THE GENERAL MISSION ANALYSIS TOOL (GMAT): A NEW RESOURCE FOR SUPPORTING DEBRIS ORBIT DETERMINATION, TRACKING AND ANALYSIS

Moriba Jah(1), Steven Hughes(2), Matthew Wilkins(3), Tom Kelecy(4)

(1) Air Force Research Laboratory, Directed Energy Directorate, 535 Lipoa Pkwy, Suite 200, Kihei, HI, 96753, USA
(2) NASA/GSFC, Flight Dynamics Analysis Branch, Code 595, Greenbelt, MD, 20771, USA, gmat@gsfc.nasa.gov
(3) Schafer Corporation, 535 Lipoa Pkwy, Suite 200, Kihei, HI, 96753, USA, mpwilkins@gmail.com
(4) Boeing LTS, 5555 Tech Center Drive, Colorado Springs, CO, 80919, USA, thomas.m.kelecy@boeing.com

Distribution Statement A: Approved for public release; distribution is unlimited. AFRL PA# 377ABW-2009-0295.

ABSTRACT

The General Mission Analysis Tool (GMAT) was initially developed at NASA's Goddard Space Flight Center (GSFC) as a high accuracy orbital analysis tool to support a variety of space missions. A formal agreement has recently been established between NASA and the Air Force Research Laboratory (AFRL) to further develop GMAT to include orbit determination (OD) capabilities. A variety of estimation strategies and dynamic models will be included in the new version of GMAT. GMAT will accommodate orbit determination, tracking and analysis of orbital debris through a combination of model, processing and implementation requirements. The GMAT processing architecture natively supports parallel processing such that allow it can efficiently accommodate the OD and tracking of numerous objects resulting from breakups. A full first release of the augmented GMAT capability is anticipated in September 2009 and it will be available for community use at no charge.

1. WHAT IS GMAT?

The General Mission Analysis Tool (GMAT) is a space trajectory optimization and mission analysis system developed by NASA and private industry in the spirit of the NASA Vision. GMAT contains new technology and is a test-bed for future technology development. To satisfy NASA's mandate and maximize technology transfer, GMAT is an open source software system licensed under the NASA Open Source Agreement (http://www.opensource.org/licenses/nasa1.3.php).

GMAT is written to run on Windows, Linux and Macintosh platforms, using the wxWidgets cross platform UI Framework, and can be built using either commercial development tools or the GNU Compiler Collection (gcc). The system is implemented in C++ using an Object Oriented methodology, with a rich class structure designed to make new features simple to incorporate. Extensive documentation is available that describes the architectural design, mathematical models and algorithms, testing procedures, system interfaces, and how to use GMAT.

2. ORIGIN OF GMAT

GMAT has its roots in the goals of NASA, and cannot be truly understood without a clear statement of NASA's goals. The NASA mission and charter contain broad and lofty objectives for the Agency and its employees. Like any good vision statement, the objectives form the basis from which numerous activities and projects at NASA, including GMAT, derive guidance and justification.

One of NASA's Mission Statements is:

To research, develop, verify, and transfer advanced aeronautics and space technologies.

NASA's Charter contained in the Space Act of 1958 states that:

NASA shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof.

The NASA Mission Statement, Strategic Plan, and Charter provide fundamental guidance and justification for the GMAT project, and are ultimately the source of the GMAT Mission and Vision.

3. THE GMAT MISSION AND VISION

Put simply, the goal of the GMAT project is to develop new space trajectory optimization and mission design technology by working inclusively with ordinary people, universities, businesses, and other government organizations, and to share that technology in an open and unhindered way. GMAT is a free and open source software system: free for anyone to use in development of new mission concepts or to improve current missions, freely available in source code form for enhancement or further technology development.

