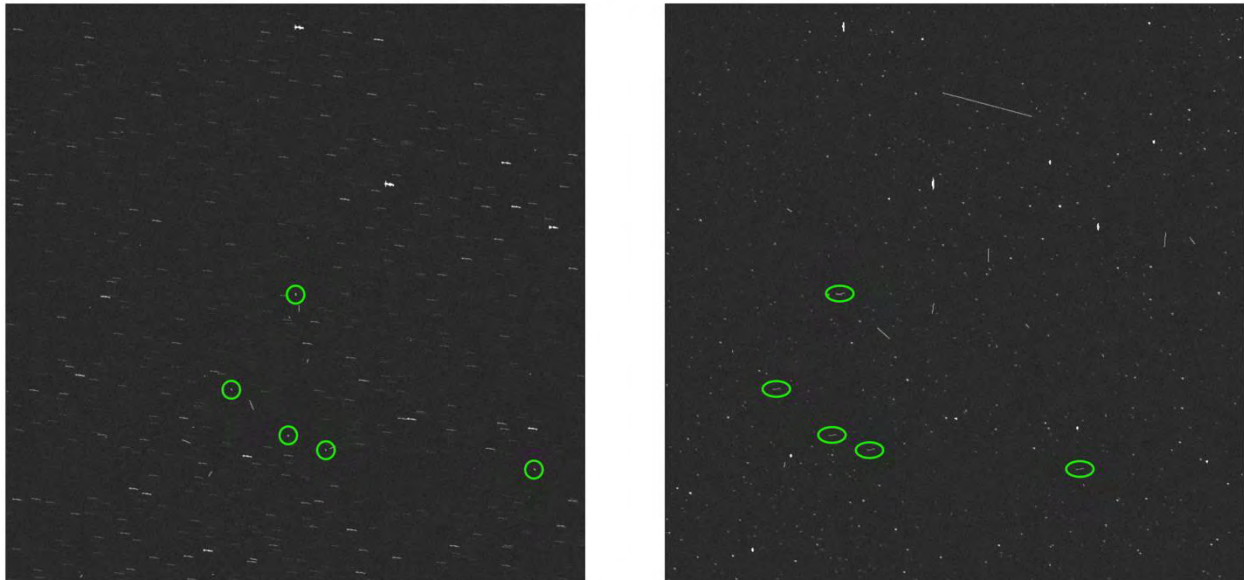

Exhibit 5. Sample images from PROXOR™ showing rate mode tracking (left) and sidereal mode tracking (right). In rate mode, the boresight moves to match the motion of the RSO's (circled in green) and the background stars smear during the integration time. For sidereal mode, the boresight is pointed at a fixed location on the celestial sphere so the stars appear fixed and the RSO's smear during the integration time.

Once images of all target satellites have been rendered, PROXOR™ establishes an initially blank scene with the same number of rows and columns as the sensor detector. Each target is inserted into this scene according to its LOS relative to the sensor boresight. Prior to adding targets, PROXOR™ calculates stars in the field of view of the sensor computed from the sensor boresight pointing and the Hipparcos-Tychos2 star catalog and places these into the blank scene. The motion of the stars due to orbital motion of the observer, intentional LOS motion (e.g. rate mode), and any boresight jitter/drift, is accounted for by pointing oversampling during the integration time. Both high frequency (during integration time) and low frequency (frame to frame) jitter and drift can be simulated as Gaussian, sinusoidal, or as described in an external file. Finally, the optical system PSF is calculated. PROXOR™ then combines the effects of pointing motion, LOS jitter/drift, and diffraction to create each star image and add it into the scene. As mentioned above, the spatial resolution used for these calculations oversamples the detector pixel to ensure correct apportionment of the signal over multiple pixels. Required detector pixel oversampling depends on the PSF as this determines the ultimate scene resolution. Rendered target satellite images are added into the scene in the same fashion as the stars, applying motion and diffraction, beginning with the most distant target and proceeding to the nearest.

Optical PSF is determined using a standard Airy function including obscuration by default. A separate option allows defocus modeling using an approach from Stokseth [3]. The PSF can also be calculated using Fourier optics and a phase map defined by a set of Zernike coefficients generated from a Code V optical design. Using this approach, an amplitude mask allows the inclusion of diffraction from support vanes and central obscuration (see Exhibit 9). Fourier optics code may also be used to include the environmental effects of the atmosphere as discussed later.

