LLNL-TR-635108

2013 R&D 100 Awards Entry Form

Lawrence Livermore National Laboratory

Testbed Environment for Space Situational Awareness

The world's most accurate simulation of space debris and orbital object tracking

Figure 1: Images generated by the TESSA visualization system that highlight some of the novel capabilities: A) high-accuracy orbital dynamics, B) maneuvering satellite path prediction, C) simulation of radar and telescope observations, D) close-approach and collision analysis of orbital object, E) computation of possible locations of maneuvering satellites, and F) high-fidelity debris generation and orbital debris cloud estimation.

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Auspices Statement
This work performed under the auspices of the U. S. Department of Energy (DOE) by LLNL under Contract DE-AC52-07NA27344.

1. ORGANIZATION CONTACT INFORMATION

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Indicate relationship to product being submitted:
__ Public Relations or Marketing Agency
X Product Developer
__ Other (explain) _____

B. Developer Organization Information

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What role did this organization play in development of technology?
X Principal developer organization (All or majority of development responsibility)
__ Co-developer organization (Equal share of development responsibility with other organizations)
__ Supporting developer organization (Contributed less than 50% of development responsibility)

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C. Principal/primary investigator, developer, inventor, or team leader
List the individual(s) who are designated as principal/primary investigator, developer, inventor, or team leader for this entry. These individuals will receive special recognition if the entry wins. Copy the template to add additional individuals. List all team members in Appendix A.

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2. PRODUCT INFORMATION

A. Product brand name
Testbed Environment for Space Situational Awareness (TESSA)

B. Generic description of product
Software for the simulation of orbital objects (satellites and space debris), the generation of space debris, and the sensors used for observing and tracking those objects.

C. Product photo
See Figure 2.

D. Product Video
We have provided two videos of TESSA. The first may be found at:
http://www.youtube.com/watch?v=u0NEnPOx6ic
This video demonstrates a TESSA simulation of the 2009 Cosmos/Iridium satellite collision. The video showcases a number of TESSA features including visualization, debris generation, radar and telescope simulation, and close-approach analysis. This video has no sound.

The second video is a recording of a news segment describing TESSA that appeared on the San Francisco Bay Area's ABC affiliate KGO. It may be found at:
http://www.youtube.com/watch?v=W3pJYgo3uo4

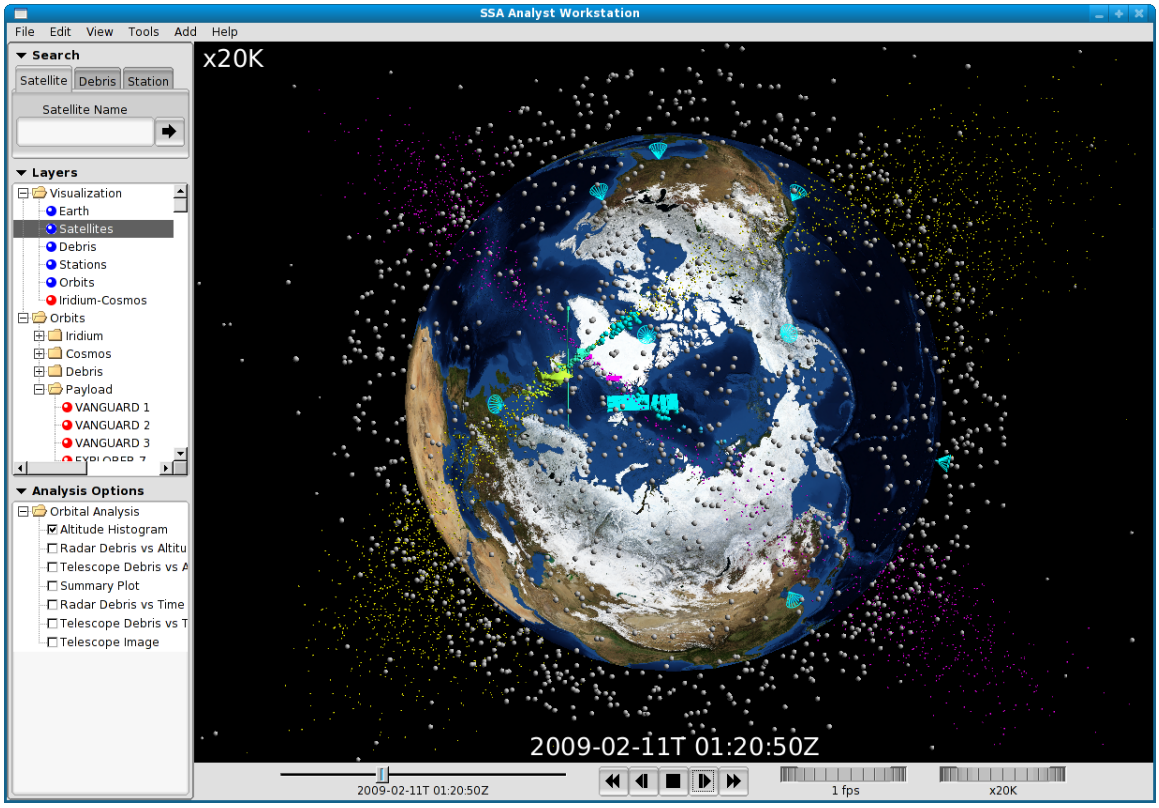

Figure 2: Screen shot of TESSA showing debris from an orbital collision.

3. EXECUTIVE SUMMARY

The Testbed Environment for Space Situational Awareness (TESSA) is a modeling and simulation environment designed for efficient exploration of scenarios involving satellites and space debris and their detection by both ground and space-based radars and optical sensors. TESSA is a Parallelized Discrete Event Simulator [1] optimized for deployment on a large cluster of high-performance computers running Linux. TESSA includes capabilities for predicting the future location of a satellite using the satellite's current location and velocity, determining an object's orbit from sensor data, finding new orbital objects, predicting close approaches, determining the probability of collisions, modeling radar and optical and dynamic sensors, and modeling the generation of debris. TESSA also includes a scalable visualization environment implemented as a post-processor on workstation-class platforms.

