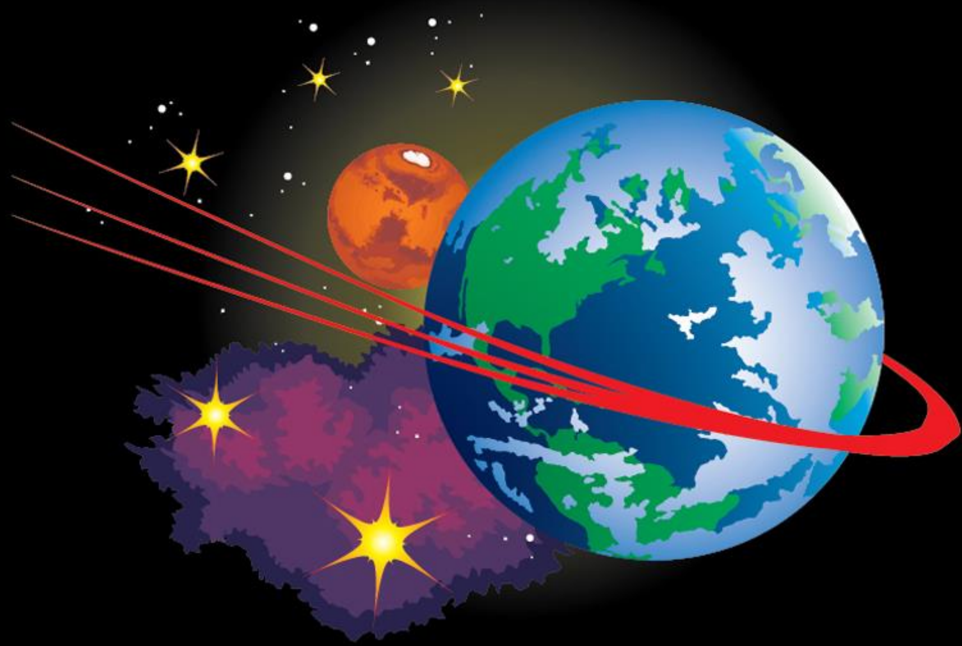
National Aeronautics and Space Administration



general mission analysis tool

Verification and Validation of the General Mission Analysis Tool (GMAT)

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August 4, 2014

NASA Goddard Space Flight Center

Contents

- Introduction to GMAT
- Verification and Validation Overview
- Numerical Results
  - Dynamics and Modeling
  - Finite Maneuvers
  - Mission Data Calculation Parameters
- Sample Functional Testing Activities
- GUI Testing
- Conclusions

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What is GMAT?

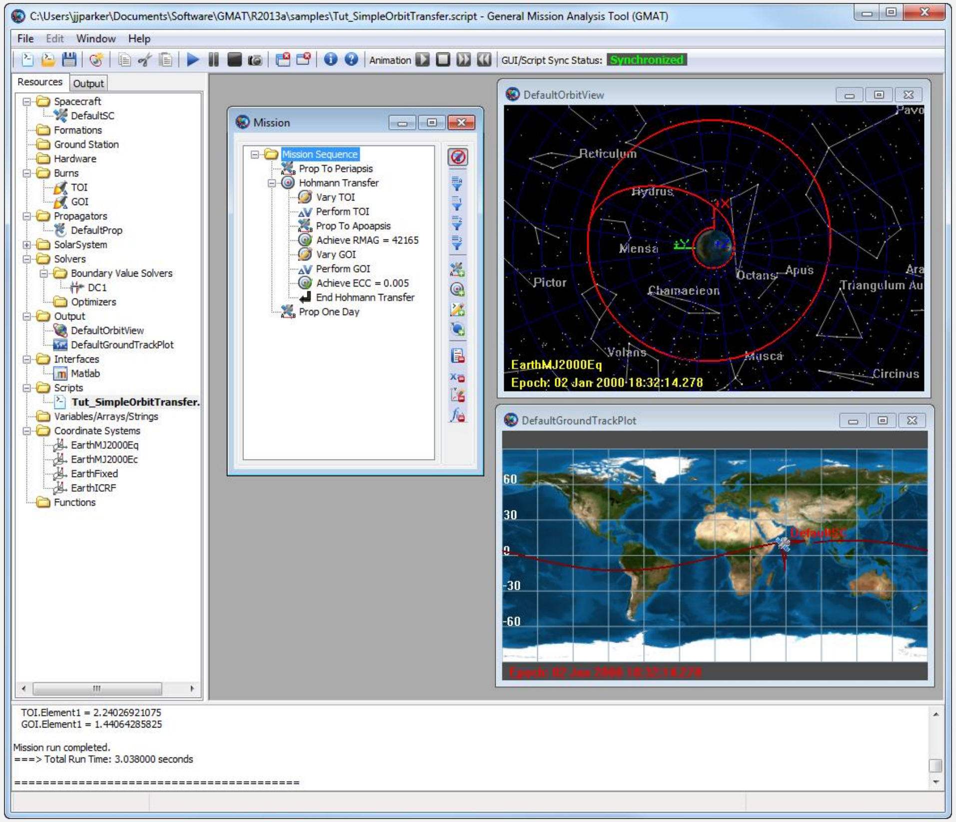
GMAT is a **g**eneral **m**ission design and **a**nalysis **t**ool.

