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PHYSICS-BASED, HIGH-FIDELITY SIMULATION: STRATEGIC SCENE GENERATION MODEL

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ABSTRACT

This paper describes a computerized system to generate reliable line-of-sight radiometry and time-sequenced digital images in support of the design, development and test of advanced strategic surveillance systems and for strategic engagement simulations required by the Ballistic Missile Defense Organization (BMDO). The Naval Research Laboratory (NRL) is developing the Strategic Scene Generation Model (SSGM) to provide valid images, and the capability to generate them, to various BMDO program elements and technology demonstration and measurements programs — thereby serving as a standard against which different BMD concepts and designs can be tested. Consequently, the SSGM has emerged as a highly visible focus for the on-going development of phenomenology models and currently provides many projects in the BMD community with integrated, consistent, dependable, accessible and affordable state-of-science modeling and simulation capability.

1 INTRODUCTION

The Ballistic Missile Defense Organization (BMDO) must simulate the detection, acquisition, discrimination and tracking of anticipated targets and predict the effect of natural and man-made background phenomena on optical sensor systems designed to perform these tasks. NRL is developing such a capability using a computerized methodology to provide modeled data in the form of digital realizations of complex, dynamic scenes.

The Strategic Scene Generation Model (SSGM) is designed to integrate state-of-science knowledge, data bases and computerized phenomenology models to simulate strategic and theater engagement scenarios and to support the design, development and test of advanced surveillance and weapon delivery systems. Multi-phenomenology scenes are produced from validated codes — thereby serving as a traceable standard against which different BMD concepts and designs can be tested.

Sensor-perspective radiance maps are derived from an ensemble of the best available government standard models and authenticated data bases via an interactive software system that selects the required data bases and executes the pertinent codes to generate the scenes or the line-of-sight radiance values desired. The phenomenology consists of quiescent and enhanced natural and perturbed backgrounds with imbedded targets and target induced/related events. Backgrounds include earth terrain; opaque and semi-transparent clouds; low-altitude atmospheric emission, scattering, and absorption; the quiescent and enhanced atmosphere at high altitude, including airglow and aurora; man-made nuclear perturbations; and celestial backgrounds. Target phenomena include missile bodies and plumes, fuel vents, reentry vehicles, inflatable replicas, decoys and other space objects and debris. The phenomenology treatments are all deterministic. Stochastic structure may be added to gaseous phenomena whose statistics can be described as power spectral density functions. The scene realizations span all relevant space and time and have spatial, temporal, and spectral sampling regimes that are set by anticipated surveillance system specifications and engagement scenarios.

The SSGM is being developed to integrate, for the first time, the various "government-standard" phenomenology codes to provide valid, standard scene data to a community of users. The SSGM consolidates the development of BMDO scene generation capabilities into a single, all-encompassing effort which eliminates duplication, promotes standardization, and guarantees trusted engineering results. Traditionally, individual phenomenology models allow the user to estimate the nature and importance of observables when it is not feasible to measure all required spatial or temporal resolutions, viewing aspects, or wavelengths. The SSGM is a critical capability which combines various first principles and semi-empirical codes and data bases into an architecture specific to anticipated BMDO application requirements. Where appropriate, the SSGM project makes direct use of existing data archived in one of three Phenomenology Data Centers being developed by the BMDO. These are the Missile Defense Data Center at USASSDC in Huntsville, AL, the Plume Data Center at AEDC in Tullahoma, TN, and the Backgrounds Data Center at NRL in Washington, DC. This interface facilitates the validation of SSGM methodology by providing direct access to the relevant empirical data. As an example, the Plume Data Center has recently embarked on a program to assess SSGM boosting missile plume phenomenology by conducting extensive, yet careful comparisons of measured plume data with SSGM scenes. The purpose of the activity is to inform SSGM users, particularly those which use the SSGM to validate their system design criteria, of the relationship of the simulated scenes to reality.

The SSGM development is occurring in three phases, two of which have been completed. These are: Prototype, Baseline, and Operational. The activity began in 1987 as the *Strategic* Scene Generation Model and has evolved to address *Theater Missile Defense (TMD)* and *National Missile Defense (NMD)* requirements. The final release of the Baseline SSGM (SSGMB R5.1) was distributed, with documentation, to the user community in July 1993 as a mature code under formal configuration management and subject to an ongoing Independent Verification and Validation (IV&V) activity. Architecturally, it is responsive to BMDO needs, but has data base and execution speed limitations. The Operational SSGM (SSGMO) will have a full complement of data bases and achieve execution speeds adequate to support near real-time hardware-in-the-loop simulations. The Phase III activity began in during the Spring of 1993.