Proc. '5th European Conference on Space Debris', Darmstadt, Germany
30 March – 2 April 2009, (ESA SP-672, July 2009)

3.1 The GMAT Mission Statement

To research, develop, verify, and transfer new technologies in space trajectory optimization and mission design. To maximize technology transfer by using an inclusive, collaborative, and transparent technology development model where ordinary people, businesses, academia, and other government organizations participate in, and have open and equal access to, NASA technology development. To foster a vibrant community of users and contributors. Users apply technology to enable new missions, enhance current missions, and provide feedback to contributors for technology enhancement and creation. Contributors enhance current technology and develop new technology.

3.2 The GMAT Vision Statement

GMAT will enable the development of new space trajectory and mission design technology that does not currently exist, new applications of existing technology, and significant enhancements to existing technology that give new insights into well known problems as well as improve analyst productivity and/or software ease of use.

4. THE MOTIVATION BEHIND GMAT

GMAT was created with the hope that the cost of mission design technology development would be reduced by amortizing that cost over a large portion of the space community. GMAT would also serve as a platform through which NASA can develop, test, verify, and transfer new technologies fulfilling one of NASA's primary missions. That being said, GMAT is now poised to become a platform for transitioning new technology from the research environment to the operational environment because it provides a system in which mathematical models, architecture, and design are open for inspection by all users and are held to a rigorous validation and verification protocol. The GMAT software architecture and design paradigm allows users to more efficiently accommodate new and changing operational and/or mission requirements.

While the initial vision for GMAT was to provide a rich set of mission analysis features, when GMAT was initially brought to the attention of the public, AFRL's Advanced Sciences and Technology Research Institute for Astrodynamics (ASTRIA) saw the potential of GMAT to also provide an institutional quality orbit estimation software suite. In that light, AFRL partnered with NASA GSFC through a memorandum of understanding to further develop GMAT to include advanced estimation capabilities that were not available in other astrodynamics software platforms available on the open market. AFRL also desired the flexibility to pursue research and development of new trajectory estimation paradigms in line with its own mission and goals.

GMAT estimation capabilities are being actively included as part of the native GMAT system architecture in such a way that an end user can perform stand-alone OD work or use an estimator reading real-time attitude data in-line with a maneuver planning scenario, for example. The goal of the GMAT development team is to support a wide variety of current estimation theories as well as create an architecture that is flexible enough to allow for advanced research and development of new and un-anticipated estimation paradigms.

5. GMAT SYSTEM DESCRIPTION

GMAT is an open source, platform independent trajectory optimization and design system. We use an open source process to permit anyone to develop and validate new algorithms and to enable new algorithms to quickly transition into the high fidelity core. GMAT is designed to model and optimize space object trajectories in flight regimes ranging from low Earth orbit to lunar applications, interplanetary trajectories, and other deep space missions. The system supports constrained and unconstrained trajectory optimization and built-in features make defining cost and constraint functions trivial so analysts can determine how their inclusion or exclusion affects solutions. The system also contains initial value solvers (propagation) and boundary value solvers and efficiently propagates spacecraft either singly or coupled. GMAT's propagators naturally synchronize the epochs of multiple space objects and shorten run times by avoiding fixed step integration or interpolation to synchronize epochs of spacecraft A user can interact with GMAT using either a graphical user interface (GUI) or script language that has a syntax similar to the MathWorks' MATLAB®1 system. All of the system elements can be expressed through either interface and users can configure elements in the GUI and then view the corresponding script, or write script and load it into GMAT.

Analysts model space missions in GMAT by first creating resources such as spacecraft, propagators, and optimizers to name a few. These resources can be configured to meet the needs of specific applications and missions. After the resources are configured they are used in the mission sequence to model the motion of spacecraft and simulate events in a mission's time evolution. The mission sequence supports commands such as Nonlinear Constraint, Minimize, Propagate, Estimate, Function Calls, Inline Math, and Script Events among others.

The system can display trajectories in space, plot parameters against one another, and save parameters to files for later processing. The trajectory and plot capabilities are fully interactive, plotting data as a mission is run and allowing users to zoom into regions of interest. Trajectories and data can be viewed in any coordinate system defined in GMAT, and GMAT allows users to rotate the view and set the focus to any object in the display. The trajectory view can be animated so users can watch the evolution of the trajectory over time.