Key Applications:

- Mission analysis/optimization
- All orbital regimes

Key characteristics:

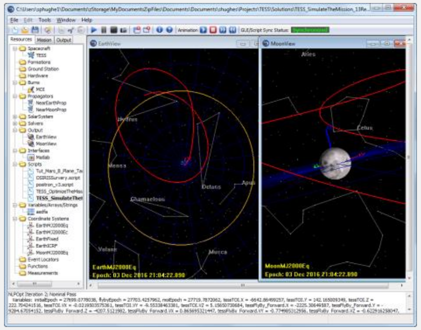
- open source
- high fidelity
- feature rich
- desktop oriented



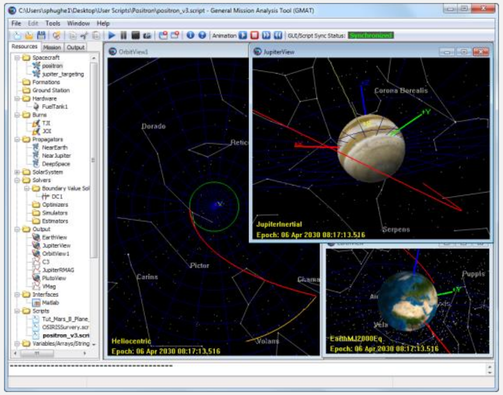
Status: **Fully tested** and flight qualified

Customizable Tools to Go Anywhere

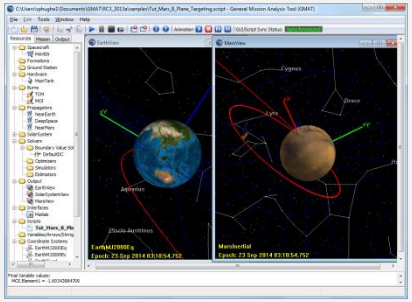
- **Customizable trajectory solutions to go anywhere**
  - LEO
  - Libration points
  - Lunar
  - NEO
  - Interplanetary
- **End-to-End Support**
  - Design the mission
  - Optimize the mission
  - Win the proposal
  - Fly the mission