The final release of the Baseline SSGM was independently evaluated in June 1993 by the National Test Facility (NTF) for inclusion in the BMDO Analytical Tool Box (ATB). To be included in the ATB, the SSGM underwent the initial phase of a process called "Confidence Assessment" -- similar, in some respects, to IV&V but that is largely independent of the development process. The SSGM was recommended for inclusion in the ATB and is scheduled for follow-on assessments.

2 SSGM REQUIREMENTS

The scene data needed to support SDIO program elements consists of radiometrics of scene elements plus time-sequenced 2-D scenes and sensor-perspective pixel radiance maps of backgrounds with imbedded targets. For general sensor-target-background engagement scenarios, various target and background observables could exist within the scene sequence. Phenomenology associated with targets might consist of the missile hard body, missile plume and target related persistence phenomena (fuel dumps), spent stages, satellites, post-boost vehicles, re-entry vehicles, decoys, penetration aids, and post-kill debris (including salvage-fused, nuclear warheads). Backgrounds might include "hard" earth (terrain, ocean, and ocean ice), meteorological phenomena (semi-transparent/opaque clouds), quiescent atmospheric phenomena (scattering/emission/absorption, earth-limb airglow emission), the perturbed atmosphere (aurora and man-made backgrounds including single or multiple nuclear detonations), and celestial sources (zodiacal, galactic, and extragalactic).

The problem confronting the SSGM is to provide such digital scene sequences constrained only by limitations in the physical models and empirical data bases incorporated within on-line phenomenology codes and/or pre-computed data bases. The goal is to encompass the totality of spatial, temporal, and spectral sampling regimes set by anticipated BMD passive Electro-Optical sensor system specifications and engagement scenarios. The frame size may range from a few hundred to several thousand pixels in each dimension and the duration of the scenario may span a hundred or more seconds at a fraction of a second framing rate. The size of the digital scene data base produced may range from several tens to several thousands of megabytes and, when coupled with event-driven simulations, must be produced in reasonable times by a software architecture which is responsive to the external interrupts implicit when unforeseen events influence the flow of the simulation. The dynamic range, spectral range, and resolution must also span likely sensor candidates. The SSGM must simulate images and point-source intensity data entering the aperture of the sensor. The SSGM is not required to model optical or sensor systems which modulate the calculated scene radiance values. Furthermore, the SSGM is not required to treat radar systems. The ability to treat active illumination of the target by laser is a future requirement.

3 SSGM ARCHITECTURE

Figure 1 is the architecture flow diagram for the Baseline SSGM Baseline. The SSGM process consists of three major modules (GETSNR, RUNMODELS, and MAKEFRAMES) interfacing with four data base libraries (Scenario, Element, Runtime, and Output). The SSGM is also supported by a Scenario Construction Tool (SCT) which serves as an interactive, but independent, graphical user interface for scenario specification. The SCT and the three primary SSGM software modules which accomplish these functions will be described below. Additional tools for display and critical analysis of SSGM generated scenes and scene sequences are packaged with the SSGM software to provide a complete capability to script, generate and inspect composite multi-phenomenology scenes and LOS radiance values.