5.1 GMAT OD Vision

The GMAT team will release the first stable release of GMAT containing basic OD capabilities and a rigorous set of mission analysis features. We will employ a working model for multiple organization software development and promote the adoption of GMAT among multiple organizations.

5.2 GMAT OD FY09 Goals

The specific GMAT product goals for FY09 have been defined as:

- Deliver a non-beta version on all platforms
- Deliver a beta version on Linux and Mac platforms
- Deliver existing GMAT features plus the following:
    - Ground station measurement modeling
    - Batch least squares estimator
    - SPICE ephemeris generation and use
    - Discrete event prediction
    - State transition and mass flow rate dynamics

We have goals for the GMAT process this year to define the process for multiagency collaboration and development as well as to modify and document core processes for CMMI and NASA Policy Regulations compliance. Finally, the GMAT team has goals that GMAT be used by at least one university in a classroom or research setting, by the LCROSS project for trajectory design and optimization, by ASTRIA for preliminary Orbit Determination, by the MMS project for formation Monte Carlo Analysis, and by NASA GSFC Flight Dynamics Analysis Branch for preliminary mission analysis.

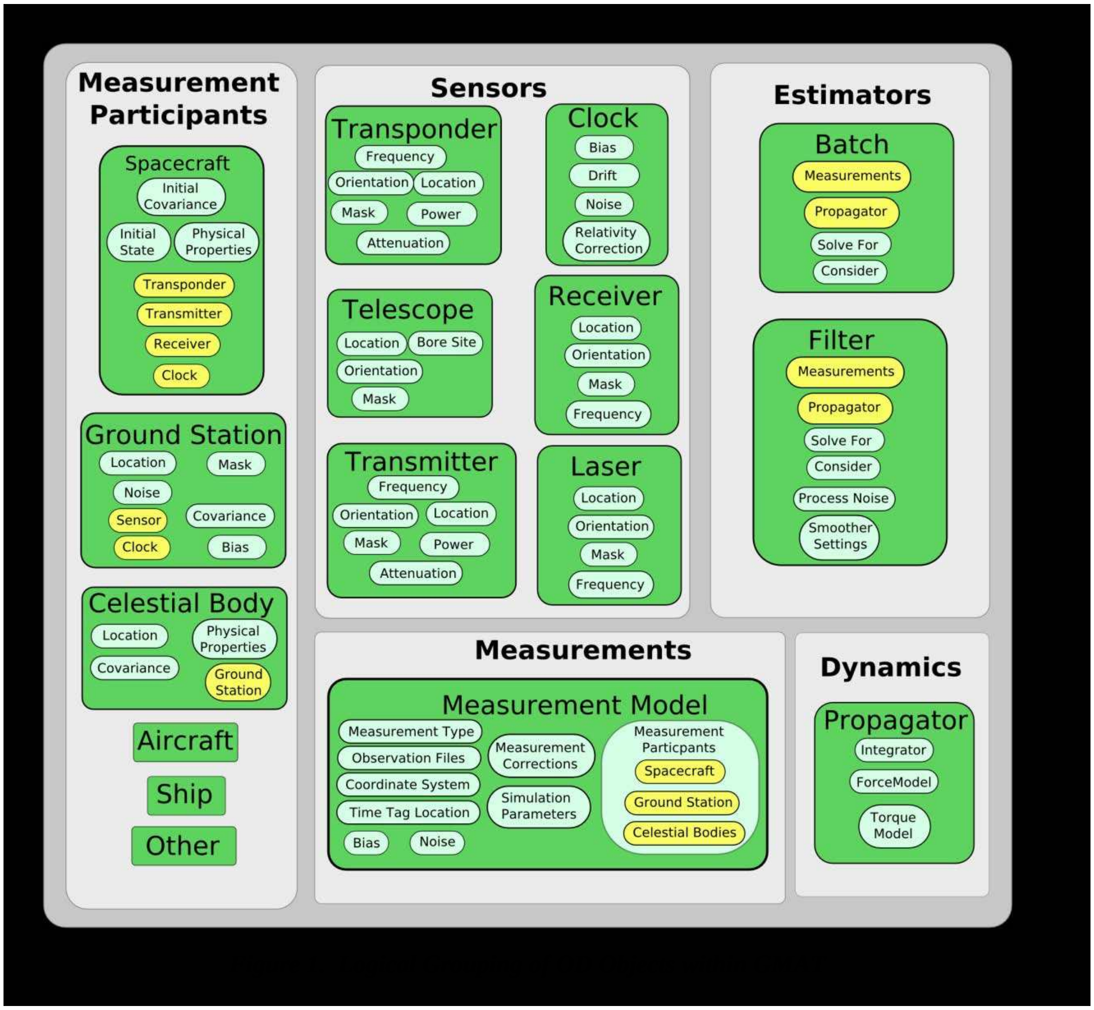
The trajectory estimation capabilities are being written in a separate code development branch from the primary code tree currently available to the public. Once the trajectory estimation capabilities have been thoroughly vetted and verified, it will be merged into the full source distribution. We anticipate that GMAT OD capabilities will be included with the full software release expected in September 2009.

