Modeling laser effects on imaging spacecraft using the SSM

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ABSTRACT

The Satellite Survivability Module (SSM) is an end-to-end, physics-based, performance prediction model for directed energy engagement of orbiting spacecraft. Two engagement types are currently supported: laser engagement of the focal plane array of an imaging spacecraft; and Radio Frequency (RF) engagement of spacecraft components. For 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. For RF engagements, the user creates a spacecraft (as a set of subsystem components), any protection techniques, and an RF source. 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. SSM currently supports two laser and three RF protection techniques.

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. 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.

1. INTRODUCTION

Protecting space assets against laser threats has been of great interest in the defense community for a number of years. The challenge was to create an easy-to-use, industry accepted, satellite survivability tool. The Ball team developed the Satellite Survivability Module (SSM), an end-to-end, physics-based, performance prediction model for directed energy weapon attacks on satellites. End-to-end, physics-based, means that we model the laser from a ground based location, through the atmosphere to the spacecraft, through the imaging system to the detector where laser effects are measured. At the detector, we measure four levels of effect: degradation, saturation, damage, and catastrophic damage. Details of how these effects are calculated will be presented later in the paper. SSM leverages the capabilities of Satellite Tool Kit (STK), an industry accepted, independently validated and verified satellite simulation tool. 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 takes advantage of STK's extensible architecture to enhance its capabilities in several key areas. SSM adds two objects: laser and laser protection, with the same look-and-feel as other STK objects, as shown in the SSM main GUI, Fig. 1. SSM calculates laser transmission through the atmosphere which is presented as an extension of the laser object. SSM extends the existing sensor object to include definitions for an optical system, focal plane array (FPA), and off-axis rejection curve (ORC). Once the laser, atmosphere, and optical system are defined, SSM computes laser effects by computing access between the laser and the satellite sensor. To determine effects at intermediate time steps, SSM integrates along the orbit path to provide precise laser effects measurements. SSM enhances the STK display by overlaying the orbit traces generated by STK with laser effects regions based on calculation results. Each laser effect is represented by a different color. An example of this will be shown in section 9 of the paper.

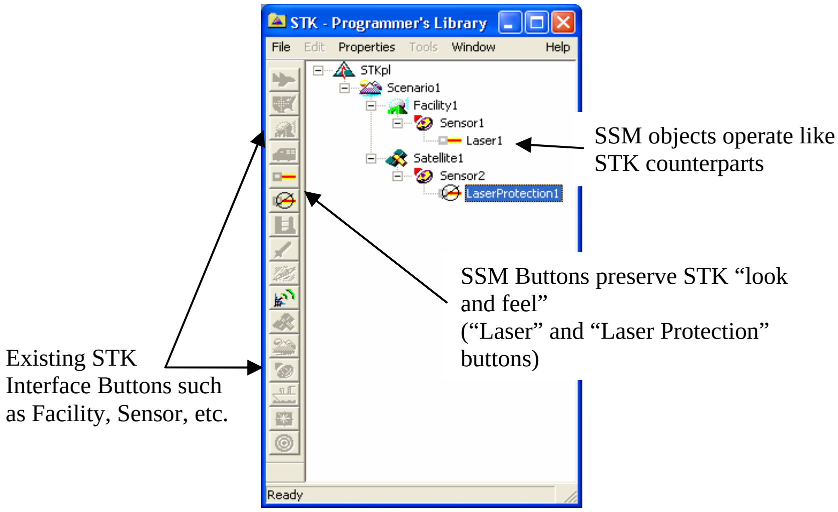

Fig. 1: SSM Main Interface

The rest of this paper will focus on the details of SSM and how we represent input parameters needed to compute laser effects at the detector, and report those effects both visually and textually. Section 2 will explain the process for modeling a ground-based laser threat. Section 3 will provide details about factoring in laser transmission through the atmosphere. In sections 4, we model irradiance at the detector. Section 5 covers the optics, FPA, and ORC, and how their respective inputs are used to measure the optical system and estimate the quality of the optics. Section 6 will explain laser effects calculations. Section 7 will present two optical protection techniques that can be applied to the optics to mitigate laser effects. Section 8 presents a comparison of the SSM irradiance calculation against results calculated from the Starfire Optical Range (SOR) using the same sample data, and Section 9 provides a final summary of SSM.