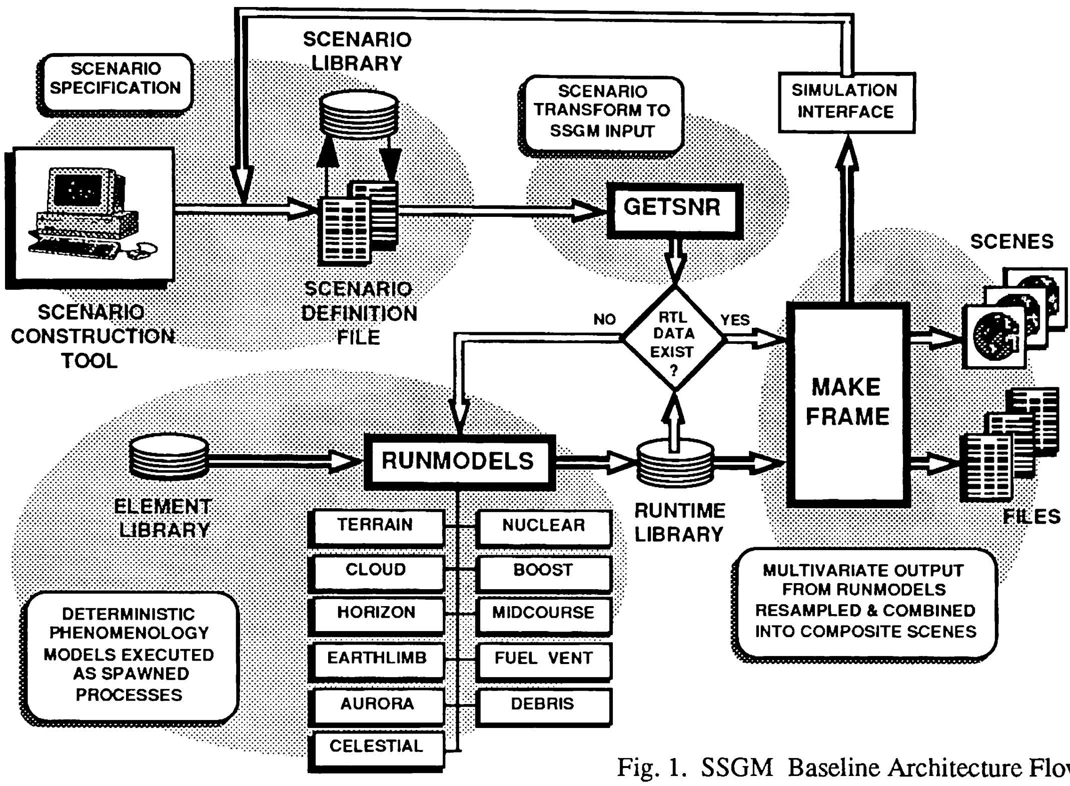

Fig. 1. SSGM Baseline Architecture Flow Diagram

3.1 Scenario Construction Tool

The SCT has been implemented on the family of Silicon Graphics workstations to enable the user to actually "build" a scenario interactively through the window menu interface. SCT functionality includes: invoking sensor and target trajectory computations, computing sensor-target background engagement geometries, displaying graphical sensor FOV representations and views from the perspective of any number of independent "meta-observers", and creating and updating the SSGM *Scenario Definition File* through menu selections and keyboard inputs. The SCT was designed to aid preparation and specification of the scenario parameters by means of dynamic 3D graphics and visual feedback — it provides a graphical way of editing the ASCII SSGM input file and for viewing the battle space.

3.2 GETSNR Module

The GETSNR module accepts all sensor, background, and target input specifications from the Scenario Definition File (generated either by the SCT or by a user-developed off-line process). GETSNR transforms this "script" into a format acceptable for input to subsequent SSGM processing and also invokes certain options pertaining to the SSGM Data Base Management System (DBMS).

3.3 RUNMODELS Module

The RUNMODELS module calculates all phenomenology data base files needed to generate the frames defined by the scenario definition file. This is achieved through on-line execution of one or more of eleven phenomenology software models. This is done only when the required data do not exist in the Runtime Library. Specifically, RUNMODELS transforms the scenario parameters into an input file for each relevant model code, spawns the code (or codes), and organizes their output into the Runtime Library. The phenomenology code output ranges from "image-like" data (*e.g.*, terrain and cloud backgrounds) to multivariate data (*e.g.*, variable-grid line-of-sight radiance versus altitude and aspect for missile plumes) which can be accessed quickly during the process of frame generation. The phenomenology code input files are pre-stored in the Element Library and contain such information as atmospheric chemistry data, material properties, bi-directional reflectivity functions, *etc.*

3.4 MAKEFRAME Module

The MAKEFRAME module converts the Runtime Library data base files into viewer-perspective two-dimensional images and point-source intensity data (for selected targets and stars) as given by the scenario parameters. This is achieved in basically three steps: image component generation, stochastic structure overlay, and image composite generation.

Image component generation computes images of each component phenomenology (*e.g.*, terrain, cloud, missile plume, and midcourse hardbody). These are completely deterministic and are most frequently computed through interpolation and sampling, but can also involve actual image generation for hardbody targets and for cloud backgrounds when illuminated by a "dynamic sun" (*i.e.*, nuclear fireball). This process also computes an image transmission mask for each phenomenology which attenuates phenomenology lying behind it (*i.e.*, at a larger distance from the sensor).

Gaseous phenomenologies (*e.g.*, earthlimb, aurora, nuclear events, and missile plumes) may have stochastic radiance components which are additive to their deterministic radiance structure. "Deterministic structure" refers to spatial variations in radiance which can be specifically computed from the physics models involved. "Stochastic structure" refers to irregularities in the target or background which cannot be predicted in a deterministic manner, but for which statistics can be generated. The mathematical and computational techniques used to generate stochastic representations of different types of structure are similar, regardless of whether the phenomenon is the ambient atmosphere, the auroral-disturbed atmosphere, or the nuclear-perturbed atmosphere. Thus, the SSGM uses a single structure generation submodule for all of these environments. The submodule creates a normalized (zero-mean, unit variance) Gaussian noise image with spatial correlation characterized according to a model-prescribed power spectral density function. The structured image is produced by combining the deterministic image with the product of the image variance and the normalized Gaussian noise.