The scene after inserting stars and targets, represents the photon image at the focal plane of the sensor detector. The effects of the sensor detector or the environment are not yet included in the image. After application of the sensor model, the output data frames are stored as a 3-D "data cube" organized as 2D image frames over time. PROXOR™ high fidelity sensor models include EO and LIDAR sensors, and are described in the next sections.

PROXOR™ EO SENSOR MODEL

EO sensors respond to light in the reflective part of the electro-magnetic spectrum (visible / near IR 0.4 - 0.9 um). Our EO sensor model can simulate both CCD and CMOS readout architectures. PROXOR™ simulates fixed pattern noise on a per-pixel basis with Gaussian random pixel gain (QE) and dark current. PROXOR™ calculates the summed dark current and scene photon generated electrons and draws a random sample from a Poisson distribution for that sum. That sample is combined with a Gaussian random sample of read noise to generate the signal to be digitized for each pixel. An A/D model quantizes this electron signal with user selectable full well, bit depth, and offset. This has the effect of adding quantization noise to the resulting digital number assigned to each pixel. This overall sensor model and approach is fundamental to the realism of the simulated data frames as it behaves close to actual sensor data both spatially and temporally. We can also include additional high fidelity detector effects such as CCD blooming, left/right bias, and image persistence. CCD smear arising from readout of an unshuttered sensor can be mimicked (see Exhibit 9), as well as the output from an interline CCD that would eliminate this smear.

Examples of simulated imagery at different ranges are shown in Exhibit 6. Exhibit 7 shows an example of generated imagery for SSA mission analysis and algorithm development/testing. Exhibit 8 shows an example of our exquisite-image-based light curve generation.
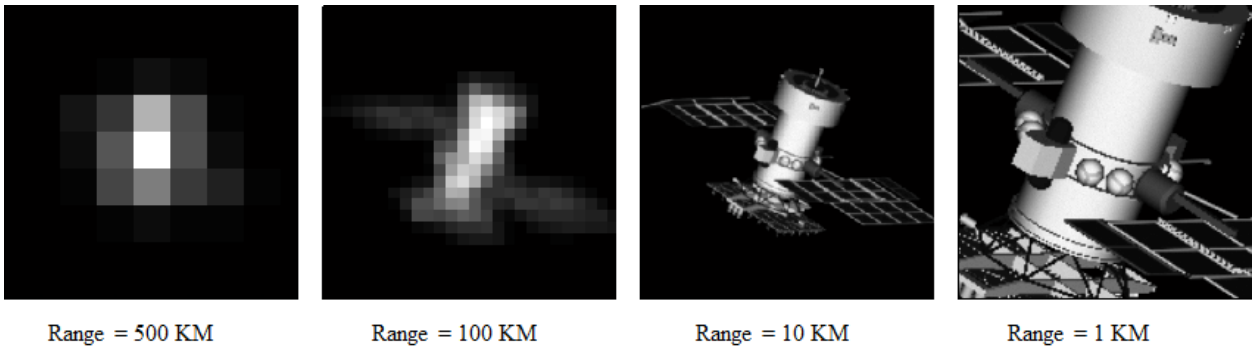
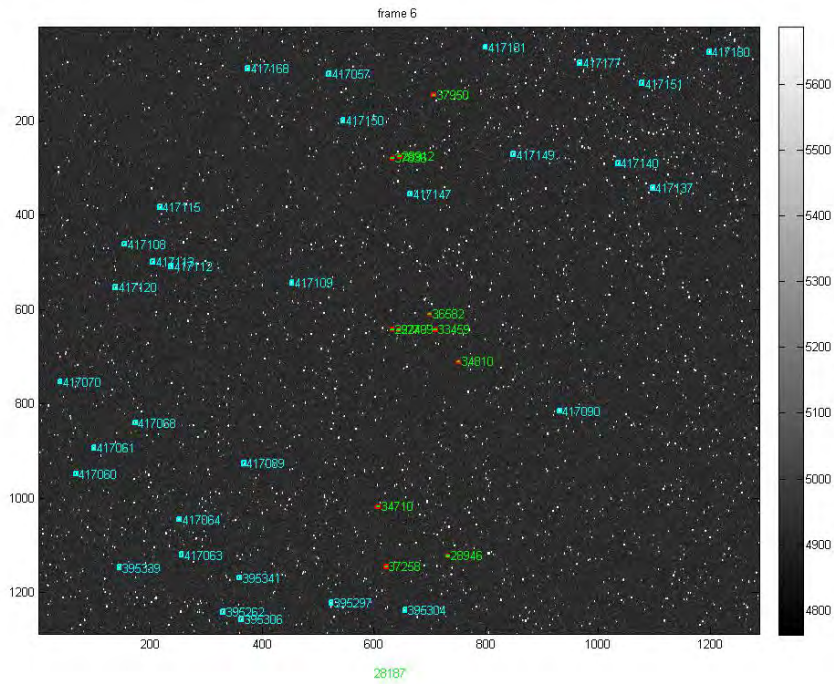Exhibit 6. PROXOR™ sensor images showing Resident Space Objects (RSOs) at various ranges.

