Satellite Survivability Module (SSM), Version 2.0

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ABSTRACT

The Satellite Survivability Module (SSM) is an end-to-end, physics-based, performance prediction model for the effects of adversarial directed energy engagement of orbiting spacecraft. SSM was created as an add-on module for the Satellite Tool Kit (STK). Two engagement types are currently supported: laser engagement on the focal plane array of an imaging spacecraft and Radio Frequency (RF) engagement of spacecraft components. This paper will focus on the laser engagement scenario, the process by which it is defined, and how we use actual laser effects data to help validate the SSM tool.

SSM allows the user to create and implement a variety of "what if" scenarios. Satellites can be placed in a variety of orbits. Threats can be placed anywhere on the Earth or, for version 2.0, on other satellites. Satellites and threats can be mixed and matched to examine possibilities. Protection techniques for a particular spacecraft can be turned on or off individually, and can be arranged in any order to simulate more complicated protection schemes. Results can be displayed as 2-D or 3-D visualizations, or as textual reports. A new report feature available in version 2.0 will allow laser effects data to be displayed dynamically during scenario execution.

In order to test SSM capabilities, the Ball team used SSM to model several engagement scenarios using actual lab and field test data. Actual laser, optics, and detector characteristics were entered into SSM to determine what effects we can expect to see, and to what extent. We concluded that SSM results match reasonably close to actual lab and field test results.

1. SSM INTRODUCTION

Protecting space assets against laser threats is a growing concern in the defense community. To address this concern, the Ball team developed an easy-to-use, industry accepted, satellite survivability tool called the Satellite Survivability Module (SSM). The SSM is an end-to-end, physics-based, performance prediction model for the effects of directed energy weapon attacks on domestic satellites. End-to-end means that the SSM models a laser from the source (ground, air, or space-based), propagates it through the atmosphere (if applicable) to the spacecraft, and then models it through the imaging system to the detector. At the detector, we model four laser effects: degradation, saturation, damage, and catastrophic damage. These effects can be calculated with or without the presence of laser protection techniques. Physics-based means that SSM uses first principles physics to develop the propagation and effects models. Performance prediction means that SSM models predict the effect on the spacecraft's imaging system, and provide a basis for expected performance during engagement. SSM results are presented textually, graphically, and/or dynamically. Textually, time intervals when laser effects occur can be reported during the satellite's orbit. Graphically, these time intervals can be displayed as different color bands on the satellite's orbit-trace. Dynamically, laser effects calculations, such as at-orbit irradiance, or saturation, can be displayed while the simulation is running.

SSM leverages the capabilities of Satellite Tool Kit (STK), an industry accepted, independently validated and verified satellite simulation tool. SSM was developed as an add-on module for STK, and takes advantage of STK's extensible architecture to enhance its capabilities. By expanding on STK's extensive capabilities, it allowed us to focus our efforts on laser effects calculations, and not on modeling orbital dynamics. SSM models the laser object, and STK provides the platform where the laser resides, whether it is ground, sea, air, or space, and allows the SSM laser to inherit the properties of the platform. SSM models the imaging system, and STK provides the imaging system platform defined as a satellite-sensor pair, and allows the SSM imaging system to inherit the properties of the satellite-sensor. SSM models laser effects on the imaging system during laser engagement, and STK determines the laser engagement period, which it calls *access*. SSM reports laser effects textually, visually, or dynamically, and STK provides the 2-D or 3-D visual displays.

2. TRANSITION TO SSM VERSION 2.0

Ball OPS1 began development of the SSM in 2001, and at the time, the STK-Programmer's Library (STK-PL) was the "latest-and-greatest" development environment for building STK add-on modules. STK-PL functions and libraries gave developers the ability to create a *seamless experience* for the user, by allowing them to embed custom features directly into the STK interface. The disadvantage was that STK-PL applications were tightly coupled and highly dependent on the STK architecture. By the middle of 2002, near completion of SSM version 1.0, the program ended and development stopped for approximately two years. During this down time, STK created a new, more efficient, development environment for creating custom add-on applications, and moved away from the tightly coupled STK-PL. In late 2004, Ball OPS1 revived the SSM project and decided that it was cost effective to complete the STK-PL version of SSM, and then upgrade to the new development environment for the next version, while reusing as much of the SSM code as possible.

SSM latest upgrade, version 1.1, was completed in February 2007. We are currently working on SSM version 2.0, an STK-Connect approach that will use an HTML-page interface as the main SSM driver. The STK-Connect approach will decouple SSM from the obsolete STK-PL. It will also insulate SSM from future changes to the STK software, keeping it up-to-date with current versions of STK. For SSM version 2.0, we will need to develop event handlers for the new controls on the main panel; however, by design, we will be able to reuse a significant portion of the SSM software already developed for version 1.1.