Although the GMAT FY09 goal is to provide simply a verified batch least squares estimator along with basic measurement models, the initial release of GMAT with OD will most likely contain several estimators including batch least squares, sequential batch, as well as simple and extended Kalman filters. The remainder of this paper will discuss the implementation of these goals and also describe some features and functionality that are desired elements for FY09 but will not be used as part of the acceptance phase of GMAT prior to full release. Depending upon the test and validation schedule, we anticipate that initial orbit determination solvers as well as a sigma-point filter will also be part of the core OD release. The next section describes at a high level the process that GMAT OD uses to perform estimation.

5.3 GMAT OD System Components and Interactions Overview

To uniquely define an orbit determination problem, a user must often provide hundreds of pieces of information ranging from clock drift parameters, process noise characteristics, spacecraft physical properties, ground station properties, and atmospheric modeling parameters to name just a few. The objects and supporting data for OD in GMAT are summarized in Figure 1. The logical organization establishes key physical and computational elements into one of five categories: (1) Measurement Participants, (2) Sensors, (3) Estimators, (4) Measurements and (5) Dynamics. In GMAT, the user has access to the objects shown in Fig. 1, and can configure the data identified on each object in a gray bubble. A yellow bubble indicates that the user can attach a previously created and configured object of the identified type. Below we briefly discuss each logical category of object from a user perspective starting with measurement participants.

Measurement participants are models of physical objects that “participate” in the process of creating a measured quantity that is related to the spacecraft state. Examples of measurement participants include spacecraft, ground stations, and celestial objects. In GMAT, measurement participants are created and configured separately from measurement objects (which are discussed below). For example, if a user requires a Doppler measurement between, say, Hubble and Canberra, they first configure a spacecraft to model Hubble, and then they configure a ground station to model Canberra.



The sensor models contained in GMAT include but are not limited to clocks, receivers, transmitters, transponders and lasers. The user can create and configure sensors for their application and attach the sensor to the appropriate parent object such as a spacecraft or ground station.

Measurement objects are complex and a large amount of user-provided data is required to perform the functions described above. In GMAT, a measurement provides the following data: (1) observed measurement values which are read from a file, (2) computed (or expected) values of measurements, (3) simulated measurement values if requested, and (4) internal to GMAT, the measurement partial derivatives.

GMAT contains several estimators including batch, sequential and initial orbit determination solvers. These algorithms solve for a state estimate by processing measurements generated by measurement objects configured by the user. Hence, the user provides a list of all measurements to include in a particular estimation run. In addition, the solver object is where the user specifies which parameters are to be treated as solve-for and consider quantities.

Propagators are used in two areas for estimation problems. Propagators are attached to an estimator to propagate all objects associated with the solve-for and consider parameters and expected values of the measurements. For these cases, a user creates and configures a propagator just like in a mission analysis problem: A separate propagator can be provided so that simulated observations use different dynamics than those used for the computation of expected values.