2. MODELING THE GROUND-BASED LASER IN SSM

To define a laser, we first need to define where it is located, what kind of pattern it emits, and what it will be pointing at. This is a three step process in SSM: 1. Specify the ground location, represented by a facility object. The facility's attributes include latitude/longitude and elevation, and either of these properties can be edited by the user. 2. Define the pointing pattern and target. This is accomplished by adding a sensor to the facility. The sensor provides the modeling for scan patterns and targeting. 3. Define the laser. The laser object inherits the attributes of the sensor and facility objects and is a good example of how we leverage the capabilities of STK. The laser input panel, as shown in Fig. 2, provides fields for specifying power, aperture diameter, beam divergence, pulsed vs. continuous wave (CW), and wavelength. The input parameters gathered from the input panel are used to compute the laser irradiance at the target.

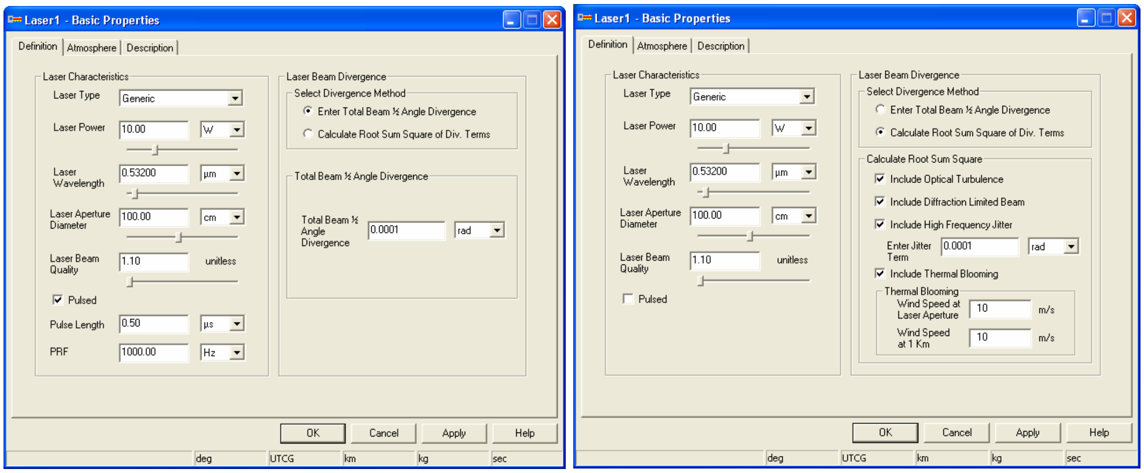

Fig. 2: The laser definition tab allows you to specify laser properties

The equation used to determine laser irradiance at the outer aperture of the satellite's sensor 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)

σ_{DIV} = Total beam half-angle divergence (radians)

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)

The simplified laser propagation equation above is used in SSM to provide peak at-orbit irradiance. Laser power comes from the input panel. Atmospheric transmission is specified on the "Atmosphere" panel, and is described in detail in section 3. The range from laser to satellite is provided by STK. Beam divergence is estimated through direct specification or through some boundary condition of the laser itself. For direct specification, we provide an input field for entering total beam ½ angle divergence, as shown in the left panel of Fig. 2. Alternatively, beam divergence may result from a number of factors including: the diffraction limit of the laser pointer aperture; aberrations in the laser pointer optics; beam spreading due to optical turbulence and/or boundary layer turbulence on moving platforms; high frequency line of sight stability errors (pointing jitter) averaged over the dwell time, and, thermal blooming, as well as the degree to which any of these effects are compensated for by adaptive optics or otherwise. The divergence may be specified as a total including some or all of the individual terms, or each term may be estimated separately and combined to obtain the total divergence. Calculating a root-sum-square (RSS) of some or all of the divergence terms is shown on the right panel of Fig. 2.

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

3. ATMOSPHERIC TRANSMISSION

To conservatively estimate irradiance, it is important to consider the best atmospheric transmission case. In visible and near infrared wavelengths, where "clear air" absorption is minimal, this will often mean near-unity transmission. For other spectral regions, this assumption may be too optimistic. Therefore, SSM provides two methods for specifying atmospheric transmission. The first method is selecting unity (corresponding to no atmosphere), which sets the atmospheric transmission term to 1.0. Where non-unity transmission estimates are made, the overall atmospheric transmission is 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 of the 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. By assuming a scale height smaller than that of the atmosphere as a whole (~ 8000 meters), we assure a conservative treatment, since a larger scale height means the absorbing density falls with the altitude more slowly, resulting in more of the absorbing medium along the path. This results in more irradiance delivered to the sensor for the same at-laser power output and divergence. Table 2 provides gaseous absorption coefficients for a few laser types.