4. INTRODUCTION DATE

TESSA was available for licensing in 2012, and continues to be available. The TESSA advertisement may be seen on the LLNL Industrial Partnerships Office webpage: https://ipo.llnl.gov/?q=technologies-tessa. TESSA became fully operational in September 2012. (See Figure 3.)

5. PREVIOUS R&D 100 ENTRY

Lawrence Livermore National Laboratory

March 14, 2013

To Whom It May Concern

Development of the Testbed Environment for Space Situational Awareness (TESSA) at Lawrence Livermore National Laboratory was completed on September 30, 2012 with the culmination of the three-year Laboratory Directed Research and Development Strategic Initiative on "Real-time Space Situational Awareness".

Sincerely,

Scot S. Olivier
Deputy Program Director for Science
Lawrence Livermore National Laboratory

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To Whom It May Concern:

The TESSA project, funded under the Laboratory Directed Research and Development program at Lawrence Livermore National Laboratory, completed on 09/30/2012. This project, tracking code 12-SI-007, met its proposed deliverables.

William Craig
Director, Laboratory Directed Research and Development
Lawrence Livermore National Laboratory

Figure 4: Documentation that TESSA was completed in September 2012.

No

6. PRICE

TESSA has been advertised as a Federal Business Opportunity (FBO). The price is determined by the licensee.

7. PATENTS

U.S. Patent Application No. **13/488,377,** *Internal Parallelism in a Parallel Discrete Event Simulation for Space Situational Awareness*, filed June 4, 2012.

8. PRODUCT DESCRIPTION (Limit: 1,000 words)

8A. What does it do?

TESSA is a parallelized scalar simulation environment designed to simulate the Space Surveillance Network (SSN), the worldwide network of radar and telescope sensors, computers, and databases involved in discovering, observing, and tracking objects in orbit. TESSA models the SSN sensors and computers as well as the tens of thousands of objects that are in orbit, their reflective properties, and their orbital motions.

TESSA works by linking modules simulating individual pieces of the SSN, such as telescopes and computers, with a parallel discrete events simulation (PDES). TESSA is designed to run on standard x86 Linux cluster machines. The simulation framework has been tested up to tens of thousands of processors, although production TESSA runs have not required more than 500.

8B. Describe the principal application of this product.

TESSA's primary application is mitigating the effects of space debris, a serious societal issue. Much of the information in our highly connected world finds its way through communication satellites, and satellites are also integral to both scientific and defense research. The rapid multiplication of space debris over the past 50 years threatens to make continued satellite use and space exploration nearly impossible. At some point the

large number of uncontrolled objects in orbit will enter a collision cascade where objects will regularly collide, generating more debris and causing more collisions. This is popularly referred to as “The Kessler syndrome.” [10]

The primary concern with space debris is that it may collide with—and damage or destroy—valuable satellites. TESSA seeks to mitigate orbital collisions, and therefore space debris, by demonstrating methods to improve the accuracy of our orbital knowledge. The SSN may then implement those methods to increase the accuracy of collision warnings and allow valuable space assets to avoid collisions.

The weakness of the current state-of-the-art orbital knowledge was dramatically demonstrated by the 2009 collision of the privately owned Iridium 33 and defunct Russian Kosmos-2251 satellites. The information available does not seem to have even been sufficient to predict the collision, as Iridium claims to have not received a collision warning. However, even if a warning is issued, the false-positive rate is cripplingly high. Iridium claims to ignore all collision warnings due to over-reporting, as they receive up to 400 close-approach warnings per week for the Iridium constellation. Furthermore, those warnings lack the information required to avoid the possibility of collision.

The key issue is data accuracy. The information available on the position of each object in orbit is insufficient to predict if a collision will occur, how to avoid it, and what debris will result from the collision. TESSA seeks to improve this situation by detailed simulation of the SSN and the events and objects it observes in orbit. In addition, TESSA models the tens of thousands of objects that are in orbit, their reflective properties, and their orbital motions. No other tool provides this level of integration. No other tool can simulate tens of thousands of orbital objects, their observation by ground and space-based radars and telescopes, the determination of their orbit, if they may collide, and the result of such a collision.

TESSA includes all capabilities the SSN should have, including the ability to predict the future location of a satellite (orbital propagation), determining a satellite’s orbit from observation (orbit determination), discovery of new objects (uncorrelated track processing), sensor modeling, dynamic sensor tasking, and modeling of debris generation. TESSA also includes a scalable visualization environment for visualizing the result of a simulation.

TESSA simulates how the SSN would perform with new sensors in new configurations, new processing algorithms, and new CONOPS (concept of operations). Unlike most sensor simulators, TESSA’s sensor modules do not rely on statistical or empirical models; they simulate the physics of the sensor. They can therefore accurately simulate nearly any new kind of radar or telescope just by setting a few physical parameters in the configuration file. This capability has been used to simulate new sensors such as binocular telescopes, space-based orbiting telescopes, and a proposed new “space-fence” radar system [2]. TESSA has also been used to demonstrate new experimental

algorithms, including a high-performance module for detecting close approaches between orbiting objects, a method to calculate the possibility of collision, and a method to quickly locate a maneuvering satellite.

8C. How will this product benefit the market that it serves?
TESSA is the only tool in existence that can fully simulate the SSN, including all objects in orbit, all relevant sensors, and all the computers used to correlate and simulate the sensor-acquired data. TESSA provides the ability to accurately simulate additions to the SSN without the costs associated with actually deploying them. TESSA has demonstrated that it can be used to quickly and cheaply evaluate new space technologies.