6. HIGH FIDELITY MODELING IN GMAT

GMAT integrates all space object equations of motion using the Earth’s Mean Equator and Equinox of J2000 coordinate system and a variety of integration methods that the user can choose from. The user can also choose central bodies other than the Earth as the origin of the coordinate system of integration. For a more complete description of the mathematics and dynamics incorporated within GMAT, please read the GMAT

Mathematical Specification [1]. The following is a brief summary of salient points regarding high fidelity modeling in GMAT.

6.1 Non-spherical Gravity Fields and Earth Tides

Gravitational forces are conservative and only a function of position. In the standard non-spherical gravity model, a singularity occurs at the poles of the Earth. To avoid this singularity, GMAT employs the uniform gravitation potential field developed by Pines [2]. In order to accomplish precision orbit determination, IERS Earth Tide models will be included in GMAT as soon as practical.

6.2 Atmospheric Density

GMAT currently provides an assortment of more or less "standard" atmospheric models that users expect to see: Jacchia 1977, NRLMSIS-90, NRLMSISE-00, Jacchia-Bowman 2008, and the Russian GOST. Yet mismodeling of the atmosphere remains a persistent and dominant source of error in orbit determination and prediction for low earth orbit (LEO) space objects despite the scientific community's best efforts to construct realistic models of the Earth's upper atmosphere. In over fifty years of progress in space flight, one can still expect no better than 10 − 15% error in the instantaneous estimate of atmospheric density during quiet space weather periods. During active space weather periods, instantaneous errors can approach 80 − 200% [3- 6]. Most recently, Bruce Bowman *et al.* claims to achieve better than 10% error in atmospheric density modeling with a newly formulated version of the Jacchia 1970 model that includes new solar flux and geomagnetic proxies [6].

Given that each of these models has various levels of inaccuracy and are more applicable in certain space regimes than others, GMAT will also support dynamic calibration of the atmosphere techniques such as the one developed in the 1980s by Drs. Nazarenko and Yurasov, which was applied to the NRLMSISE-00 model in 2005 [7]. In 2006, these corrections were verified and validated at the AFRL Maui High Performance Supercomputing Center by Dr. Wilkins et al [8]. This expertise will be ported to GMAT and allow for state of the art atmospheric density modeling as well as provide a platform for future research and development activities in this area.