One of the requirements that have stayed with SSM throughout its development is the requirement that individual components are *severable* – that is, SSM components such as interface screens and physics models must be self-contained components useable in other applications. All of the SSM input panels (laser, atmosphere, optics, focal plane array (FPA), off-axis rejection curve (ORC), laser protection, and laser effects) were developed as Common Object Model (COM) objects, and fulfill this requirement. In like manner, the physics models are implemented as stand-alone Dynamic Link Libraries (DLLs) that we call automation objects. These automation objects can also be re-used in other applications. This separation of input and calculation functionality gives us a leg up on transitioning SSM from its current, Programmer's-Library-dependent version, to SSM version 2.0 that will operate with current and future versions of STK, by allowing us to reuse all of our COM interface panels and automation objects.

With the latest version of the software, we added a dynamic display to view laser effects calculations during the laser engagement simulation. We added a database to store and retrieve specific laser, optics, detector, and laser protection data, as well as scenario data. We also added and/or modified input fields in response to suggestions and concerns from both internal and external space community sources.

In the remaining sections of this paper, we will present three basic laser engagement scenarios using SSM version 2.0, the physics behind the SSM, and a comparison between actual test data and SSM data.

3. GROUND-TO-SPACE LASER ENGAGEMENT

SSM provides the flexibility to create a wide variety of laser engagement scenarios. For this paper, we will present three scenarios: ground-to-space, air-to-space, and space-to-space. It is important to note that in SSM, a laser can be placed on any STK object that a sensor can attach to (i.e. aircraft, facility, ground vehicle, or ship).

A typical ground-to-space laser engagement scenario consists of a laser, laser platform, imaging system, and an imaging system platform. A laser platform defines the location of the laser, its illumination pattern, and its ability to track its target. These characteristics are defined in STK as a facility-sensor pair. All available laser platforms are displayed on the SSM main window, as shown in Fig. 1. The laser object is defined on the SSM panel, and must be attached to a laser platform. If there are no laser platforms defined in STK, you can create a new one by selecting the default laser platform, *NewFacility/NewSensor,* from the laser platform list.

Selecting "Add Laser" on the SSM panel attaches a new laser to the currently selected laser platform, and adds it to the "Available Laser Threat(s)" window on the bottom left of the SSM main window. To edit the properties of the laser, (i.e. power, wavelength, beam divergence, etc.), select the laser from the "Available Laser Threat(s)" and then click "Edit Laser Properties." The SSM input panel will appear over the SSM main window, as shown in Fig. 2. Only the laser properties and atmosphere tabs will be active when editing laser properties, and likewise, only the optics, FPA, ORC, and laser protection tabs will be active when editing imaging system properties.
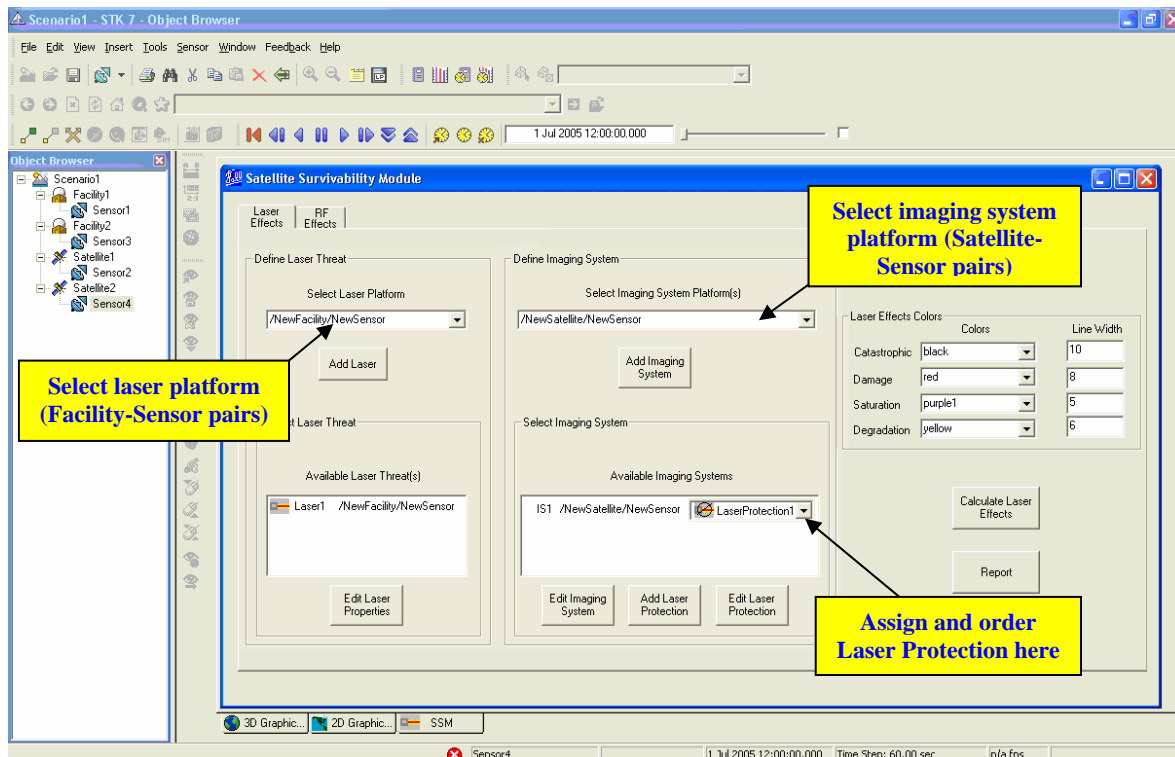
Fig. 1: SSM v2.0 Main Window