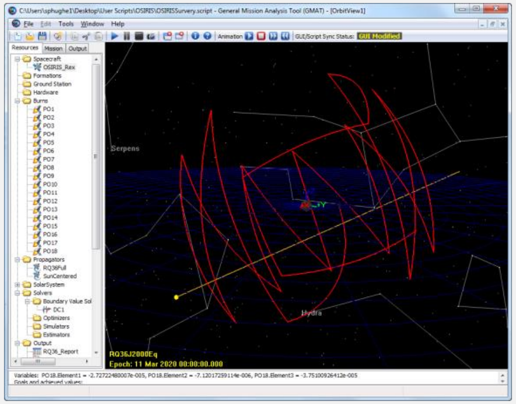
Optimal Lunar Flyby



Outer Planet Transfers



Optimal Mars Trajectories



Asteroid (RQ36) Survey

Download and find out more: gmatcentral.org

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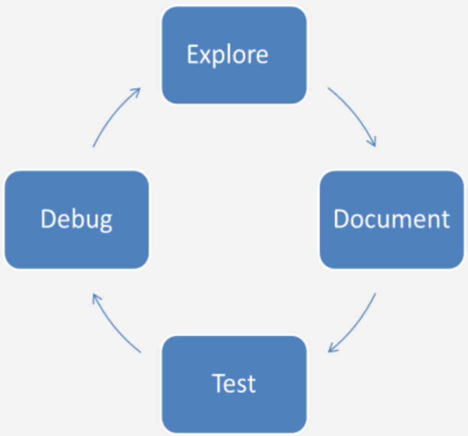
Project Context

- 2001: Requirements gathering
- 2002: Architectural design
- 2003: Implementation of system core
- *…feature development…*
- 2010: Decision to prepare for operational use
- *…feature development…*
- **2012–2013: V&V effort**
- Apr. 2013: First production release (R2013a)
- Aug. 2013: Operationally certified (R2013b)

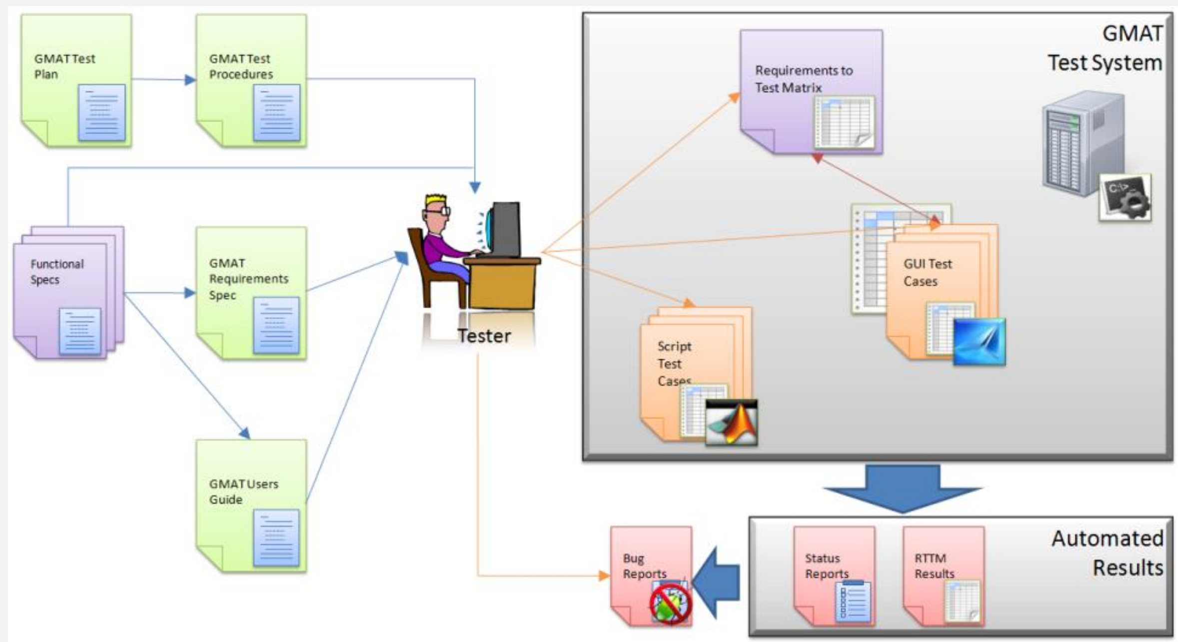
Goals of the V&V Effort

- Technical Goals
  - Systematically evaluate and validate all models, components, and functionality
  - Fix all critical system defects
  - Update working specifications that define system behavior
  - Provide high quality end user documentation and training material
  - Prepare for system maintenance and further development of a Class B flight qualified system
- Strategic goals
  - Position GMAT for larger community adoption
  - Position GMAT for flight qualification to begin in the spring of 2013.