6.3 6DOF Attitude Dynamics

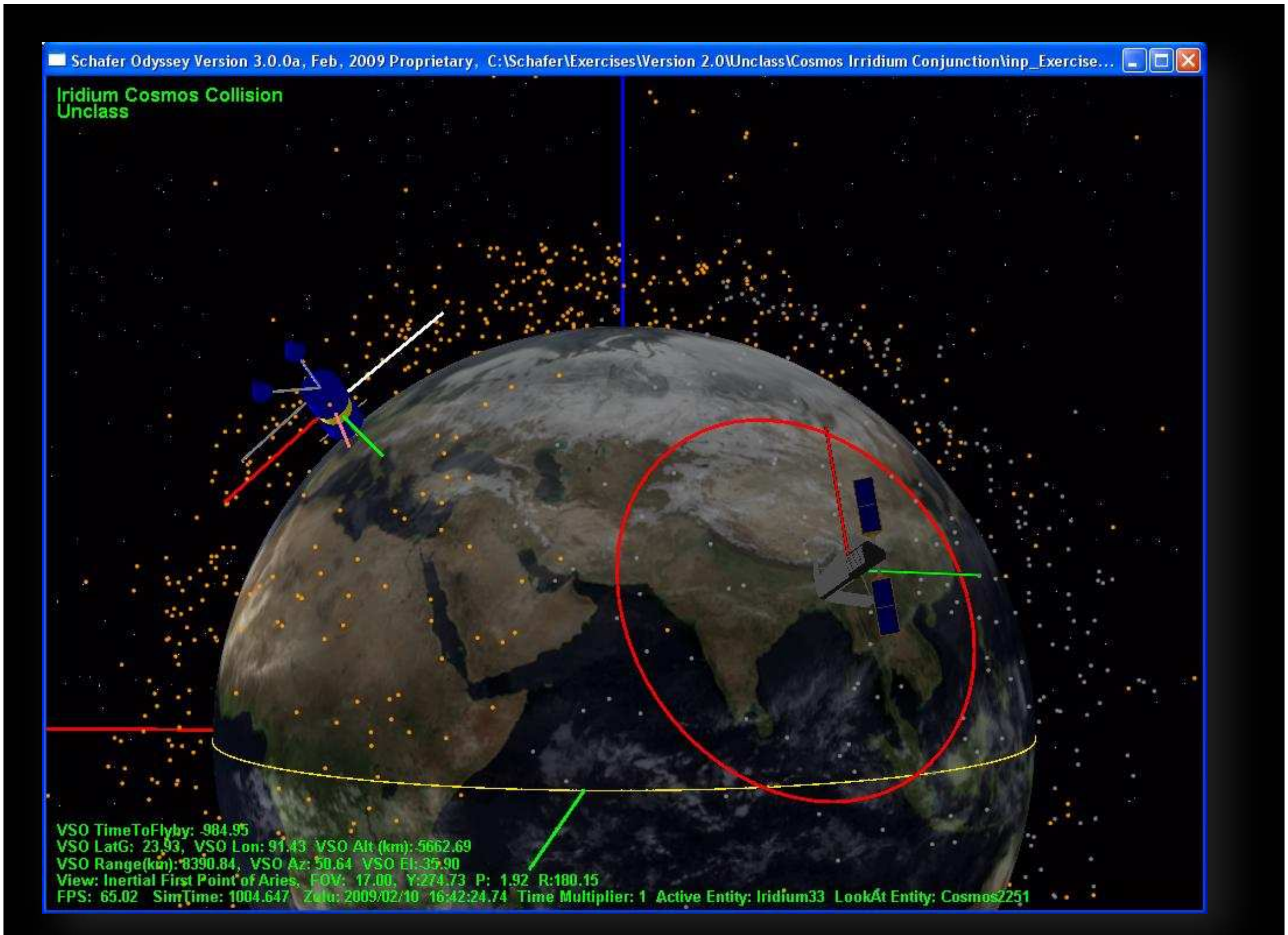
GMAT has a core attitude dynamics capability that allows a user to specify one of several common attitude parameterizations including quaternions, Euler angles, the Direction Cosine Matrix, Euler angle rates, and the angular velocity vector. Given an initial attitude state, GMAT can propagate the attitude using one of several kinematic attitude propagation models. Schafer Corporation has been tasked with adding full 6DOF attitude dynamics into GMAT. This work will be coupled with the High End Visualization work discussed below so that high fidelity CAD models of a space object can be used to calculate the environmental forces and moments acting upon a space object. These perturbing forces will be coupled with the 6DOF attitude dynamics model to facilitate precision orbit estimation and prediction.

6.4 Solar Radiation Pressure

The GMAT team is concerned with accurately modeling all resident space objects (RSOs), including inactive high area-to-mass ratio (A/m) RSOs in the geosynchronous orbit (GEO) regime that pose a hazard to active GEO RSOs [9]. The combination of SRP and solar and lunar gravitational perturbations causes perturbations in the orbits of these RSOs. The high A/m nature of these RSOs results in greater sensitivity to SRP resulting in the perturbation of mean motion, inclination and eccentricity. The subsequent drift with respect to the Earth, combined with time varying orientation with respect to the sun and transitions into and out of Earth's shadow, results in many of these RSOs being "lost" after initial acquisition as they transition through periods of days to weeks out of view of observing sites [10,11]. The work presented in [12] examined the sensitivity of the prediction accuracies to inadequate modeling of the SRP acceleration in the force models.