Exhibit 7. PROXOR™ sensor image illustrating simulation of realistic star backgrounds and RSOs based on actual sensor pointing. Green labels indicate RSOs detected by our algorithms and cyan labels indicate stars used by the algorithms during processing.
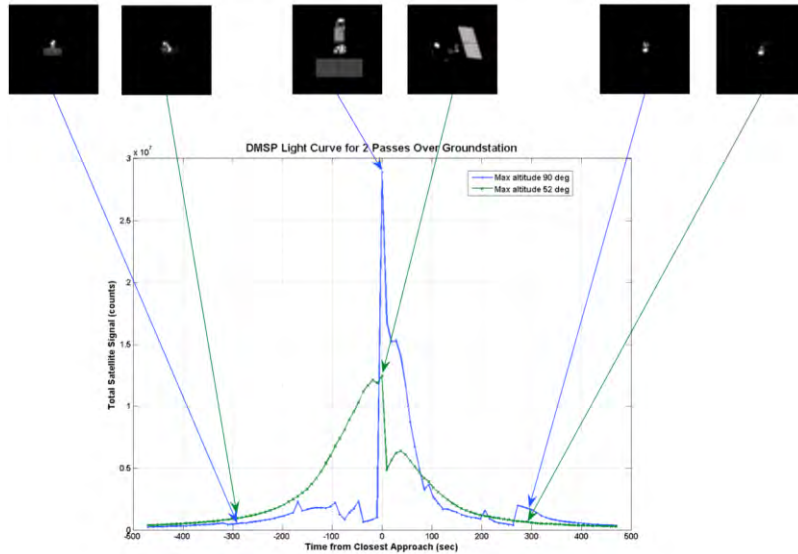
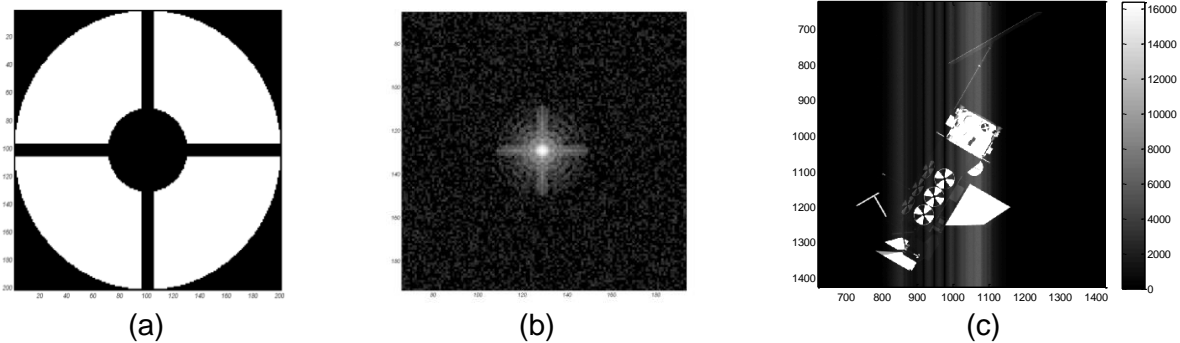Exhibit 8. PROXOR™ generated light curves for two passes of DMSP over ground station show effect of glint.

Exhibit 9. PROXOR™ modeling of a) central obscuration and vanes in pupil plane, b) effect of pupil obscurations in
image plane, and c) CCD transfer smear.