Data appearing on the laser properties panel, as shown in Fig. 2, is populated from the database. Laser type data can be saved to the database while running SSM or in standalone mode. Previously saved lasers can be selected from the "Laser Type" list, which automatically populates laser properties associated with the selected laser.
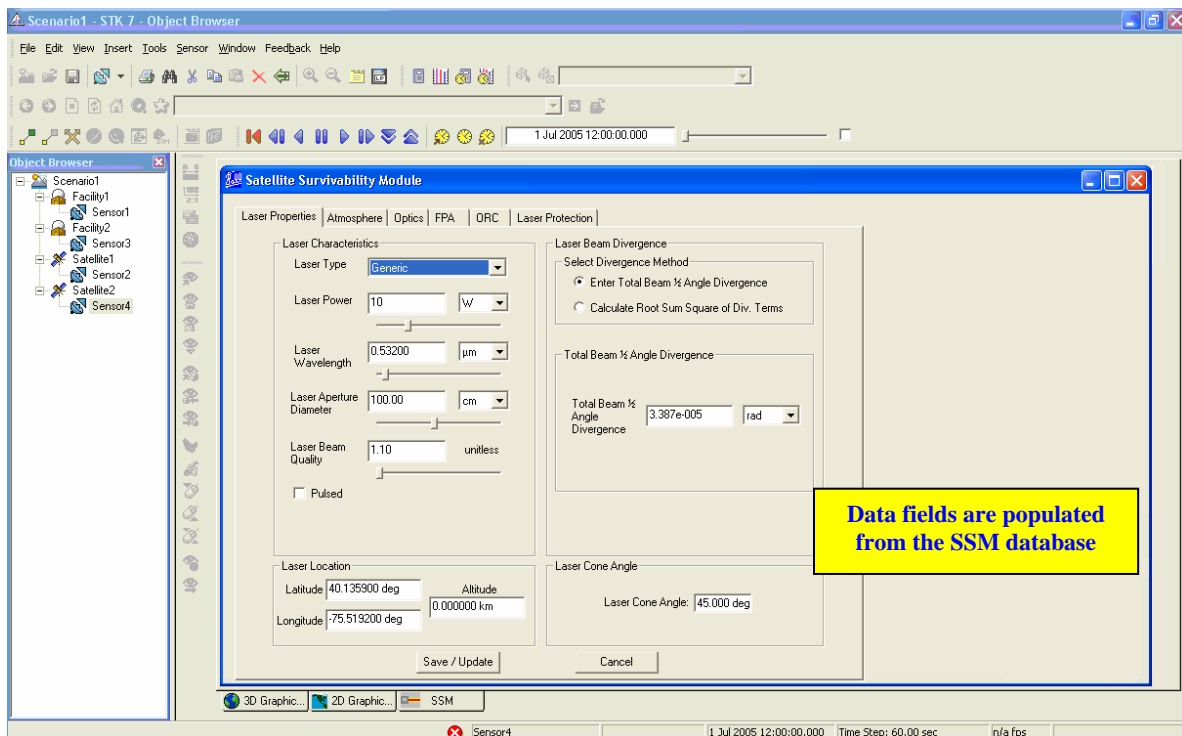

Fig. 2: SSM Laser Properties Input Panel

Defining an imaging system and platform is very similar to defining a laser. An imaging system platform consists of a satellite and its sensor, which can be defined in STK. The satellite defines the orbital dynamics, and the sensor determines the scan pattern and tracking ability. All available imaging system platforms are displayed on the SSM main window, as shown in Fig. 1. The imaging system is defined on the SSM panel, and must be attached to an imaging system platform. If there are no imaging system platforms defined in STK, you can create a new one by selecting the default imaging system platform, *NewSatellite/NewSensor* from the list. This will create a new satellite in circular orbit with all the STK defaults.