Most prediction and orbit determination processes treat penumbral and/or umbra eclipses as simple geometric models (cylindrical or dual conic), and assume fixed cross-sectional area of the orbiting object with respect to the sun. A physical solar radiation pressure model which includes the effects of refraction and absorption from Earth's atmosphere during penumbral transitions has been examined.

Additionally, variations in the area with respect to the sun were also analyzed using representative orbits with representative eclipsing cycles. Assumptions about the reflective properties of the object contribute additional errors. The orbit prediction errors have been examined for each potential source of error, both separately and combined, for a range of high A/m orbit parameters and have been found to be significant [12]. Hence, these models will be incorporated into GMAT to allow better determination and prediction of orbits for this class of RSO.



Schafer Odyssey Version 3.0.0a, Feb, 2009 Proprietary, C:\Schafer\Exercises\Version 2.0\Unclass\Cosmos Irridium Conjunction\inp_Exercise...

Iridium Cosmos Collision
Unclass

VSO TimeToFlyby: -984.95
VSO LatG: 23.93, VSO Lon: 91.43 VSO Alt (km): -5662.69
VSO Range(km): 8390.84, VSO Az: 50.64 VSO El: -35.90
View: Inertial First Point of Aries, FOV: 17.00, Y:274.73 P: 1.92 R:180.15
FPS: 65.02 SimTime: 1004.647 Zulu: 2009/02/10 16:42:24.74 Time Multiplier: 1 Active Entity: Iridium33 LookAt Entity: Cosmos2251

Figure 2. An example of High End Visualization that will be ported to GMAT in the near future. This graphic

7. HIGH END VISUALIZATION IN GMAT

The GMAT team would like to upgrade GMAT's core visualization capabilities to include close up views of space object models. This new capability will also include spacecraft attitude, shading, texture mapping, appendage articulation, and displaying the view through spacecraft sensors based on how they are pointing and their field of view. Schafer Corporation has its own proprietary 6DOF space simulation named "Odyssey" that already has these high end visualization features. When Schafer joined the GMAT team, they were tasked, among other things, with porting these visualization features into GMAT and using their expertise to add a rich feature set of graphical tools to enhance the GMAT user experience.

One critical component of High End Visualization is the ability to create and display a space object model. Figure 2 is a screen shot of Schafer's Odyssey software that depicts some of the capabilities that will be ported to GMAT in the near future. This graphic depicts representative CAD models of the Iridium 33 and the Cosmos 2251 space objects just before collision. There are many CAD industry formats available, and models can be saved in ASCII or binary format. The eventual goal for GMAT would be to find a CAD tool that is also open source that can build models in a non-proprietary open format with open source parsers that can be incorporated in GMAT to read in and display such models. Currently, Odyssey uses the POV-Ray or "Persistence of Vision – Ray" format for its models because it is an easily readable ASCII format. These features most likely will not be included in the full release planned for FY09 but will be included as soon as practical.

8. PARTICIPATION AND COLLABORATION

The GMAT project has been a collaborative effort between NASA and industry partners at every step in the project lifecycle from requirements definition, to design, implementation, and testing. Any of the numerous disciplines required in the GMAT technology development process are welcome collaborators. For example, collaborators can include users, developers, documenters, graphic designers, and web development experts. Collaborators can come from private sector, academia, government agencies, and the population at large. GMAT promotes transparency at all levels: Design, documentation, numerical models, implementation, test procedures, issues and bugs are open to community inspection. GMAT employs a service model as opposed to a product model. Government collaborates with industry, and industry provides a service instead of a product. The product is U.S. tax payer funded and therefore freely available to all including executable and source code.

We invite interested parties to send us contact information so we can start to explore ways we can work together to make GMAT as useful as possible to the aerospace community. We welcome new contributors to the project, either as users providing feedback about the features of the system, or developers interested in contributing to the implementation of the system. Please visit our Web site at http://gmat.gsfc.nasa.gov for more information.