V&V Philosophy and Environment



Our V&V Philosophy



Our Test Environment

Test Summary

- Produced about 13000 script tests
- Produced about 3500 GUI tests

Regression Testing

- Script tests run nightly for regression
- GUI tests run weekly

Component Breakdown

- GMAT contains many components
  - ~30 resources (objects)
  - ~25 commands
  - System-level components
- We divided the testing effort into logical “component areas”
- Then, we performed V&V for each component area as a unit

Component Area	Description/Features
Dynamics/Models	Numerical models for orbit and attitude propagation, solar system and coordinate system models including spacecraft orbit state representations, spacecraft ballistic and mass properties, etc.
Powered Flight	Impulsive and finite maneuvering including tanks, thrusters, impulsive maneuver, finite maneuver
Solver Infrastructure	Algorithms and infrastructure for solving boundary value and optimization problems.
Programming Infrastructure	Algorithms and features for customization including custom scripting, user defined variables and arrays, scripted custom equations, built-in astrodynamic computations, control flow, and external interfaces.
Output\Utils	Components to support graphical and data output such as xy-plots, 3-D graphics, report files, and ephemeris files.
Application Control	Inherently interface elements such as file menus, command line interfaces, and the script editor.

We tested components in logical groups.

Test Types

- A particular feature can be tested in several ways
  - Does it operate correctly on nominal input?
  - Does it respond appropriately on invalid input?
  - Does it work as a part of the whole system?
- We defined 6 test types and applied them to each feature.

Test Type	Description
Numeric	Tests of physical and mathematical models. Numeric tests are performed by comparing output to external "truth".
Functional	Tests that verify non-numeric functionality, such as plotting styles, file formats, and control flow behavior.
Input validation	Tests that ensure user inputs are validated by the system and the correct error messages are provided for invalid user input.
End-to-end	Tests that solve an end-to-end engineering problem such as a lunar transfer or orbital maneuver. These tests are "fit for use" tests and are applications of GMAT to real-world problems.
Stress	Test designed to stress the system and make heavy use of system resources.
Edge/Corner	Tests designed to test models at the boundaries of applicability, in the GMAT context this often means testing models near numerical singularities.

We performed standard test types.

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  - **Finite Maneuvers**
  - **Mission Data Calculation Parameters**
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Dynamics and Modeling

- Dynamics and modeling are core to GMAT.
- Component area consists of:
  - Orbit epoch/state representations
  - Spacecraft mass properties
  - Attitude representations
  - Solar system models
  - *Numerical integrators*
  - *Force modeling*
  - *Coordinate systems*
- All went through the full V&V cycle.
- Here, we show results for force modeling, integrators, coordinate systems only.
  - See the paper for details on the others.

Orbit Propagation Comparison: Individual Force Modeling

Orbital Regime	Dynamics Model								
	Spherical Gravity	Harmonic gravity	Tides	Point mass perturbation	SRP	MSISE90	NRLMSISE00	Jacchia-Roberts	Relativistic Correction
ISS	7.1E-06	2.5E-03	3.3E-01	1.5E-05	1.3E-01	1.8E-01	1.1E+00	1.9E+00	3.8E-02
Sun Sync	3.9E-05	5.0E-04	5.7E-01	3.6E-05	1.7E-01	1.8E-02	5.8E+00	2.0E+00	x
GPS	2.7E-06	1.5E-04	2.5E-02	2.3E-05	4.7E-02	1.4E-05	4.2E-06	2.7E-06	x
GEO	6.3E-06	2.8E-05	5.0E-02	1.8E-04	2.4E-05	6.3E-06	5.2E-05	6.3E-06	2.3E-03
Molniya	2.4E-04	6.1E-03	6.0E+00	2.0E-04	5.8E-01	1.8E-03	4.3E+00	1.3E-01	x
Luna	7.3E-05	1.9E-04	N/A	2.2E-04	1.1E-04	N/A	N/A	N/A	x
Venus	9.0E-03	1.1E-02	N/A	1.4E-02	3.7E-02	N/A	N/A	N/A	x
Mars	6.1E-02	1.2E-01	N/A	3.2E-01	6.0E-01	N/A	N/A	N/A	x