Table 1. Atmospheric absorption characteristics for some important laser types

Laser	Wavelength	Sea Level Absorption Coefficient	Scale Height	Source
COIL	1.315 μm	1.58×10^{-4} m^{-1}	3425 m	2-1 line; Leslie[2]
HF	2.7 μm	0.2 m^{-1}	3000 m	P02-02 line; Leslie[2]
DF	3.8 μm	2.26×10^{-4} m^{-1}	3250 m	P01-11 line; Leslie[2]
CO_2	10.6 μm	3.2×10^{-4} m^{-1}	8000 m	EO/IR Handbook[3]

Aerosols differ more than almost any atmospheric parameter. 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. The user interface for atmospheric transmission is shown in Fig. 3.

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[2] Leslie, D.H., *Altitude-Dependent Atmospheric Absorption of DF, HF, and Iodine Laser Radiation, NRL Memorandum Report 4906*, Naval Research Laboratory, Washington, DC 28 September 1982. Scale heights based on first 1000 meters of the atmosphere.

[3] Miller, J.L., and E. Friedman, *Photonics Rules of Thumb*, adapted from equation, page 180, McGraw-Hill, 1996. Scale height from assumption of constant mixing in troposphere and 8 km scale height.

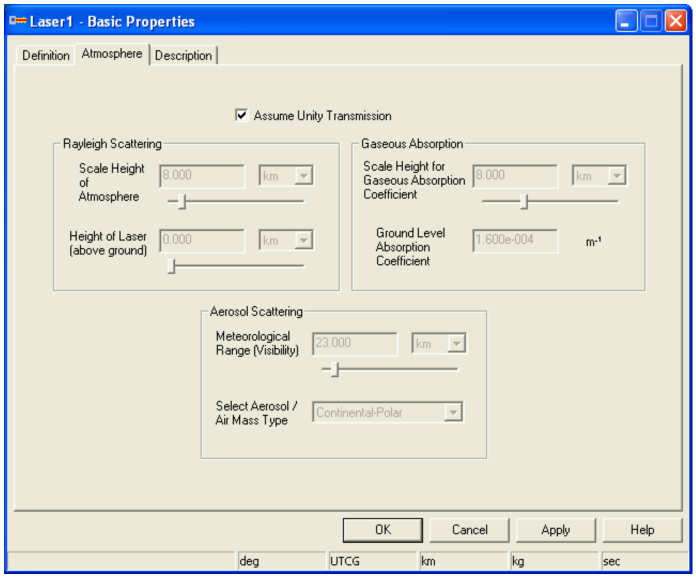

Fig 3. Atmospheric transmission interface panel

4. IRRADIANCE AT THE DETECTOR

To calculate irradiance at the detector, we first calculate irradiance at-orbit, as discussed in section 2, and then we add transmittance through the optical train and optical gain. The basic calculation we use to obtain this value is:

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

where:

$I_{DETECTOR}$	=	Irradiance at the focal plane (W/cm^2)
$I_{AT\text{-}ORBIT}$	=	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. The 1/e spot radius, for a uniformly illuminated aperture, depends on the wavelength, sensor aperture diameter, focal length or f/number, and overall optical quality of the system:

$$r_e = 0.46 \cdot \left(\frac{1.22\lambda}{D}\right) \cdot fl \cdot \beta$$

where:

r_e	=	1/e spot radius (cm)
λ	=	Wavelength (cm)
D	=	Outer optics diameter (cm)
fl	=	focal length (cm)
β	=	Optical quality of satellite optics

noting that for a diffraction limited spot, the 1/e radius of the equivalent Gaussian is 46% of the Airy radius given by the value in parentheses. Given this formulation, the optical gain is just:

where variables are as defined above and:

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

G	=	Optical gain
$f_{AREAOBS}$	=	Fraction of aperture area obscured
D_{OBS}	=	Diameter of central circular obscuration (if appropriate)

5. THE OPTICAL SYSTEM

In order to measure laser effects at the detector, we propagate the laser through the optical train. Modeling the optical train of a space sensor can be very complex. However, for damage assessment purposes, a simplified representation is often adequate. Such a representation of a notional sensor optical train includes an external window or lens, an internal critical transmissive optic, a critical mirror, a secondary focus, a Dewars window, and a detector, as shown in Fig. 4.