TESSA has already inspired a new project to research the use of a constellation of cheap mini-satellites that can track orbital debris much more accurately than ground-based optics. The full implementation of that project is estimated to cost $30 million, whereas some competing technology estimates range up to the billions of dollars. If such a project can successfully reduce the number of in-orbit collisions, TESSA may help save billions of dollars in satellites, as well as improve manned mission flight safety.

8D. List all other applications for which your product can now be used.
TESSA has a number of other applications beyond simply improving the SSN. These potential applications include:

- Enhancing space operators' understanding of space events and potential impacts of these events on space assets
- Simplifying the design of satellites and satellite constellations
- Selecting orbits
- Predicting satellite communications issues
- Predicting mission efficacy
- Simulating long-term collision effects, such as the Kessler syndrome.

9. TECHNOLOGY DESCRIPTION (Limit: 1,000 words)

9A. How does the product or technology operate?
TESSA blends a parallel discrete events simulator (PDES) and multiple continuous time-stepped simulators running on massively parallel supercomputers. TESSA's scalable, conservative PDES allows parallel computation inside events using the Message Passing Interface (MPI). This allows complex physics, such as radar pulses and realistic telescope image construction, to happen modularly so as not to affect the other processes of the simulation. Orbit propagation and determination algorithms can run in parallel, permitting the simulation of hundreds of thousands of objects in orbit.

9B. What scientific theories, if any, are involved?

Each TESSA module simulates a different portion of the SSN, and every module simulates some physical phenomena. Each module is described, with its scientific basis, in section 9C.

9C. What are the building blocks of your technology?
TESSA comprises a set of simulation modules running within a PDES.

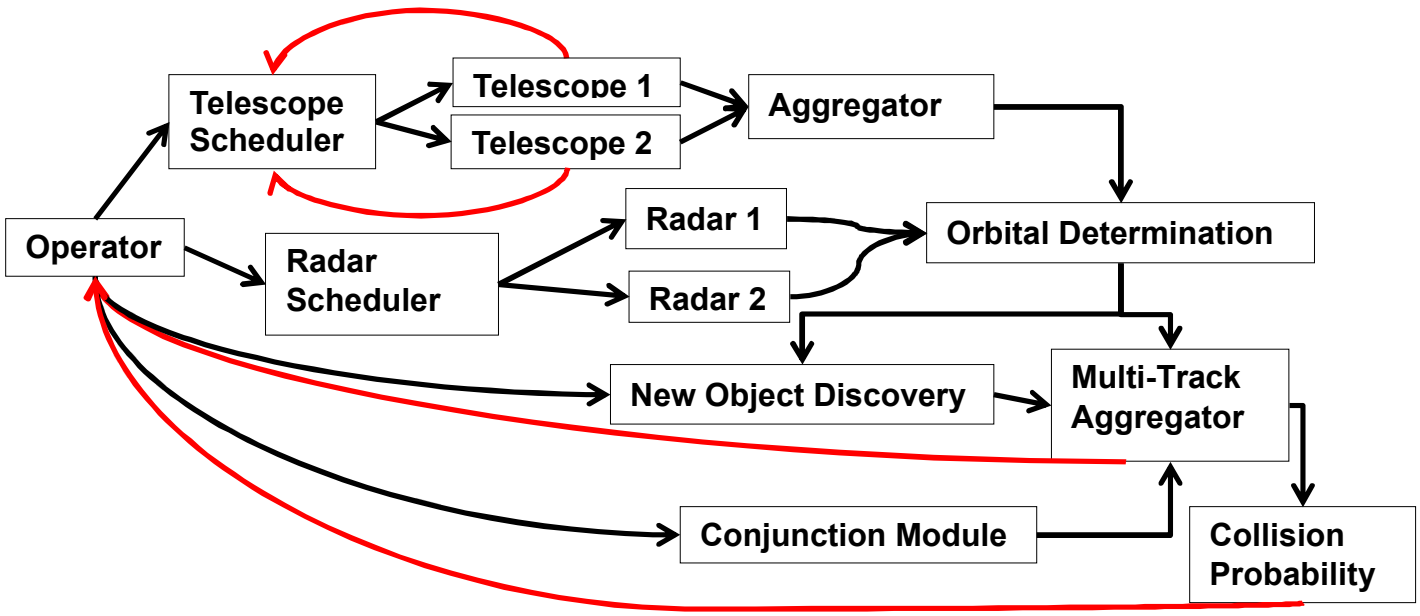

Figure 4: An example of a possible TESSA configuration. This configuration is used for discovering new objects and determining their orbits.

TESSA's PDES allows each simulation module to be parallelized internally with the MPI, taking advantage of the best features of two, very distinct, branches of simulation. TESSA can handle arbitrarily changing time scales, seven orders of magnitude is standard in a TESSA simulation, and can skip large amounts of simulation time when nothing is happening. However, within modules we use physically accurate time-stepped algorithms.

Orbital Dynamics Modules
The central feature of any space simulator is propagation of the paths of objects in orbit (orbit propagation). An orbiting object remains in its orbit if other forces do not work on it. However, there are unpredictable forces that modify orbits, such as atmospheric drag, which depends upon space weather (e.g. solar radiation). The SSN uses sensors to correct the errors that creep into the known orbit data (orbit refinement) [8]. The SSN must also discover the orbits of new satellites and new debris (orbit determination).

TESSA contains two orbit propagators: SGP4 and the force model propagator. SGP4 is used by the U.S. Space Command; it is fast, but less accurate. The force model propagator attempts to take as many forces into account as possible to generate the

most accurate possible orbit. The user may choose from different gravity models and atmospheric models.

TESSA's covariance-based track association (CBTA) module provides orbit determination features. The CBTA module can simultaneously determine the orbits of thousands of new objects, as well as refining the orbits of all known objects [9]. TESSA has successfully simulated the proposed new "space-fence" radar with 2,000 new objects generating 15,000 orbital tracks.