- Difference between GMAT and reference system for each force model individually
- RSS position errors after propagation duration (m)
- Most cases show mm- to cm-level agreement.
- See paper for initial state vectors, durations, etc.
- Velocity errors consistently 2–4 orders of magnitude lower

Orbit Propagation Comparison: Combined Force Modeling

Test Case	Max Position Diff. RSS (m)
GEO (TBPM,HG,Drag,SRP,Tide)	9.2227E-01
GEO (TBPM,HG,Drag,SRP)	1.7184E-04
GPS (TBPM,HG,Drag,SRP,Tide)	5.2289E-01
GPS (TBPM,HG,Drag,SRP)	7.5020E-02
ISS (TBPM,HG,Drag,SRP,Tide)	1.9932E+00
ISS (TBPM,HG,Drag,SRP)	1.6639E+00
Molniya (TBPM,HG,Drag,SRP)	5.1301E-01
SunSync (TBPM,HG,Drag,SRP)	3.3214E-01
Lunar Transfer (TBPM, HG, SRP)	8.6480E-01
Mars Transfer (TBPM, HG, SRP)	5.2626E+00
Asteroid (TBPM, HG, SRP)	4.6731E-03
Earth Moon L2 (TBPM, SRP)	8.0749E-01
Deep Space (TBPM, Rel)	3.8275E-02
Titan(TBPM, SRP)	2.5002E-01

Meter-level or better agreement for full force modeling.

- Worst-case (bounding) comparisons between STK and other tools
- Data from Vallado[1], with GMAT added
- GMAT shows comparable or better worst-case results.

Software	Harm. Gravity	Point Mass	SRP	Drag
GTDS	0.07	0.06	2.50	575.00
TRACE	**0.0020**	0.02	1.50	750.00
Special K	N/A	0.07	N/A	N/A
GMAT	0.01	**0.0002**	**0.58**	**5.77**
GEODYN	N/A	N/A	N/A	1000

GMAT compares very well against industry-standard tools.

[1]Vallado, David, A. "An Analysis of State Vector Propagation Using Differing Flight Dynamics Programs", AAS/AIAA Space Flight Mechanics Conference, 2005.

Numerical Integrators

Orbit	Data	RKV89	RKN68	RK56	PD45	PD78	ABM
ISS	Run Time	1.53	**1.00**	2.14	2.78	1.46	3.41
	Error (m)	*0.003*	*64.060*	*0.022*	***0.002***	*0.006*	*0.012*
Molniya	Run Time	1.32	1.47	1.99	3.08	**1.00**	3.35
	Error (m)	***0.007***	*0.601*	*0.059*	*0.032*	*0.043*	*380.125*
Lunar Flyby	Run Time	**1.00**	1.01	2.26	2.98	2.21	3.30
	Error (m)	*0.063*	*0.017*	*0.002*	*0.023*	***0.000***	*0.236*
Mars Transfer	Run Time	1.02	1.04	1.14	1.40	**1.00**	3.07
	Error (m)	*0.030*	***0.001***	*0.043*	*0.194*	*0.009*	*25.231*
Finite burn 1	Run Time	1.27	N/A	1.24	1.26	**1.00**	1.45
	Error (m)	*0.002*	*N/A*	*0.006*	*0.002*	*0.002*	***0.000***
Finite burn 2	Run Time	1.03	N/A	1.18	1.31	**1.00**	1.54
	Error (m)	*0.002*	*N/A*	*0.000*	***0.000***	*0.001*	*0.003*

- Integrators tested via “closure” tests
  - Propagate forward, then backward
  - Compare initial and final states
- Test performed with and without finite burn
- Results shown for both error and performance
- Performance results normalized: 1.0 is best-performing result

All integrators were validated. Prince-Dormand 7(8) is the best general-purpose integrator available.