Selecting "Add Imaging System" on the SSM panel attaches a new imaging system to the currently selected imaging system platform, and adds it to the "Available Imaging System(s)" window on the bottom right of the SSM main window. To edit the properties of the imaging system, (i.e. aperture diameter, focal length, optical bandwidth, detector size, detector material, ORC, etc.), select the imaging system from the "Available Imaging System(s)" window and click "Edit Imaging System". The SSM input panel will appear over the SSM main window, as shown in Fig. 2; however, the Optics tab will be selected with the Optics input panel active. As a reminder, only the optics, FPA, ORC, and laser protection tabs are active when editing an imaging system. The editing process is very similar to the laser in that the database populates the fields with default data. In addition to defining the optics, detector, and ORC, you will have the option of adding laser protection.

SSM provides two laser protection techniques, both designed to reduce the overall irradiance reaching the sensitive detector. The notch filter ideally blocks out light energy for a wavelength band inside the "notch." For wavelengths outside the notch, transmission loss occurs. A power limiter, on the other hand, isn't wavelength dependent. It is designed to attenuate energy starting at a certain intensity threshold, identified as the "turn-on" irradiance, until it reaches a saturation threshold, which we identify as "saturation" irradiance.

Select "Add Laser Protection" to add a laser protection object to the selected imaging system's laser protection list. To edit the properties of the laser protection object, select "Edit Laser Protection" and also select filter or power limiter on the laser protection panel, and then fill in the appropriate field data.

4.   GROUND-TO-SPACE LASER EFFECTS OUTPUT

Once the laser, laser platform, imaging system, and imaging system platform have been defined, we can calculate laser effects on the imaging system. This is accomplished by selecting an available laser threat, and an available imaging system, and then selecting "Calculate Laser Effects" on the SSM main window. Laser effects results can be displayed visually, textually, or dynamically. Visually, SSM colors segments of the satellite's orbit trace to reflect a time period when laser effects has occurred. For example, Fig. 3 shows a 3-D simulation of a satellite experiencing three levels of laser effect, as it passes over a laser facility. As the satellite approaches the facility, it first encounters saturation (purple), then experiences damage (red), and finally catastrophic damage (black) when it is almost directly overhead.
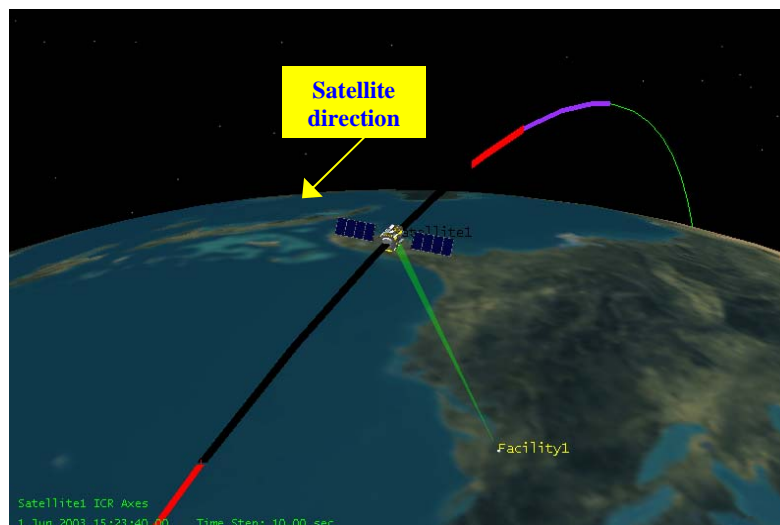

Fig. 3: 3-D output - colors represent different levels of laser effect

A textual report providing the start and stop times corresponding to each laser effect is shown in Fig. 4. Note that the times correspond to the color bands on the 3-D display. The report can be generated by selecting "Report" on the SSM main window.

```
Catastrophic Damage
-------------------                                   Duration
     Start Time (UTCG)          Stop Time (UTCG)         (sec)    Min Range (km)    Max Range (km)
   ---------------------     ----------------------   ---------   --------------    --------------
    1 Jun 2003 15:22:17.12    1 Jun 2003 15:25:59.26   222.146      663.703144        1022.258055


Damage
------                                                 Duration
     Start Time (UTCG)          Stop Time (UTCG)         (sec)    Min Range (km)    Max Range (km)
   ---------------------     ----------------------   ---------   --------------    --------------
    1 Jun 2003 15:21:04.56    1 Jun 2003 15:22:17.12    72.560     1022.252494        1445.492431
    1 Jun 2003 15:25:59.26    1 Jun 2003 15:27:11.82    72.558     1022.258055        1445.496284


Saturation
----------                                             Duration
     Start Time (UTCG)          Stop Time (UTCG)         (sec)    Min Range (km)    Max Range (km)
   ---------------------     ----------------------   ---------   --------------    --------------
    1 Jun 2003 15:18:09.69    1 Jun 2003 15:21:04.56   174.867     1445.492431        2582.516532
    1 Jun 2003 15:27:11.82    1 Jun 2003 15:30:09.88   178.061     1445.496284        2603.797794
```