Conjunction Analysis and Collision Probability

The SSN must predict when any orbital object will come close to a valuable satellite (conjunction analysis). The U.S. Space Command's current conjunction analysis tool takes hours to determine if any space debris is approaching any of about 400 valuable satellites. TESSA's parallelized algorithm can do this calculation in less than a minute. TESSA also has a dedicated "collision probability" module that uses the orbit accuracy and satellite size and shape to determine how likely two objects are to collide. [11]

Telescopes

TESSA contains the world's first fully accurate simulation of telescopic observation of orbiting objects [4]. TESSA's telescope module generates an accurate telescope image (from both ground-based and orbiting space–based detectors) and extracts the streaks generated by passing satellites from it. The module simulates light along its full path, from the orbital object, through the optics, finally generating the image from the light that reaches the detector. Each step along this path adds noise and other light sources, such as stars. Typically first-principle telescope simulations are too slow to be practical; TESSA solves this problem by dividing the image into pieces, with each processor responsible for a different piece.

Radars

The radar module in TESSA uses physics-based radar simulators suited to studying both the expected behavior of existing radars and proposed radar designs. Typically physics-based radar simulations are too slow to be practical; TESSA solves this by parallelizing the model on a pulse-by-pulse basis, with each processor responsible for a single pulse. Highly accurate models have been included for most aspects of radar (Figures 5 and 6).

Environment

Atmosphere Model
- weather effects
- US Standard Atmo
- exponential atmo

Pulse Propagation
- MWM model
- radiative transfer
- attenuation, dispersion
- refraction effects
- ray tracing, analytical approximations
- static & turbulent atmo models

Environmental Noise
- solar, galactic
- RF Interference
- ground, man-made

Antenna

Antenna Types
- phased array (linear, planar)
- dish
- element models
- monopulse

Antenna Parameters
- phase shifter error
- gain, pattern
- polarization, efficiency

Antenna Noise
- atmospheric, ground

Antenna Structure
- IMU, GPS units

Figure 5: The individual modules that make up the radar physics simulation.

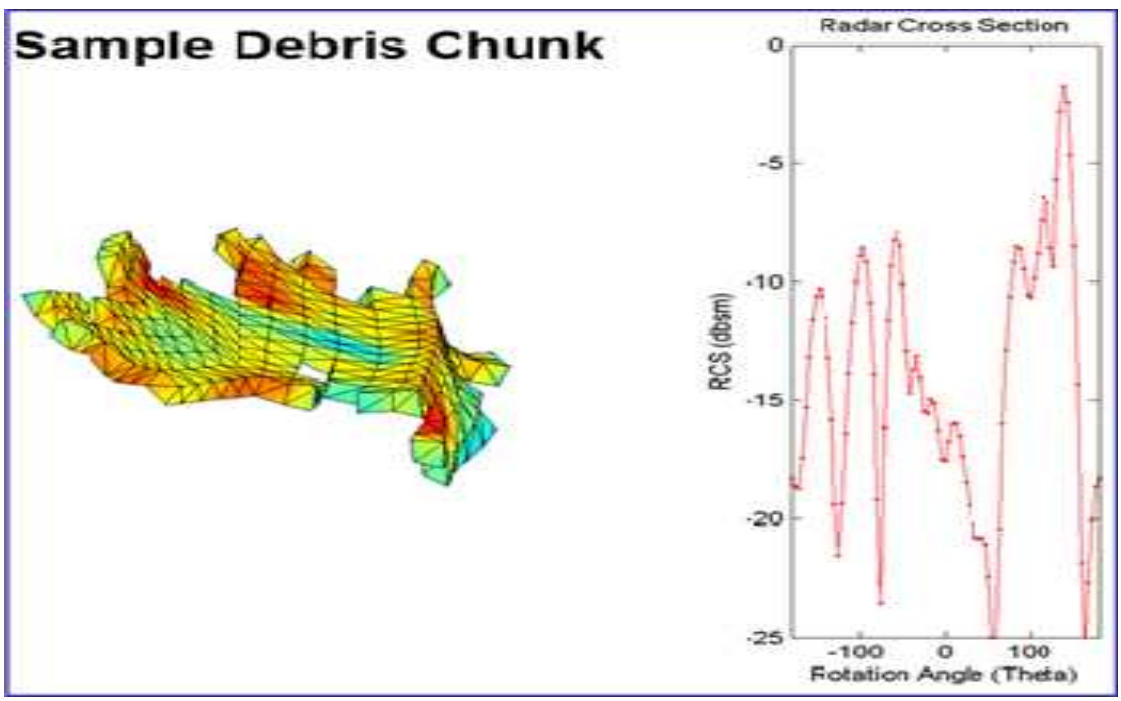

Figure 6: Sample debris chunk with radar cross-section simulation as a function of debris rotation.

Debris Generation

We have developed two approaches for debris prediction [3]. The first simulates the collision using a hydrocode with special physics packages developed to predict the fragments that result from a hypervelocity collision (see Figure 7). This operation takes

too long to be embedded in TESSA, but can be used when high accuracy is required. Second, we used the results of the high-fidelity model to develop a statistical model that makes predictions based on a few key collision parameters.