The time-sequenced deterministically and/or stochastically computed radiance maps for individual scene elements are assembled into composite, full field-of-view images. Following MAKEFRAME, the composite scenes are stored as files in the Output Library where they can be analyzed and displayed. MAKEFRAME also generates metric and radiometric summary files and computes a report of radiance statistics for each output frame.

When a user's purpose is to generate input data bases for testing sensor or system models or for use in actual hardware simulations, certain features or events in a scene may trigger changes in the definition of subsequent frames. The SSGM contains a *Simulation Interface Module* which effects the event-driven feedback process when dealing with possible, but unpredictable, events. This module performs a scene diagnostic, in accordance with preassigned decision logic, to test whether subsequent scene generation must be altered. Typically, this feedback loop would only interface with MAKEFRAME, but could require RUNMODELS to create new Runtime Library data.

4 SSGM PHENOMENOLOGY

The phenomenology consists of quiescent and enhanced natural backgrounds and perturbed backgrounds with imbedded targets and target induced or related events. Endorsed and validated predictive models for these phenomena continue to be developed and refined by government agencies (PL, USASSDC, NRL, DNA, *etc.*) which are also responsible for code verification, validation, and configuration management. The NRL rehosts these standard codes, or output data bases generated off-line, within the SSGM architecture and verifies that the composite scenes are accurate renditions as specified by the input scenario. A major technical challenge is that the SSGM must simultaneously address configuration management issues relating to SSGM maintenance, augmentation, and traceability in an environment where the fundamental codes themselves are undergoing development. Furthermore, the SSGM project has the difficult task of integrating phenomenology codes, that differ in origin and level of sophistication, into a common architecture.

Table 1 lists codes which are currently incorporated in the SSGM or scheduled for on-line implementation. Some of these codes, specifically NORSE for nuclear effects and OSC for hardbody target signatures, are too large or computationally intensive to host within the SSGM. In these cases, the codes are run off-line to generate data bases which are stored in the Element Library and subsequently accessed by more manageable "engagement level" codes within the SSGM. Alternatively, submodules of the codes are incorporated to treat a specific image components.

The SSGM, in general, does not presume to model physical interaction between individual phenomenologies beyond that which is incorporated within the standard models themselves. Some limited interaction has been incorporated within the SSGM when believed to be a significant concern to known systems. Such is the case for low-altitude, early-time nuclear fireballs which illuminate clouds. Similarly, high-altitude nuclear detonations may effectively elevate earthlimb, auroral and plume radiances by modifying atmospheric density — a phenomenon known as nuclear heave. Hence, a "dynamic sun" capability has been included in MAKEFRAME to treat nuclear burst irradiation of cloud backgrounds. Also, the Earthlimb, Aurora and Plume modules have access to atmospheric state data (including chemistry) from the Nuclear module. Aerodynamic heating of the body of a boosting missile is another example of an "interactive phenomenon" currently treated in the SSGM Baseline.

For further information on SSGM phenomenology, the reader is referred to the paper by Heckathorn and Anding (1993) and the technical references and SSGM manuals cited therein.

5 SSGM BASELINE AND OPERATIONAL DEVELOPMENT

An evolutionary, multi-phase approach was taken for the SSGM development since interim capabilities were needed to meet changing BMD requirements. The computer architecture was designed to be fully responsive to long-term needs; however, the supporting data bases on targets and backgrounds address near-term requirements and are limited in the Baseline. The Phase I Prototype development tested this model architecture, several on-line software modules and representative data bases to create scene elements, the system to manage the various data bases and libraries, and the verification and validation methodology which is based on comparison with empirical data.

The Phase II SSGM Baseline retains Prototype functionality, but with somewhat modified architecture and significant additional capabilities required by the expanded SSGM user community. Anding (1991) discusses these requirements in the context of the Baseline development. Upgrades to the phenomenology codes and resulting software functionality for the seven Baseline software releases (R1.1, R2.1, R2.3, R3.1, R4.0, R5.0, and R5.1) are discussed by Heckathorn and Anding (1993).

The historical focus of SSGM development has been strategic surveillance and weapon delivery against the central Asian (formerly, Soviet) threat. Recent developments and the worldwide proliferation of ballistic missile systems required growth of SSGM capability to include the perceived threat emanating from the Third World. The general requirement is to expand the SSGM phenomenology code integration effort to include targets, backgrounds, and engagement scenarios appropriate for any number of likely global threats which might be confined to a region, or "theater" of operation. NRL incorporated many of the required enhancements in the final two releases of the SSGM Baseline.