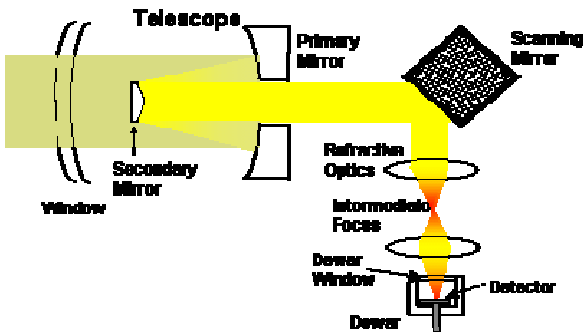

Fig 4. A typical sensor optical train

In order to gather information about the optical system, we provide three SSM input panels, which we created as extensions to STK's sensor object. It is not necessary to show all of these here. The optics panel provides input fields for entering specifics about the optical system including aperture size, focal length, f-number, total transmittance, bandwidth, and scene type. This panel's input parameters contribute to calculating the signal-to-noise ratio, which is used to determine the level of degradation to the scene image. Specific laser effects will be discussed in detail in section 6 of this paper. The FPA panel provides details about the detector, including material type, initial temperature, melt temperature, surface reflectivity, quantum efficiency, and area of the detector. These parameters are used in determining the detector saturation and damage irradiance thresholds.

Laser effects on the sensor are determined in large part by the sensor's point source transmission (PST) function, which is equivalent to the off-axis rejection curve (ORC), except that the ORC is normalized to a peak value of unity. The ORC describes the spatial distribution of light on the focal plane, and, specifically, how much light winds up other than where it is nominally focused. It is used to determine the radius of the affected area on the detector array based off the input irradiance. Fig. 5 shows the ORC input panel. This panel is used to determine the quality of the optics. The "GOOD", "FAIR", and "POOR" ORC's represent 3 levels of quality. The user can also enter data pairs to represent a custom ORC. The field on the top right allows the user to specify if they wish to exclude saturation and degradation effects below a certain percentage. In other words, if 20% is entered in this field, then the visual effects reporting on the orbit trace will only appear if greater than 20% of the field-of-view is saturated.

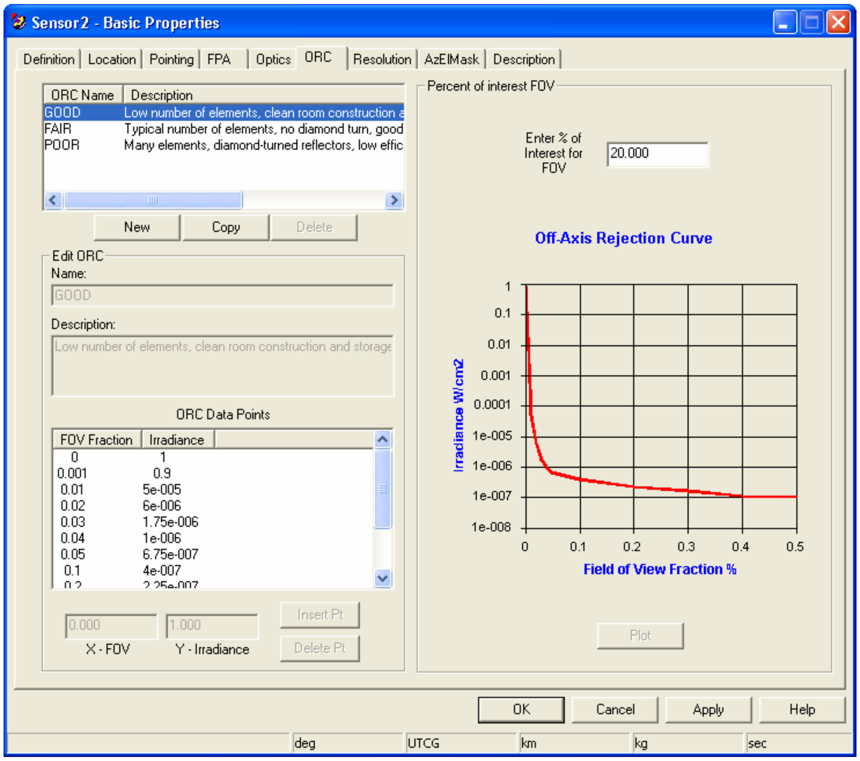

Fig. 5: ORC panel

6. MEASURING LASER EFFECTS

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[4].