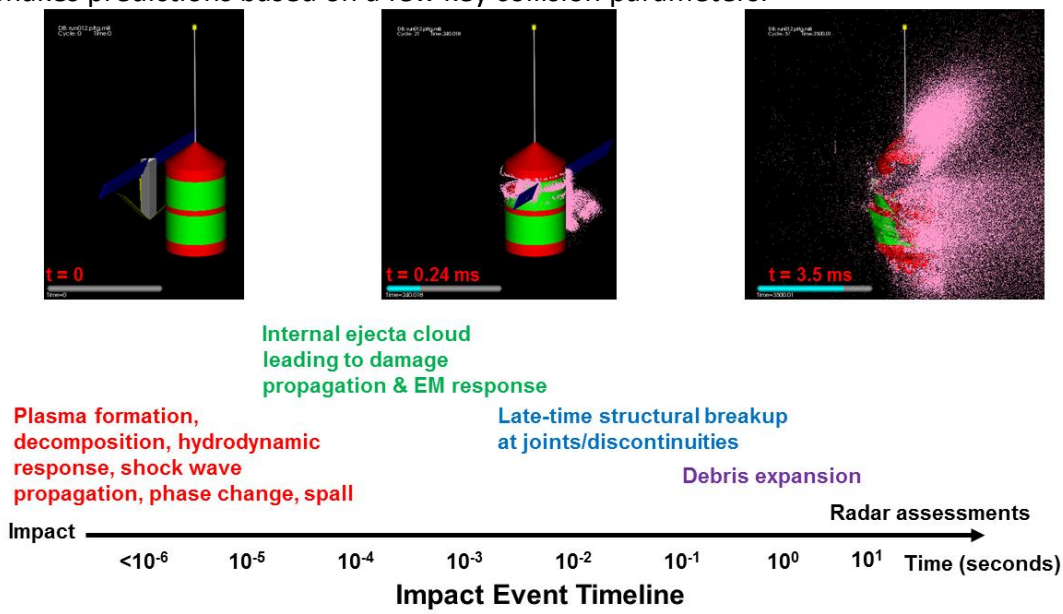

Figure 7: The phenomena and physics of satellite collisions.

Reachable Volume

If a satellite maneuvers, its orbit changes and it quickly moves away from its initial trajectory. Finding that satellite and determining its new orbit becomes a serious challenge. The set of all possible locations within reach of such a maneuver is known as the Reachable Volume (RV). TESSA's RV module is the only available simulator that can determine the limits of the RV, informing the SSN of where to search to quickly find the satellite's new location and orbit [6]. The module uses a Monte Carlo approach to compute the possible new orbits for the satellite (see Figures 8 and 9).

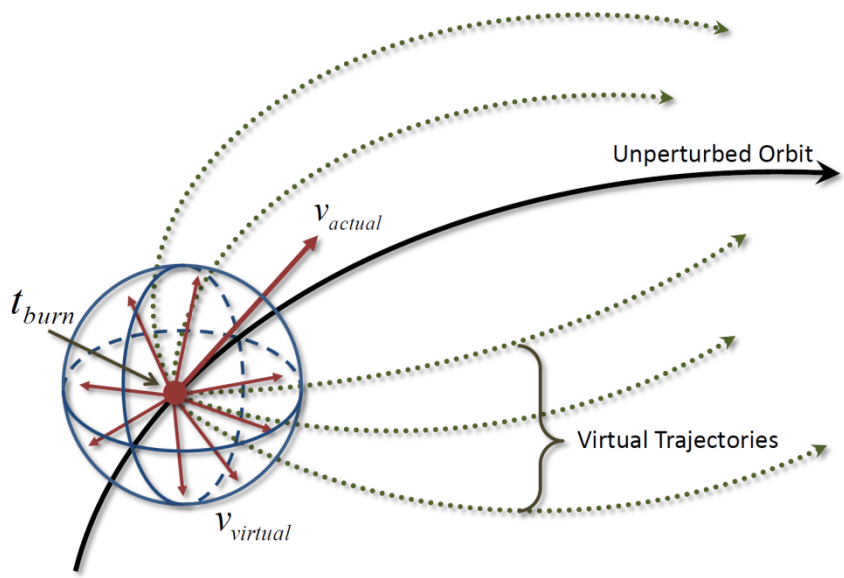

Figure 8: Monte Carlo approach to computing the virtual trajectories for the RV of a given object and its unperturbed orbit.

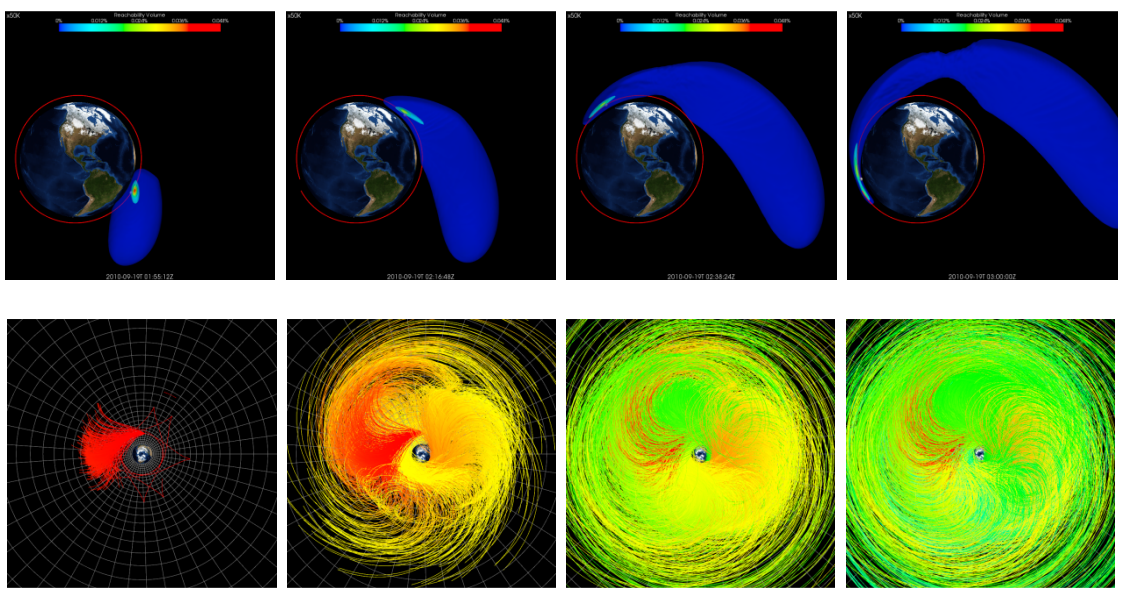

Figure 9: Top row shows how the possible locations of the maneuvering satellite change over time. Bottom row shows the results from rendering the new orbits.