Fig. 4: Textual report of laser effects intervals

The dynamic display, a new feature of SSM version 2.0, is shown in Fig. 5. This display provides real-time laser effects data during scenario simulation, and is useful in viewing laser effects data at points of interest in the simulation. For example, you may want to display irradiance at the point when saturation begins.
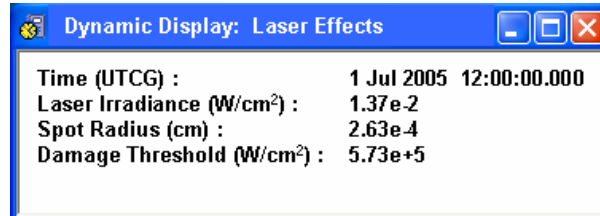

Dynamic Display: Laser Effects

Time (UTCG) :	1 Jul 2005 12:00:00.000
Laser Irradiance (W/cm^2) :	1.37e-2
Spot Radius (cm) :	2.63e-4
Damage Threshold (W/cm^2) :	5.73e+5

Fig. 5: SSM Dynamic Display

5.   AIR-TO-SPACE SCENARIO

The SSM was built using object-oriented architecture. This is beneficial in scenario development because SSM objects, such as lasers, imaging systems, and laser protection, can be saved in one scenario and used in another. In defining an air-based laser engagement scenario, we will not need to redefine the process for creating a laser, imaging system, and imaging system platform, since the process for creating these objects has already been defined in the previous section. This section focuses on differences between airborne and ground-based laser platforms, and presents challenges that may arise when determining where to place the sensor on the aircraft, and whether the sensor location will limit its pointing ability.

A typical air-to-space laser engagement scenario consists of a laser, laser platform, imaging system, and an imaging system platform. The laser platform is defined in STK as an aircraft-sensor pair. Similar to ground-based platforms, available airborne platforms are also displayed in the "Select Laser Platform" list on the SSM main window. If there are no airborne laser platforms defined, you can create a new one by selecting the default, *NewAircraft/NewSensor,* from the laser platform list. The rest of the scenario process is the same as described in the ground-based scenario.

When adding a sensor to an aircraft, we need to specify where on the aircraft it is to be mounted. Side-mounted from inside the aircraft could be constrained by cargo doors or the aircraft itself. Nose-mounted could be a safety concern for the pilots. Logically, the least constrained area is the top of the aircraft. Fig. 6 shows laser effects from an airborne laser engagement scenario. In this scenario, the airborne laser tracks the imaging system, and the

imaging system tracks the aircraft, and it reuses the same laser and imaging system used in the ground-based scenario. The three colors on the orbit-trace represent saturation (purple), damage (red), and catastrophic damage (black). For illustration purposes, it was necessary to capture the aircraft and satellite in two separate pictures, and then overlay the satellite experiencing laser effects on the aircraft picture. The important point is that both pictures come from the same air-to-space laser engagement scenario.
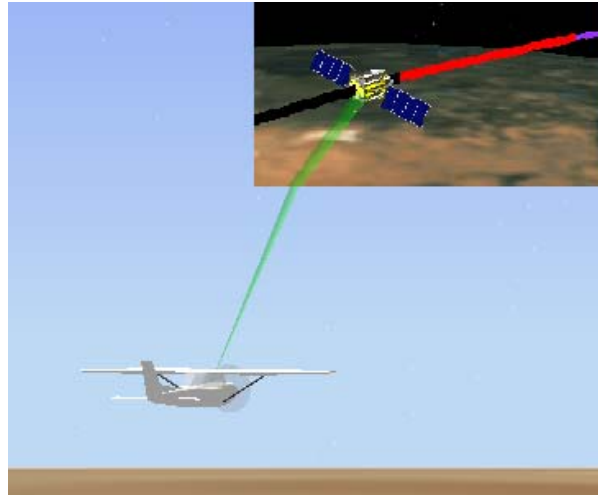

Fig. 6: Air-to-Space laser engagement

6. SPACE-TO-SPACE SCENARIO

Like the airborne and ground-based scenarios, a typical space-to-space laser engagement scenario consists of a laser, laser platform, imaging system, and imaging system platform. In this scenario, the laser platform is defined in STK as a satellite-sensor pair. It is true that a satellite-sensor pair also defines an imaging platform. What this means is that satellite-sensor pairs will appear in both the "Select Laser Platform" and "Select Imaging System" lists on the SSM main window. However, a satellite-sensor pair cannot be assigned to a laser platform and imaging system platform at the same time. Therefore, once a satellite-sensor has been defined as either platform, it is removed from the other platform list.