PROXOR™ LIDAR MODEL

Ball has developed an accurate flash LIDAR model that supports reconstruction of 3-dimensional information on
the RSO.

The primary components of a flash LIDAR system are a laser, transmit and receive optics, focal plane array (FPA),
and read out integrated circuit [4, 5]. Other supporting components, such as power supplies and communications
electronics that are common to all remote sensing systems will not be discussed here.

All LIDAR systems have a light source and a detector. Continuous wave (CW) systems modulate the light source,
while flash systems pulse the light source. Flash LIDAR systems typically use a narrow band source, such as a laser,
so background light can be differentiated from the transmitted light pulse reflection. Using pulsed light also allows
for higher light flux intensity on the target for the same input power as a CW system, increasing the system range.

In a flash LIDAR system, the outgoing light beam is spatially spread out so that every laser pulse covers the
desired imaging area. This laser light is reflected off of the surface being imaged, gathered by the receive optics and
focused onto the FPA. Each pixel in the FPA acts like a single beam LIDAR aimed at a slightly different angle. Each

pixel captures a time history of the reflected light pulse as it arrives. The peaks in this light pulse represent the largest cross-section area within the FOV of that pixel. Flash LIDAR used for navigation, such as the one on the Sensor Test for Orion Relnav Risk Mitigation (STORRM) mission, returns only the first two peaks (in time) in the imaged light pulse, while systems used for science return the complete waveform of the captured light pulse.

PROXOR™ uses a higher fidelity model than common noise-based models. PROXOR™ renders an oversampled radiometrically accurate LIDAR image based on target characteristics, imaging system effects, sensor characteristics, and viewing and illumination geometry.   A temporally and spatially oversampled, time-phased LIDAR return is generated from the image using high- resolution range information for the oversampled points in each LIDAR pixel. Finally LIDAR detector characteristics are applied to the high fidelity LIDAR return to generate the time sequenced Flash LIDAR detector output. Post-detector electronics or algorithms reconstruct range/intensity images from the Flash LIDAR detector output. Exhibit 10 shows an example of our Flash LIDAR modeling.
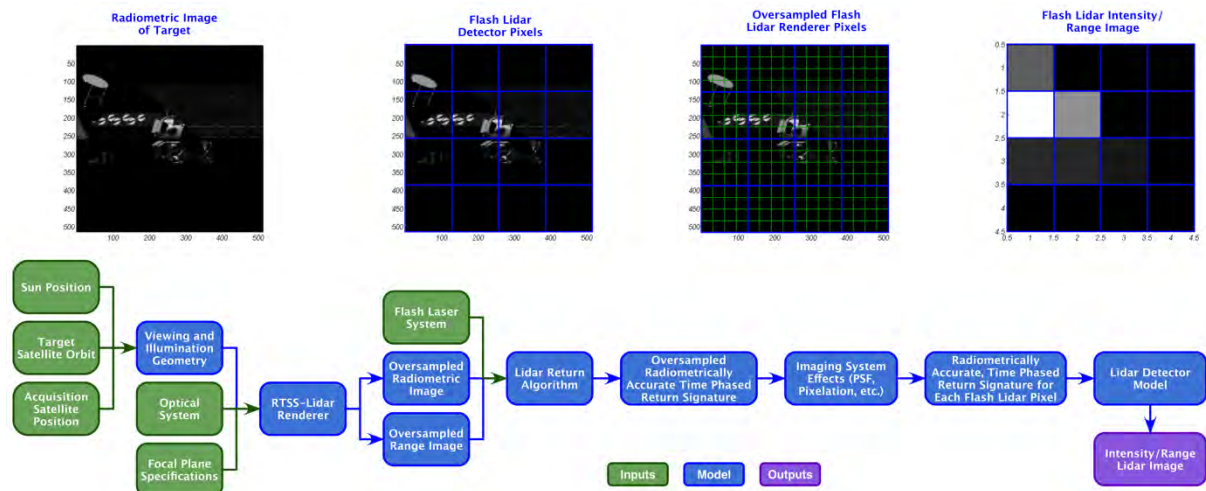

Exhibit 10. PROXOR™ modeling of LIDAR intensity and range image.

ENVIRONMENTAL EFFECTS

In addition to sensor effects, environmental effects can degrade the quality of the sensor output. We have implemented several common environmental effects: scattered light, radiation hits, and atmospheric turbulence for ground based sensors.