Visualization

Visualization is crucial to orbital analysis, but the improvement in computer simulations and the increase in space debris produce a torrent of data that easily overwhelms traditional visualization tools. We developed a scalable visualization system that keeps only the data necessary for the algorithms in main memory while keeping as much data

as possible on larger storage systems (e.g. disk) [7]. Our visualization tool interactively renders millions of orbits and particles on a standard desktop system (see Figure 10).

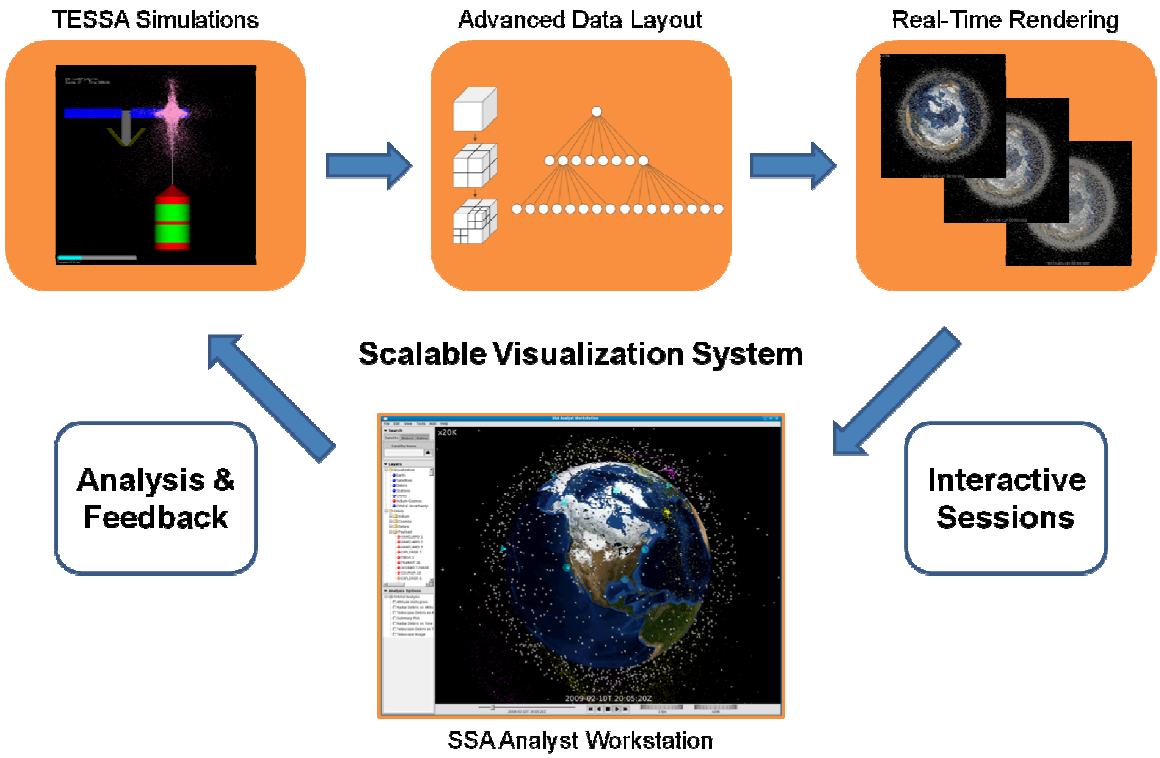

Figure 10: Diagram illustrating the data flow and components for the TESSA scalable visualization system.

10. PRODUCT COMPARISON

10A. List your product's competitors by manufacturer, brand name, and model number.

TESSA has no competitors that attempt to simulate the entire SSN from end-to-end. While there are many tools that may compete with individual simulation modules in TESSA, they are too numerous to list here, and do not constitute real competition for TESSA. Here we only list competitors that contain multiple TESSA-like features.

The closest competitor for TESSA is Analytical Graphics Inc.'s (AGI) Satellite ToolKit (STK) combined with its optional Orbit Determination Toolkit (ODTK) add-on. STK/ODTK contains many TESSA-like features, including orbit propagation, determination, and refinement; sensor models; conjunction analysis; and visualization. STK/ODTK does not include reachable volume or physics-based sensor simulators. However, the primary difference is that STK/OTDK is not massively parallel, and therefore can only simulate a limited number of orbits. Where TESSA can simulate and visualize tens of thousands of orbiting objects, STK/ODTK begins to slow down at around 50 objects.

Orbital Dynamics
Other notable competitors for orbit propagation include A.I. Solutions' FreeFlyer and NASA's General Mission Analysis Toolkit (GMAT). These tools, however, lack the key ability to discover the orbit of a new object from sensor data. FreeFlyer has the ability to refine an orbit based on sensor data. Like STK, all the listed tools run on desktops, not supercomputers, and so they are strictly limited in how many objects they are able to simultaneously propagate or correlate.

Telescope Competitors
The main competitor for the optical sensor simulations is the AGI's STK, with its Electro-Optical/Infrared (EOIR) module. While also physics-based, EOIR does not model the Point Spread Function at the same level of detail as TESSA. In addition, the stellar background in EOIR is based on the Hipparcos/Tycho catalogs (i.e., relatively bright stars), which makes it unsuitable for modeling the images from large-aperture telescopes, e.g., PanSTARRS or Large Synoptic Survey Telescope (LSST). TESSA uses the more complete USNO-B star catalog.

Radar Competitors
Competitors for the radar models vary in their applicability to space situational awareness. There are in-house radar-specific models for the SSN radars, but these are proprietary and likely unsuitable for combining in a system-level simulation. For some aspects of the radar simulation, there are a large number of competitors, but they focus on only one aspect of radar simulation. For instance, there are a number of radar cross-section modeling codes available, including XPatch, FEKO, and others. However, no other radar simulation contains all the modules necessary for a physics-based, end-to-end radar simulation capable of running the entire variety of SSA sensors.