The SNR is calculated as:

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

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%)

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

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:

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

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

To determine if saturation occurs, we compare the saturation threshold to the peak detector irradiance. If the peak irradiance is greater than the threshold, then saturation has occurred. If we plot the saturation threshold on the ORC, we can determine what percentage of the FOV is saturated.

In SSM, we also measure two **non-recoverable effects**. **Damage** to a FPA is measured by using the NRL model[5], 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:

$$I_{DET} = E_0 \left(\frac{1}{\Delta t} + \frac{k \cdot \alpha \cdot \sqrt{\pi}}{r_e \tan^{-1}\left(\sqrt{\frac{4 \cdot k \cdot \Delta t}{r_e^2}} \right)} \right)$$

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, given by:

$$E_0 = \frac{(T_{MELT} - T_0) \cdot \rho \cdot c_p}{(1 - R) \cdot \alpha}$$

and:

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

Fig. 6 shows an example of a damaged detector. In SSM, to determine if damage occurs, we compare the damage threshold to the peak detector irradiance. If the peak 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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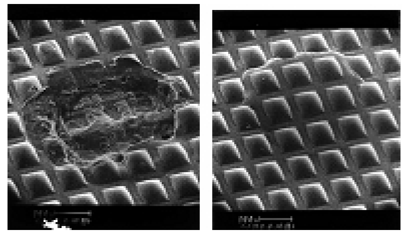
[5] Bartoli, F., et. al., A generalized thermal model for laser damage in infrared detectors, *Journal of Applied Physics*, Vol. 47, No. 7, July 1976



(Images courtesy of AFRL/MLPJ. Used by permission)

Fig. 6: Catastrophic Damage (left), and Damage (right) are permanent effects

7. PROTECTION TECHNIQUES

In SSM we model two protection techniques, the notch filter and power limiter. The power limiter is designed to reduce the peak irradiance, possibly due to a laser, arriving at the focal plane. The power limiter's turn-on irradiance determines when the limiter begins to attenuate energy, limiting the increase in throughput power to a smaller proportionality factor, or in some cases, capping it to the output level at turn-on (proportionality factor = 0). Eventually the device will saturate, and basic throughput will resume, but from a lower base irradiance than if there were no attenuation. Addition of a power limiter has an impact on the transmission of the overall scene, known as insertion loss. This is the broad band transmission value of the power limiter. This term must be included in the overall transmission of the optics when a power limiter is included in the optical train design. The inputs for including a power limiter in the design are: turn-on irradiance, saturation irradiance, and insertion loss. The difference between the turn-on irradiance and saturation irradiance is the dynamic range.

The notch filter is designed to provide several orders of magnitude of protection against a laser at a specific wavelength, while minimally affecting the overall transmission of a much larger sensor band. Such filters can be designed with very large attenuations (e.g., 10^7) over very small bandwidths (e.g., 0.01mm), and can be very effective against fixed-wavelength laser threats. Unfortunately, as more and more wavelengths are blocked (more notches are added), the overall losses for the broader sensor band grow as well, which can adversely affect sensitivity and image quality. This shows up as a reduction in signal level, which reduces the SNR even under nominal circumstances (readout noise and other system noise sources, as well as scene shot noise). Quantifying the tradeoffs between nominal performance degradation and performance in the presence of a threat is one of the main goals of SSM. As a conservative estimate, the filter transmission is assumed to be its maximum value from the graph (the assumption is that the portion of the overall band embodied in the notches is small). The transmission affected by the filter will be entered by the user as the total transmission value of the system. The input values for a notch filter are the starting wavelength, ending wavelength, transmission in the notch, and transmission outside the notch.