Fig. 7 shows a laser on a satellite engaging a satellite imaging system, resulting in saturation (purple) and damage (red). Both satellites are in circular orbit. The satellite with laser has a 45 degree inclination, with all other STK satellite defaults accepted. The imaging system satellite has a 60 degree inclination, 5 degree right ascension of ascending node, and all other defaults accepted. During damage, the satellites pass within 900 km of each other.
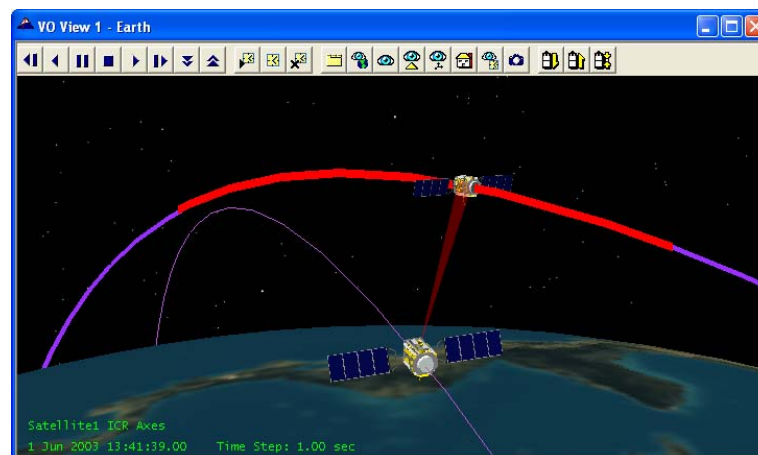

Fig. 7: Space-to-Space laser engagement

7. SSM PHYSICS-BASED MODELING

a. At-Orbit Irradiance

Equations used in SSM are based on first principles physics. For example, we use the basic laser propagation equation in **Photonics Rules of Thumb** to propagate energy from the threat laser, through the atmosphere (if applicable), to the satellite. Essentially, the equation is a simplified propagation model that calculates irradiance at the entrance aperture of the satellite imaging system. The simplified propagation equation that calculates irradiance is given by[1]:

$$I_{AT-ORBIT} = \frac{P \cdot \tau_{ATM}}{\pi R^2 \cdot \sigma_{DIV}^2} = \frac{P \cdot \tau_{ATM}}{\pi R^2 \cdot \left(\sigma_{DB}^2 + \sigma_T^2 + \sigma_J^2\right)} \quad (W/cm^2)$$

where:

$I_{AT-ORBIT}$	=	At-orbit peak irradiance (W/cm^2)
P	=	Laser pointing aperture output power (W)
τ_{ATM}	=	Atmospheric transmission
π	=	pi ~ 3.14159265….
R	=	Range (cm), provided by STK
σ_{DIV}	=	Total beam half-angle divergence (radians), user specified, or calculated
σ_{DB}	=	Optical diffraction limited beam spread half angle, including aberrations and thermal blooming (radians)
σ_T	=	Optical turbulence beam spread half angle (radians)
σ_J	=	High frequency jitter averaged beam spread half angle (radians)

b. Atmospheric Transmission

In visible and near infrared wavelengths, where "clear air" absorption is minimal, we conservatively estimate irradiance at unity transmission. For other spectral regions, this assumption may be too optimistic. Therefore, SSM allows either direct specification of a transmission term, or computes atmospheric transmission as given by:

$$\tau_{ATM} = \tau_{RAYLEIGH} \cdot \tau_{ABS} \cdot \tau_{AER}$$

where:

τ_{ATM}	=	Total laser-to-satellite atmospheric transmission
$\tau_{RAYLEIGH}$	=	Rayleigh scattering component of transmission
τ_{ABS}	=	Gaseous absorption component of transmission
τ_{AER}	=	Aerosol scattering component of transmission

Rayleigh scattering refers primarily to the scattering of light off molecules in the air, and causes the blue color of the sky when sunlight scatters from molecules of the atmosphere. As a reasonable and somewhat conservative approximation, it is assumed here that Rayleigh scattering is directly proportional to atmospheric pressure, and that the atmosphere is in simple geostrophic equilibrium such that its density can be determined from a simple exponential and scale height.

Gaseous absorption is the most difficult transmission quantity to calculate accurately. Codes such as HITRAN II and FASCODE 3, and their large supporting databases, were developed and can be used to make detailed estimates. However, in SSM, we simplified the estimation process. If we can obtain a ground level estimate of the relevant absorption coefficient, and can provide a scale height for the dominant gaseous absorption component, then we can make a fairly accurate estimation of this factor.

Aerosol attenuation ranges from nearly invisible stratospheric hazes to London "pea-soup" fogs. While some radiation is absorbed by aerosols, nearly all of it is usually scattered, most by a mechanism known as Mie scattering. As a reasonable simplification, we ignore aerosol absorption in this model, and deal with aerosol scattering as a source of attenuation. In general, aerosol extinction at any wavelength is proportional to the inverse of the visibility; therefore meteorological range (visibility) is a user input field for determining aerosol attenuation.