Debris Generation Model Competitors
Competitor models for debris generation are based on remote sensing of real orbital debris generation events (e.g., the NASA Standard Satellite Breakup Model in EVOLVE 4.0). However, remote sensors often fail to detect debris less than 10 centimeters in size, which can still be harmful to satellites, and numerous assumptions are required to transform remote sensor observables into debris mass distributions. Furthermore, competitor models do not account for critical collision details, such as the orientation of larger orbital objects during the collision or the impact location on the object. In contrast, TESSA's physics-based modeling approach accounts for the orbital object geometry and materials, as well as the object orientation and impact location during collision. Full orbits are provided for each piece of debris generated from the collision.

Conjunction Analysis

AGI provides two ways to obtain conjunction assessments. AGI's SOCRATES (Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space) is an on-line subscription service. It updates a twice-daily analysis of the probability of satellite collisions based on publicly available data. Users therefore cannot get updates on demand or use proprietary data.
The STK Conjunction Analysis Tool (CAT) also provides conjunction analysis. However, because CAT is not heavily parallelized, it cannot handle the large space debris populations TESSA does.

Collision Probability

AGI's STK Conjunction Analysis Tool (CAT) is the only other tool available for calculating collision probabilities using the covariance matrices and the satellite shapes and attitudes. Other comparable tools assume both a spherical collision cross-section and a spherical uncertainty envelope. The TESSA's Collision Probability module differs from the ATK's CAT by using a novel Monte-Carlo based approach that has been specifically designed for massively parallel computers.

10B. Competitive Matrix

	Competing Technologies				
Criteria	**TESSA**	**STK/ODTK**	**FreeFlyer**	**GMAT**	**EVOLVE**
SGP4 Orbit Propagation	Yes	Yes	No	No	No
Force Model Orbit Propagation	Yes	Yes	Yes	Yes	Yes
Initial Orbit Determination	Yes	Yes	No	Yes	No
Orbit Refinement	Yes	Yes	Yes	No	No
Multi-Track Aggregations	Yes	No	No	No	No
Telescope Simulation	Yes	Yes	Yes	No	No
Telescope Image Generation	Yes	Yes	No	No	No
Radar Simulation	Yes	No	Yes	No	No
Physics-Based Radar Simulation [a]	Yes	No	No	No	No
Massively Parallel	Yes	No	No	No	No

Computation					
Conjunction Analysis	Yes	Yes	Yes	No	Yes
Collision Probability Analysis	Yes	No	No	No	Yes
Reachable Volume	Yes	No	No	No	No
Debris Generation	Yes	No	No	No	Yes
Physics-Based Debris Generation Model	Yes	No	No	No	No
Visualization	Yes	Yes	Yes	Yes	No
Visualize >10000 objects	Yes	No	No	No	No

[a] First-principles physics-based radar simulation, as opposed to the more common device-specific empirical simulation.

10C. TESSA improves upon its competitors

TESSA improves upon its competition in two major areas:

1. TESSA simulates the entire SSN, end-to-end, with actual physical simulations. The end-to-end simulation helps predict how multiple sensors can interact and synergistically cooperate. The physics-based simulation of the sensors allows much greater fidelity in the predictions of how notional sensors actually behave.
2. TESSA is a massively parallel scalable simulation that leverages modern supercomputer technology. This design allows TESSA to simulate everything in orbit and all the necessary sensors in a reasonable amount of time. No other orbital simulator even attempts to scale like TESSA does.

10D. TESSA's drawbacks

Although TESSA provides considerable capabilities for modeling space situational awareness problems, the principal drawback of the environment is that computer science expertise is needed to configure any new TESSA simulation. Most of the setup for a TESSA simulation is done by editing an XML setup file. The addition or subtraction of simple features, like sensors, is trivial, but rewiring the information flow from sensors to processors requires some understanding of discrete event simulation principals in order to avoid "deadlock" situations. ("Deadlock" is a condition in which the simulation hangs because at least two simulation nodes are waiting for input from each other before they may proceed. Since they depend on each other, neither may ever proceed, so the simulation cannot proceed.) TESSA does not have a way to detect if these situations may arise in a given simulation before running it, although it is not difficult for a trained user to anticipate and avoid them.

TESSA requires a supercomputer software stack to run. TESSA may be run profitably on a desktop if a low number of orbital objects are simulated, and low-fidelity sensor physics are used. However, that desktop would have to have compatible versions of Linux, MPI, and SLURM (Simple Linux Utility for Resource Management) installed. All the required software is free and open-source, but it is not standard desktop software.

TESSA features indirect coupling of simulation and visualization. Simulation is done on a supercomputer and the results are committed to data files. Visualization is achieved by post-processing of the simulation results on a Windows or Linux workstation. This obviously precludes any interactive changes to the simulation. Generally a whole new simulation must be run even for minor changes.

11. SUMMARY (Limit: 500 words)

Space debris is a serious issue that threatens our information-based economy, scientific research, space exploration, and intelligence assets. Even a small screw can disable a multi-billion-dollar satellite if they collide at orbital speeds. The primary problem with mitigating space debris is lack of knowledge. We do not have accurate enough knowledge about most orbital objects to conclusively determine if they could collide, or what the result of such a collision would be. Furthermore, any collision will result in a new field of debris, which may lead to further collisions and additional danger to valuable space assets.

TESSA is the only tool that can fully simulate the Space Surveillance Network (SSN), including all objects in orbit, all relevant sensors, and all the computers used to correlate and simulate the sensor-acquired data. TESSA's great value is that it provides the ability to deal with the space debris problem now, with today's technology. There are a number of radical ideas to deal with space debris, including ground-based lasers and sweeper satellites, but these ideas are expensive and usually based on unproven or speculative technology. TESSA gives us ideas for dealing with space debris that can be implemented cheaply now, as well as the ability to accurately simulate those solutions without the costs associated with actually deploying them. Therefore, TESSA's potential impact is in the billions of dollars.