Sensors will still exhibit internal scattered light when pointed near strong sources of illumination such as the Sun or Moon despite careful design and baffling. Scattering from the Earth's atmosphere can also be an issue when the sensor line of sight is pointed near the Earth limb. We simulate scattered light by having an input for additional background with specified radiance when calculating the total photon signal incident on the focal plane.

Cosmic and other energetic particle hits on sensor detectors introduce additional electron signal for pixels that each particle passes through. We have implemented a radiation hit model that includes a user-selectable spherical angular distribution with user specified parameters controlling the detector thickness, electron deposition rate, and number of hits per second. Two angular distributions are currently defined (isotropic and side-shielded) and other distributions are easily defined for use.

For ground based sensors, the atmosphere is usually a limiting factor on spatial resolution. The dynamic atmosphere through which RSO's are seen distorts and constantly changes the system PSF. Ball has implemented the atmospheric model for observations of individual objects described by Roggemann et. al. [6]. This model has 4 atmospheric layers, with independent directions and speed, and uses a von Kármán power spectrum to provide spatially and temporally correlated variations in the atmosphere-induced phase delay. A series of time-step

separated phase screens are calculated. The phase at each point in the aperture at a given time step is added to the phase input to the Fourier optics portion of the Zernike PSF calculation discussed earlier and the time varying PSF is properly calculated as a function of time. We have implemented the 6 different combinations of layer weighting/ r_0 representing different observing sites given in this paper. Time evolving examples of the phase screen and PSF are shown in Exhibit 11 and Exhibit 12.
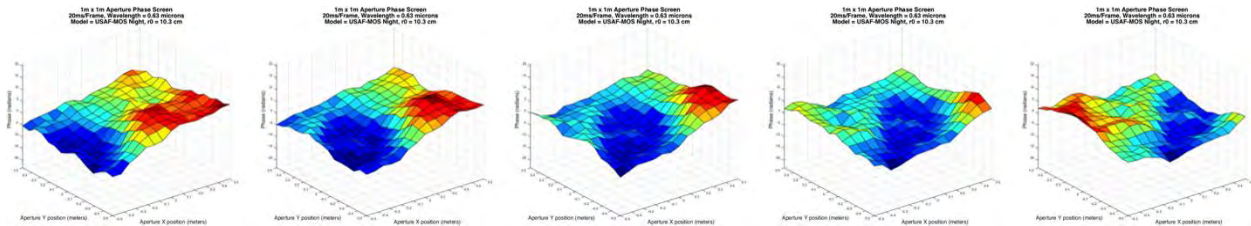

Exhibit 11. Course resolution phase screens for a 1 m x 1 m aperture at 20 ms intervals demonstrate the spatial and temporal coherence of the atmospheric turbulence model. The USAF-MAUI Optical Station Night site was chosen and all 4 layers have a velocity of 10 m/s and position angle of 0 degrees to show the flow across the aperture. (Horizontal axes show position within the 1 m x 1 m aperture and the vertical axis is phase with limits of ±20 radians.)
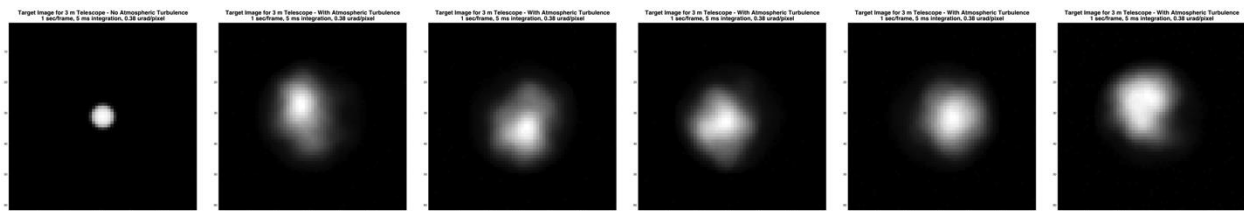

Exhibit 12. PROXOR™ modeling of atmospheric turbulence for a ground-based sensor (3 meter telescope) placed at USAF-MAUI Optical Station Night. Atmosphere modeled with 10m/s velocities. The left most image illustrates the target imaged with no atmospheric turbulence showing the resolved target (2 m Lambertian sphere at 700 km). The other images are 5 ms integrations at 1 Hz frequency and show that the atmospheric-blurred PSF dominates the resolution. Pixel resolution is 0.38 urad/pixel.