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[1] Miller, J.L., and E. Friedman, *Photonics Rules of Thumb*, adapted from equation, page 178, McGraw-Hill, 1996

c. At-Detector Irradiance

In order to measure laser effects at the detector, we start with at-orbit irradiance, then propagate laser irradiance through the optical train. A typical sensor optical train includes an external window or lens, an internal critical transmissive optic, a critical mirror, a secondary focus, a Dewar's window, and a detector. The basic calculation for at-detector irradiance is given by:

$$I_{DETECTOR} = I_{AT-ORBIT} \cdot \tau_0 \cdot G$$

where:

$I_{DETECTOR}$	=	Irradiance at the detector (W/cm^2)
$I_{AT-ORBIT}$	=	Irradiance at-orbit (W/cm^2)
τ_0	=	Total transmittance through the sensor optical train
G	=	Optical Gain of the sensor

Due to the complexity of modeling specific optical systems, we made the total transmittance in SSM a user entered value. The optical gain is calculated from an estimate of the blur circle size. Noting that for a diffraction limited spot, the 1/e radius of the equivalent Gaussian is 46% of the Airy radius. Given this formulation, the optical gain is:

$$G = \frac{D^2 \cdot (1 - f_{AREAOBS})}{4 \cdot r_e^2} \approx \frac{D^2 - D_{OBS}^2}{4 \cdot r_e^2}$$

where:

r_e	=	1/e spot radius (cm)
D	=	Outer optics diameter (cm)
G	=	Optical gain
$f_{AREAOBS}$	=	Fraction of aperture area obscured
D_{OBS}	=	Diameter of central circular obscuration (if appropriate)

d. Degradation

SSM measures two **recoverable effects**. **Degradation**, a measure of the signal-to-noise ratio (SNR), compares the scene level to the laser. SNR is determined by first calculating the nominal signal-to-noise ratio to establish a baseline for performance without laser effects. A simplified representation of the nominal SNR consists of the scene signal, shot noise, and detector noise. Then the laser is introduced by adding two additional noise terms: laser shot noise and speckle noise. SSM measures degradation when the SNR exceeds a certain threshold.

SNR is often a useful figure of merit for optical system performance. The signal is comprised of output voltage or current variations related to structure of interest in the scene. The mean signal level can be estimated as the mean scene contrast fraction multiplied by the mean scene level. The noise is comprised of variations not conveying scene information: i.e., due to random shot noise, thermal noise, etc. Noise is often low level, and can usually be neglected in the portions of a system where the signal level is high. Often however, when systems are encountered in which signal levels are low, the effects of even low-level noise can seriously degrade the overall system performance[2].

The SNR is calculated as:

$$SNR = \frac{S_{SCENE}}{\sqrt{\sum_{Noise\ Terms} N_i^2}} \cdot C$$

where:

S_{SCENE}	=	Mean scene level (photons/detector/frame)
N_i	=	Noise terms in the system (photons/detector/frame)
C	=	Scene contrast – user entered (typically 10%)

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[2] R.E. Zimmer and W.H. Tranter, Ch 6 in the *Principles of Communications - Systems Modulation, and Noise*, pp262-263, (Houghton Mifflin Company, 1976)

e. Saturation

Saturation, the second **recoverable effect**, is measured when the detector wells completely fill during a frame. The detector saturation threshold can be estimated as follows:

$$I_{SAT} = \frac{e^- \cdot \left(\dfrac{h \cdot c}{\lambda}\right)}{QE \cdot A_{det} \cdot \tau_{int}}$$

where:

I_{SAT}	=	Saturation irradiance of detector (W/cm^2)
e^-	=	Well depth of detector element (number of electrons)
h	=	Planck's constant (6.63e-34 Js)
c	=	Speed of light (2.998e8 m/s)
λ	=	Laser wavelength
QE	=	Quantum efficiency (wavelength and material dependant)
A_{det}	=	Area of detector element (cm^2)
τ_{int}	=	Integration time

SSM compares at-detector irradiance to the saturation threshold. If irradiance is greater than the threshold, then saturation has occurred.

f. Damage

In SSM, we also measure two **non-recoverable effects**. **Damage** to a FPA is measured by using the NRL model[3], sometimes informally referred to as the Bartoli model, for detector damage. The Bartoli model for detector damage due to a Gaussian laser spot is given by:

$$I_{DET} = E_0 \left(\frac{1}{\Delta t} + \frac{k \cdot \alpha \cdot \sqrt{\pi}}{r_e \tan^{-1}\left(\sqrt{\dfrac{4 \cdot k \cdot \Delta t}{r_e^2}}\right)} \right) \quad \text{and} \quad E_0 = \frac{(T_{MELT} - T_0) \cdot \rho \cdot c_p}{(1-R) \cdot \alpha}$$

where:

I_{DET}	=	Melt onset (and detector damage) irradiance threshold at detector (W/cm^2)
Δt	=	Dwell time
k	=	Thermal diffusivity (cm^2/s)
α	=	Absorption coefficient (cm^{-1})
r_e	=	1/e intensity spot radius on detector (cm)
E0	=	Basic energy to melt characteristic depth
T_{MELT}	=	Melt temperature (K)
T_0	=	Initial temperature (K)
ρ	=	Density (g/cm^3)
c_P	=	Specific heat (J/g-K)
R	=	Surface reflectivity

In SSM, we compare the damage threshold to at-detector irradiance. If the at-detector irradiance is greater than the threshold, then damage has occurred. To determine **catastrophic damage**, simply multiply the damage threshold by 2. Then perform the same comparison.

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[3] Bartoli, F., et. al., A generalized thermal model for laser damage in infrared detectors, *Journal of Applied Physics*, Vol. 47, No. 7, July 1976

3. SSM VS. ACTUAL LAB/FIELD TEST RESULTS

Ball OPS1 has conducted tests in a laboratory and in the field. In the lab test, data was collected at different power levels and wavelengths. For the field test, data was collected at an approximate range of 1.6 miles, at three different times during the day; morning, late afternoon, and after sunset. From these tests, frame data was collected and stored as pixel maps. We visually inspected three random pixel maps in MATLAB and were able to determine what percent of the total pixels were saturated due to the laser threat. We determined that less than 0.5% of the total pixel map experienced saturation.

We have been looking for a way to validate the SSM by comparing actual laser effects data with simulated results. Unfortunately, we won't have data from an actual laser engagement conducted in space. However, we do have actual data from a field test, and from our laser laboratory. In order to simulate the field test in SSM, we need to scale laser power and beam divergence from our field test distance of 1.6 miles to 450 km.

In SSM, we model a simplified optical train, and ask the user to directly enter total optical transmittance. SSM is not meant to model complex optical system designs. However, the optical design used in our field test is fairly complex, and can only be approximated in SSM, which means there will be a margin of error in compared results.

To simulate the field test, we developed an SSM scenario consisting of a satellite (450 km, circular orbit), imaging system, and a ground-based laser. We entered actual field test data for the laser, atmosphere (both scaled to 450 km), and the detector, and approximated optical input data. Once all inputs were made, we calculated laser effects to see where saturation will occur during the satellite orbit. At 450 km, while experiencing saturation, we recorded the detector irradiance and saturation threshold. By normalizing the saturation threshold to the peak irradiance, we were able to calculate the percentage of the field of view that was saturated, using the data points from the off-axis rejection curve. SSM resulted in less than 0.5% of the total, but was approximately 0.1% different than the actual field test. The difference, once again, is due to the inability to model complex optical system designs.

Because of the modular design of SSM, it is possible to improve or modify any of the modeling components in future builds, if there is enough interest and support from the space community.

4. SUMMARY

The Satellite Survivability Module (SSM) is an end-to-end, physics-based, performance prediction model for directed energy engagement of orbiting spacecraft. For SSM laser engagements, the user creates a spacecraft, its optical system, any protection techniques used by the optical system, a laser threat, and an atmosphere through which the laser will pass. SSM then models the engagement and its impact on the spacecraft using four impact levels: degradation, saturation, damage, and destruction. Protection techniques, if employed, will mitigate engagement effects. Modeling results can be displayed as either 2-D or 3-D visualizations, textual reports, or new to version 2.0, SSM, which will allow laser effects data to be displayed dynamically during scenario execution.

SSM provides the flexibility to create a wide variety of laser engagement scenarios. In this paper, we presented three scenarios: ground-to-space, air-to-space, and space-to-space, and explained how we can reuse objects, such as lasers, in each of the different scenarios. We also explained how easy it is to generate the different scenarios; air-to-space or space-to-space, and how the SSM interface remains consistent throughout the scenario generation process.

In an effort to test SSM, we conducted tests in our laser laboratory and in the field. The field test was conducted at an approximate range of 1.6 miles, and at three different times during the day. In simulate the field test data in SSM, we scaled laser power and beam divergence from 1.6 miles to 450 km, and converted laser transmission through the atmosphere from 1.6 miles at ground level to 450 km pointing straight overhead. Then, we entered inputs from the laser, atmosphere, optics, and detector, taking into account that SSM models a simplified optical train, and would only provide an approximation to the complex field test optical design. We concluded that in both cases (field test vs. SSM), saturation occurred over less than 0.5% of the total field of view. Although there was an obvious difference in the number of pixels affected between the field test and SSM, we are pleased with the results, and are confident in the SSM to produce reasonable approximations to "what-if" scenarios.