TESSA has already demonstrated multiple new algorithms for space situational awareness, including TESSA's high-performance conjunction analysis module, reachable volume module, and debris generation module. TESSA has also spawned a new project to research the use of a constellation of cheap mini-satellites to track orbital objects. The full implementation of that project is estimated to cost $30 million, whereas competing technology estimates range in the billions of dollars.

TESSA also inspired a new project to research the Kessler syndrome in depth over 100 years. Using techniques learned during the development of TESSA, its developers

combined a new extremely fast Simplified Analytic Propagator and NASA's space debris generation simulation (the Satellite Debris Model from EVOLVE 4.0) to create a new simulator to study the Kessler syndrome.

Some of the TESSA models have also been converted to integrate with the Air Force's Center for Space Situational Awareness for training and for research on anomalous space events. In the future, we hope to give the Air Force operators push-button access to the full power of TESSA simulations running on remote supercomputers.

12. AFFIRMATION

By submitting this entry to *R&D Magazine* you affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product. You affirm that you have read the instructions and entry notes and agree to the rules specified in those sections.

APPENDIX A: DEVELOPMENT TEAM INFORMATION

List all developers from all organizations:

Team Member Name:	James Leek
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APPENDIX B: MAREKTING AND MEDIA INFORMATION

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APPENDIX C: GLOSSARY

Discrete Events Simulation (DES): DES is a simulation paradigm appropriate for systems dominated by discontinuous state changes at times that must be calculated dynamically. It is used primarily for complex man-made systems like telecommunications, vehicular traffic, computer networks, economic models, etc. It is much less well known than simple time-stepped simulation methods, but has the great advantage of being time scale independent, so that one can freely mix processes that operate at time scales over many orders of magnitude with no runtime performance penalty.

Orbit Determination: Using data collected from observing a satellite to determine its orbit.

Orbit Propagation: Using a satellite's known orbit to determine the location of the satellite at a future or past time.

Orbit Refinement: Using data collected from observing a satellite to improve the accuracy its orbit.

Parallel Discrete Events Simulation (PDES): A Discrete Events Simulation where the object may run on different processors and there is no global simulation time. In a Serial Discrete Events Simulation events occur strictly in time order, while in a PDES every event on a given object happens in time order, but different objects may have different simulation times. This usually allows the simulation to run much faster, but also greatly complicates the simulator.

Point Spread Function (PSF): The response of an imaging system (e.g., telescope) to a point source. The PSF describes the fuzzy blob seen in objects that are not (or cannot be) properly resolved.

Time-Stepped Simulation: Most scientific simulations are designed to be *time-stepped*, so that the outer loop of the algorithm consists of (1) stepping simulation time forward by a constant delta, (2) updating the state of all parts of the model accordingly, and (3) repeating until completion.

APPENDIX D: REFERENCES

1. D. Jefferson and J. Leek, "Application of parallel discrete event simulation to the Space Surveillance Network," in *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference*, S. Ryan, ed. (Maui Economic Development Board, 2010), p. E34.
2. M. Horsley and B. Fasenfest, "A Parallel, High-Fidelity Radar Model," in *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference*, S. Ryan, ed. (Maui Economic Development Board, 2010), p. E33.
3. H. K. Springer**,** W. O. Miller, J. L. Levatin, A. J. Pertica, and S. S. Olivier, "Satellite collision modeling with physics-based hydrocodes: debris generation predictions of the iridium-cosmos collision event and other impact events," in *Proceedings of the 11th Annual Advance Maui Optical and Space Surveillance Technologies Conference*, Wailea, HI, 2010.
4. S. Nikolaev, "Optical modeling in Testbed Environment for Space Situational Awareness (TESSA)," *Applied Optics*, Vol. 50, Issue 22, pp. D21-D26 (2011).
5. S. Olivier, K. Cook, B. Fasenfest, D. Jefferson, M. Jiang, J. Leek, J. Levatin, S. Nikolaev, A. Pertica, D. Phillion, H. Springer, and W. de Vries, "High-Performance Computer Modeling of the Cosmos-Iridium Collision," in *Proceedings of Advanced Maui Optical and Space Surveillance Technologies Conference*, pp. 720–731, 2009.

6. M. Jiang, W. de Vries, A. Pertica, and S. Olivier, “Computing and Visualizing Reachable Volumes for Maneuvering Satellites,” in *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference*, 2011.
7. M. Jiang, M. Andereck, A. Pertica, and S. Olivier, “A Scalable Visualization System for Improving Space Situational Awareness,” in *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference*, pp. 603–612, 2010.
8. John R. Henderson, Sergei Nikolaev, Donald W. Phillion, Willem H. De Vries, Alexander J. Pertica, and Scot S. Olivier, “Intelligent sensor tasking for space collision mitigation,” published in *Proceedings Volume 7691: Space Missions and Technologies*, April 2010.
9. Don Phillion, Alex Pertica, Ben Fasenfest, Matt Horsley, Wim De Vries, H. Keo Springer, David Jefferson, and Scot Olivier (Lawrence Livermore National Laboratory), Keric Hill (Pacific Defense Solutions), and Chris Sabol (Air Force Maui Optical and Supercomputing Center), “Large-Scale Simulation of a Process for Cataloguing Small Orbital Debris,” in *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference*, S. Ryan, ed. (Maui Economic Development Board, 2010).
10. D.J. Kessler and B.G. Cour-Palais, "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt", Journal of Geophysical Research, Vol. 83, No. A6, pp. 2637-2646, June 1, 1978.
11. Willem H. de Vries, Donald W. Phillion (Lawrence Livermore National Laboratory), “Monte Carlo Method for Collision Probability Calculations using 3D Satellite Models,” in *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference*, S. Ryan, ed. (Maui Economic Development Board, 2010).

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