ETEDSS

In addition to performing modeling & simulation for open loop sidereal and rate track Space Situational Awareness missions, Ball simulates closed loop rate tracking on resident space objects and other objects of interest. Our End-to-End Dynamic System Simulation (ETEDSS) includes high fidelity models for image generation (via PROXOR), the gimbal/plant, and spacecraft and target dynamics as well as algorithms for image processing, tracking, and control (for command generation). The ETEDSS can be run closed loop (Exhibit 13) or open loop (Exhibit 14). PROXOR provides truth so that the performance of the mission image/track processing functions can be evaluated and optimized under realistic conditions. This is a crucial piece necessary for performing realistic mission data analysis for single observers, as well as constellations. In closed loop mode, PROXOR ingests the Line-of-Sight (LOS) pointing from the control system and generates the high fidelity image. This image contains the stars and RSOs in the field of view of the observer and is fed to the image processing algorithms. The image processing algorithms include artifact correction, background removal, detection, location, and initial discrimination. The tracking algorithms include stabilization (coordinate transformations to inertial space), tracking, and target of interest (TOI) identification. The control algorithms include compensators to ensure closed loop stability and optimized system performance. Closed loop tracking has a number of advantages to open loop. It provides increased metric accuracy by concentrating the target energy, which improves the centroid error. Concentrating the energy also increases the

likelihood of target identification. A concentrated blob-like target is easier to differentiate from streaked stars, as opposed to the streaked target that would be produced during open look tracking. Closed loop tracking can be initiated via a single cue from the ground, or via autonomous acquisition. The ETEDSS also has an Observations (Obs) generator for bypassing the image processing for rapid turn-around and parallel tracking algorithm development and testing. Ball's ETEDSS helps reduce risk for future missions by characterizing the ability to robustly track space-based targets, and to optimize systems for increased metric accuracy. Increased metric accuracy leads to improved orbit determination (OD) for TOIs and improved anomaly detection and therefore provides enhanced Indications & Warnings (I&W).
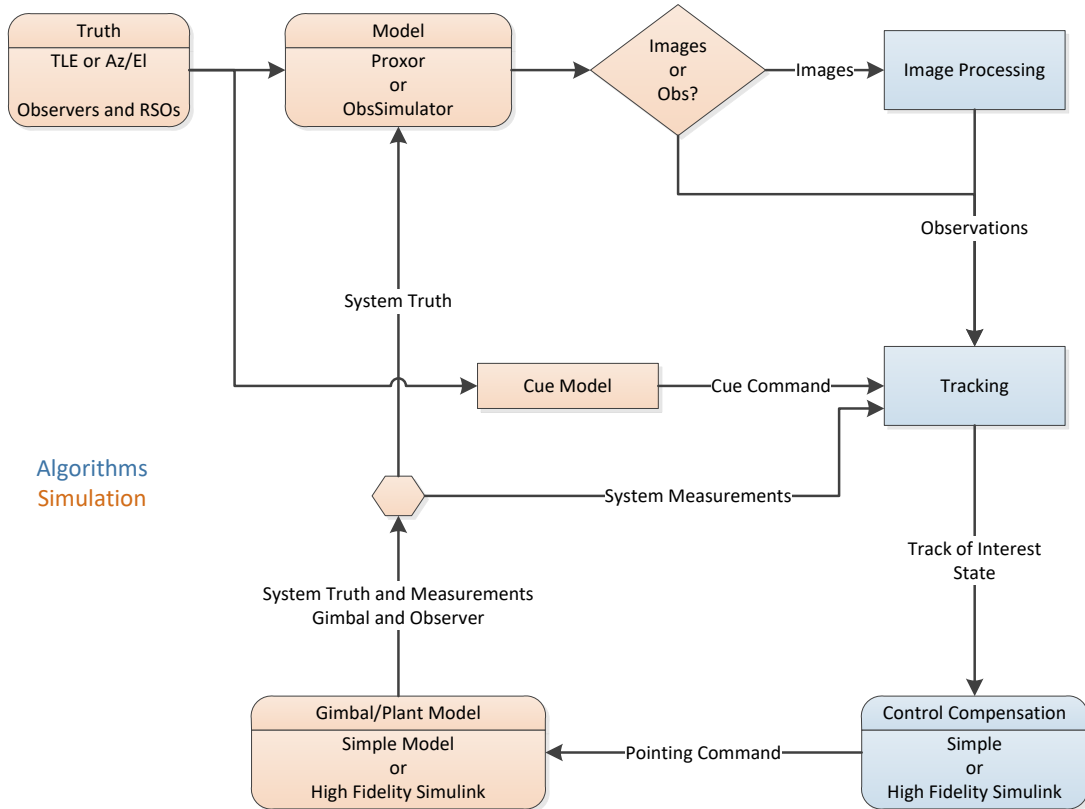
Exhibit 13. ETEDSS Closed Loop Overview
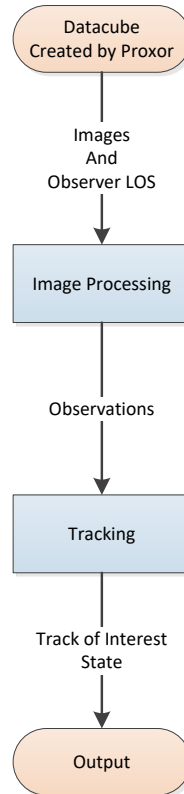
Algorithms
Simulation