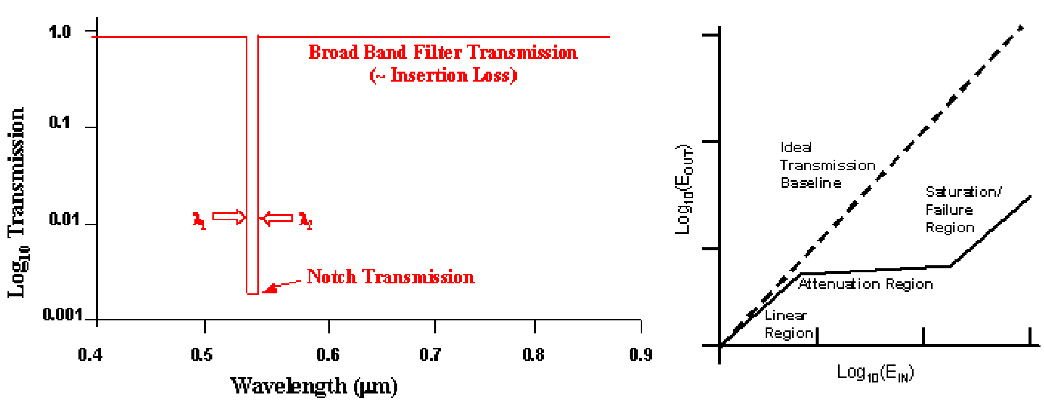


Fig. 7 provide graphical illustrations of how the 2 SSM protection techniques are used

8. SOR MODELING RESULTS

In an effort to validate SSM, we modeled an engagement scenario using a Starfire Optical Range (SOR) laser source and compared irradiance results from SSM to those obtained from the SOR. We started with the parameters shown in Table 2, and modeled the engagement for an imaging spacecraft with silicon detectors at 450 km.

Table 2. Laser parameters used in validation

Test Source	(μm) Wavelength	(W) Power	(s) Pulse width	(Hz) PRF	(rad) 1/2 angle divergence	(W/cm²) Average Irradiance at target
SOR	0.532	9.75	6.0e-9	10	1.69e-6	1.92e-4
SSM	0.532	9.75	6.0e-9	10	1.69e-6	4.08e-4

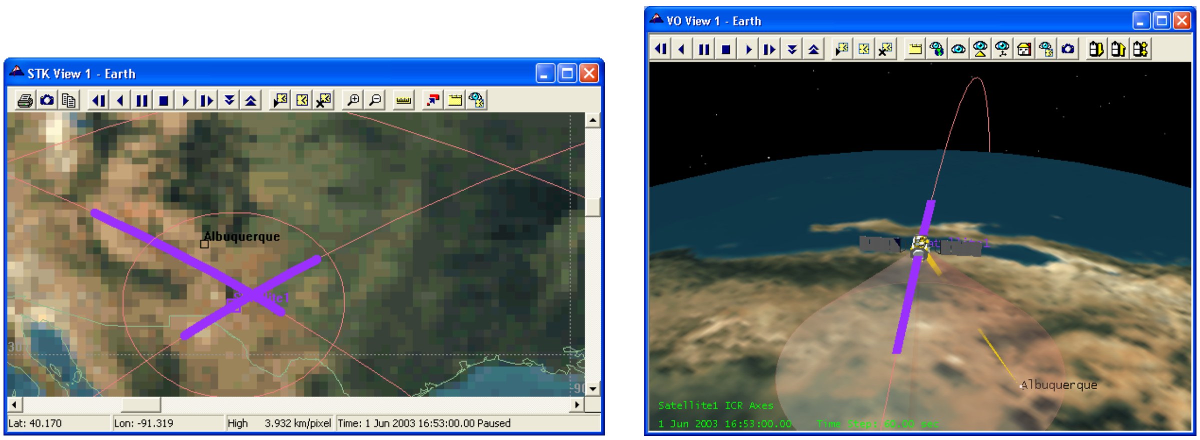


Fig. 8: Preliminary SSM results for SOR laser engagement

The SSM results indicate that the spacecraft detectors would be saturated. In SSM, the laser effects colors are editable by the user. In this case, purple represents saturation. The left side of Fig. 8 illustrates two orbit passes over SOR, and shows that in each pass saturation occurred. The right side is a 3-D depiction of one of the orbit passes in the 2-D map window. Note the satellite sensor cone reflecting on the earth while the pulsed laser cone engages it.

Please note that the results shown are preliminary. Ball OPS1 is currently developing a space experiment (Laser Threat Detection System, TDS) that will provide data to validate these modeled results.

9. SUMMARY

The Satellite Survivability Module (SSM) is an end-to-end, physics-based, performance prediction model for directed energy engagement of orbiting spacecraft. Two engagement types are currently supported: laser engagement of the focal plane array of an imaging spacecraft; and Radio Frequency (RF) engagement of spacecraft components. For 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. For RF engagements, the user creates a spacecraft (as a set of subsystem components), any protection techniques, and an RF source. 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, or as textual reports. SSM has been used to provide preliminary modeling of a laser engagement of an imaging spacecraft from the SOR facility. These preliminary results will be validated using a space experiment currently being built by the Ball OPS1 team.