The Phase III Operational SSGM has the same general requirements as the Baseline in that it must be operational, evolutionary, and state-of-science. It also has the same specific requirements as the Baseline in regard to internal design and structure, development process, and configuration management. The key differences are those related to the target, background and environmental phenomena it represents, the execution speed with which outputs can be generated (throughput optimization), and its interface to simulation test beds. In other words, the Operational SSGM will be a well defined expansion and enhancement to the Baseline, rather than a restructuring or modification. Existing phenomenology models and their databases shall be enhanced and expanded; new models shall be added as state-of-science codes become available; throughput shall be improved through a combination of the use of precomputed databases, hardware-implemented algorithms, parallel and distributed processing; and the SSGM shall be interfaced to simulation test beds, including hardware-in-the-loop test.

6 SSGM UTILIZATION

The SSGM is used for digital simulations, hardware demonstration and validation, system design and evaluation, tests of system performance predictions and development methodology, radiometric digital scene sets for focal plane illumination and stimulation, authentication of less detailed models, and extrapolations and interpolations for comparison with empirical data. It is used to perform sensitivity and trade-off analyses during research and development, and during the acquisition process. The SSGM project supports BMDO R&D technology demonstrations and measurements programs by furnishing valid pre-computed scenes and dynamic scene sequences for specific engagement scenarios and/or the software capability to generate these scenes. As of July 1993, the code is distributed to 83 organizations — government agencies and their contractors. Users include BMDO program elements and experiments, hardware-in-the-loop simulators, system simulators and emulators, and test data centers. A recent summary of the current SSGM user community and their applications is given by Heckathorn and Anding (1993).

Potential users involved in ballistic missile defense activities (be it strategic or theater) should contact one of the authors for information on how to obtain current SSGM products. The code and associated data bases are distributed on CD-ROM and are delivered complete with documentation. The SSGM runs on SGI workstations to permit user interaction and visualization of input geometries and visual inspection of computational output. New users are encouraged to participate in a two day training class which offers instruction on SSGM capabilities, current limitations and hands-on experience on a computer workstation. An active SSGM Users Group has been formed to serve as a forum to discuss user requirements and suggested improvements and to introduce and demonstrate new SSGM releases to the community.

7 SUMMARY AND CONCLUSIONS

The SSGM is a computerized methodology founded on state-of-science knowledge, empirical data bases, and phenomenological models to generate LOS radiometrics, 2D radiance maps, time-sequenced scenes, and observable data bases for BMD applications. SSGM requirements include BMD-relevant treatments for (1) targets, target-related events, natural and nuclear backgrounds (phenomenology); (2) vehicle types and trajectory phases (scenarios); (3) sensor-target-background locations and time-history sequences (geometries); and (4) spatial, temporal, and spectral samplings (dimensions). The SSGM is a physics-based computer aided design tool for BMDO system engineering applications.

The two primary near-term tasks of the SSGM project are the evolutionary development of the Operational SSGM and support for BMDO R&D program elements and studies by furnishing pre-computed scenes and dynamic scene sequences for specific engagement scenarios and/or the software capability to generate scenes. The scenes are physically valid and serve as a standard for testing different BMD concepts and designs. Basically software in nature, the technical challenges include (1) integration of phenomenology codes which differ in origin and purpose; (2) verification and validation of SSGM methodology and multi-phenomenology output scenes; (3) the computational burden for creating and resampling image and other multi-dimensional data bases in real time; and (4) requirements for event-driven scenarios, interaction of scene elements, and active illumination.

The SSGM is accepted by BMDO as a *de facto* standard for system evaluation. This is because: the SSGM uses the DoD's accepted models for scene elements, thus producing the best overall representation of given scenarios; the recognition of the importance of accurate systems simulations in the overall process of designing and evaluating complex BMDO systems; and the need to establish standards in the highly competitive R&D community where rival claims are difficult to evaluate. Furthermore, built into the SSGM program has been a deliberate effort to bring the product to the user. The SSGM program distributes the code, provides training, responds to reports of trouble or requests for new capabilities, and provides services to projects in the form of calculated project-specific scenes.

The NRL is using the experience gained in developing the SSGM to support a new initiative called Environmental Effects for Distributed Interactive Simulations (E^2DIS) that is sponsored by the Defense Modeling and Simulation Office (DMSO).

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AUTHOR BIOGRAPHIES

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