Core development partners to date include:

- NASA Goddard Space Flight Center
- Air Force Research Laboratory, ASTRIA
- Thinking Systems, Inc.
- Schafer Corporation
- Boeing LTS
- Computer Sciences Corporation
- Honeywell Technology Solutions, Inc.

9. GMAT PROJECT STATUS

While GMAT has undergone extensive testing and is mature software, we consider the software to be currently in Beta form. We anticipate that a full release will be made available to the general public in September of 2009. GMAT is not sufficiently verified to be used operationally. The optimization capabilities of GMAT have been used to develop optimal solutions for numerous missions. However, we independently verify these solutions in operational systems. Once a full stable release of the GMAT software has been made available, we plan to begin vetting the software for operational use.

10. ACKNOWLEDGEMENTS

The authors would like to thank the GMAT team for all their hard work and dedication bringing GMAT to fruition. We would also like to thank Dr. Darrel Conway of Thinking Systems, Inc. and Dr. Dunn Idle of Schafer Corporation for their insights and contributions to this paper.

11. REFERENCES

1. GMAT Mathematical Specification, published on the web at http://gmat.gsfc.nasa.gov/downloads/documentation.html
2. Pines, S., “A Uniform Representation of the Gravitational Potential and its Derivatives,” AIAA Journal, Vol. 11, No. 1, 1988, pp. 31-38
3. Jacchia, L. G., “Thermospheric Temperature, Density, and Composition: New models,” Smithsonian Astrophysical Observatory SP-375, 1977.
4. “Earths Upper Atmosphere Density Model for ballistic support of Flights of Artificial Earth Satellites. GOST 22721-77,” Moscow, Publishing House of the Standards, 1978.
5. Picone, J. M., Hedin, A. E., Drob, D. P., and Aikin, A. C., “NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues,” *Journal of Geophysical Research*, Vol. 107, No. A12, 2002, pp. 1468, doi:10.1029/2002JA009430.
6. Bowman, B. R., Tobiska, W. K., Marcos, F. A., et al., “A New Empirical Thermospheric Density Model JB2008 Using New Solar and Geomagnetic Indices,” 2008 Astrodynamics Specialist Conference, AIAA Paper 2008-6438, Honolulu, HI, August 18-21, 2008.
7. Yurasov, V., Nazarenko, A. I., Cefola, P. J., and Alfriend, K. T., “Density Corrections for the NRLMSIS-00 Atmosphere Model,” Paper AAS 05-168 of the 15*th* AAS/AIAA Space Flight Mechanics Conference, Copper Mountain, Colorado, January 2005.
8. Wilkins, M. P., Sabol, C. A., Cefola, P. J., and Alfriend, K. T., “Practical Challenges in Implementing Atmospheric Density Corrections to the NRLMSISE-00 Model,” 16*th* AAS/AIAA Space Flight Mechanics Conference, AAS Paper 06-170, Tampa, FL, January 22-26, 2006.
9. Schildknecht, et al., "Properties of the High Area-to-mass Ratio Space Debris Population in GEO," AMOS Tech. Conf., Wailea, Hawaii, Sept, 2005.
10. Kelecy, T., G. Stansbery, T. Payne and R. Thurston, "Solar Radiation Estimation and Analysis of a GEO Class of High Area-to-mass Ratio Debris Objects," the American Astronautical Society (paper AAS 07-391) Astrodynamics Specialists Conference, Mackinak Island, MI, August 16, 2007.
11. Kelecy, T., E. Baker, P. Seitzer, T. Payne and R. Thurston, "Prediction and Tracking Analysis of a Class of High Area-to-mass Ratio Debris Objects in Geosynchronous Orbit," ," AMOS Tech. Conf., Wailea, Hawaii, Sept, 2008.
12. Kelecy, T. and M. Jah, "Analysis of Orbital Prediction Accuracy Improvements Using High fidelity Physical Solar Radiation Pressure Models

for Tracking High Area-to-mass Ratio Objects", in-press, Proceedings of the Fifth European Conference on Space Debris, Darmstadt, Germany, March-April, 2009.