Datacube
Created by Proxor

Images
And
Observer LOS

Image Processing

Observations

Tracking

Track of Interest
State

Output

Exhibit 14. ETEDSS Open Loop Overview

FUTURE PROXOR™ DEVELOPMENT AND APPLICATION

Future development of PROXOR™ includes adding articulation of additional satellite components – in particular, antennas and gimbals. Modeling articulating gimbals and antennas can help analysts compare actual satellite imagery with expected imagery to support key intelligence objectives such as finding unexpected or hidden payloads and determining intent. Other future work entails adding additional fidelity to stray light modeling, updating the star catalogs, and expanding our mission level analysis support. PROXOR™ is our tool of choice for existing and future space-based and ground-based SSA and/or rendezvous and proximity operations missions. PROXOR™ adds value with high fidelity models that enable the government to solve challenging mission problems by supporting mission level analysis and developing payload solutions (trading sensor characteristics, algorithm performance, and CONOPS) to meet their needs. Future development also includes tailoring of the available fidelity level to work towards real-time simulation of these phenomena.

CONCLUSION

Space Situational Awareness is vital to maintaining US Space Superiority. A high fidelity simulation is needed to support development of constellation architectures, algorithms for SSA, CONOPS development, and mission performance predictions. The high-fidelity simulations possible through use of PROXOR™ enable architectures, payloads and algorithms developed for key space missions (e.g., near-real-time I&W) to use realistic synthetic data/models to reduce program risk and increase mission performance. This paper presents Ball's high-fidelity, time-based simulation tool, PROXOR™, that supports this need by generating realistic mission scenarios including sensor frame data over time with corresponding metric and radiometric truth.

[1] Picciano, P, and Schurr, N, Enhanced Collaboration for Space Situational Awareness via Proxy Agents, *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference,* held in Wailea, Maui, Hawaii, September 11-14, 2012, Ed.: S. Ryan, The Maui Economic Development Board, id.85.

[2] Olivier, SS, A Simulation and Modeling Framework for Space Situational Awareness, LLNL-CONF-407013, Presented at: Advanced Maui Optical and Space Surveillance Technologies Conference, Wailea, HI, United States, Sep 16 - Sep 19, 2008.

[3] Stokseth, PA, Properties of a Defocused Optical System, *J. Opt. Soc. Amer.* Vol. 59, 1314-1321, 1969.

[4] Measures, RM, *Laser Remote Sensing: Fundamentals and Applications*," Krieger Publishing Company, 1984.

[5] Ramond, T, *et al.*, Topographic Mapping Flash Lidar for Multiple Scattering, Terrain, and Forest Mapping, *Proceedings of SPIE – The International Society for Optical Engineering*, Vol. 8037, 2011.

[6] Roggemann, MC, *et. al.*, Method for Simulating Atmospheric Turbulence Phase Effects for Multiple Time Slices and Anisoplanatic Conditions, *Applied Optics*, Vol. 34, 4037-4051, 1995.