Coordinate Systems

- GMAT contains 19 coordinate system types
- Conversions from/to each were tested
- Shown: Conversion from FK5 (internal system)
  - Conversion using circular LEO state vector, SMA = 6800 km
- Order-of-magnitude results:
  - RSS position: order of mm or better
  - RSS velocity: order of μm/s or better
  - Angular: order of 10^{-8}° or better

Conversion Type (FK5 to…)	Position Comparison		Velocity Comparison	
	RSS Diff (m)	Angle Diff (deg)	RSS Diff (m/s)	Angle Diff (deg)
BodyFixed	5.79E-03	4.88E-08	5.65E-06	4.23E-08
BodySpinSun	2.17E-04	1.83E-09	1.35E-07	1.01E-09
GSE	1.11E-05	9.36E-11	1.22E-08	9.14E-11
GSM	2.13E-04	1.79E-09	3.66E-06	2.74E-08
ICRF	7.80E-03	6.57E-08	1.97E-06	1.47E-08
MJ2000Ec	9.19E-05	7.74E-10	1.05E-07	7.84E-10
MJ2000Eq	0.00E+00	0.00E+00	6.39E-12	4.78E-14
MODEc	3.33E-07	2.80E-12	2.31E-11	1.73E-13
MODEq	9.37E-10	7.90E-15	6.53E-12	4.89E-14
MOEEc	6.75E-09	5.69E-14	5.42E-12	4.06E-14
MOEEq	4.90E-09	4.13E-14	6.14E-12	4.59E-14
ObjectReferenced	1.11E-05	9.36E-11	1.22E-08	9.14E-11
TODEc	2.00E-04	1.69E-09	2.20E-07	1.65E-09
TODEq	1.98E-04	1.67E-09	2.38E-07	1.78E-09
TOEEc	6.55E-05	5.52E-10	7.20E-08	5.39E-10
TOEEq	2.05E-04	1.72E-09	2.57E-07	1.92E-09
Topocentric	5.92E-03	4.99E-08	5.68E-06	4.25E-08

Excellent agreement for all transformations

Finite Maneuvers

Test Category	Position RSS Error (m)		Velocity RSS Error (m/s)		Mass Error (g)	
	Low	High	Low	High	Low	High
Orbit	1.1e-3	5.0e-2	6.4e-7	7.7e-4	3.4e-6	1.1e-4
Thruster Configuration	3.0e-4	5.0e-3	3.8e-7	6.4e-6	2.7e-8	2.4e-5
Coordinate System	2.3e-3	4.3e-3	2.2e-6	4.5e-6	1.5e-5	3.0e-5
Tank Configuration	2.4e-4	9.7e-2	2.3e-7	7.7e-5	3.5e-7	4.8e-3
All	2.4e-4	5.0e-2	2.3e-7	7.7e-4	2.7e-8	4.8e-3

- Finite maneuvers tested from a baseline configuration, with variations in:
  - Orbit type (central body)
  - Thruster configuration (thrust vector, mass depletion, Isp, etc.)
  - Coordinate system (VNB, LVLH, inertial, etc.)
  - Tank configuration (mass, pressure, temp., pressure model, etc.)
- Over 900 cases performed
- Each propagated 120 minutes with finite maneuver turned on
- Truth data compared to Matlab, FreeFlyer
- RSS position error cm-level or better, mass error mg-level or better

Mission Data Calculation Parameters

Orbit	Body	Alt.	Beta angle	Orbit energy	Mean motion	Ang. mom.	Vel. at periapsis
GEO	Earth	5e-12	< 1e-16		5e-14	8e-12	2e-11
	Venus	2e-12	2e-12	8e-11	6e-14	2e-11	4e-11
Hyperbolic	Earth	3e-9	7e-15	6e-8	2e-11	2e-7	9e-8
	Venus	2e-11	3e-14	3e-8	1e-8	2e-8	2e-8
Mars	Earth	2e-12	< 1e-16	3e-9	4e-9	2e-9	2e-9
	Mars	4e-8	< 1e-16	2e-9	2e-12	5e-10	5e-10
Luna	Earth	2e-11	< 1e-16	5e-8	3e-14	9e-9	9e-9
	Luna	3e-9	< 1e-16	7e-10	6e-13	4e-10	4e-10

- Parameter calculations tested for multiple orbit types, with multiple dependencies
- Results compared against STK/Astrogator, custom STK/Astrogator scripting, and custom GMAT scripting
- Selection of results shown
- Results are percent difference between GMAT and truth solution
  - 1 = 100% error
  - 1e-12 = 11 digits of agreement

Excellent agreement for all calculations

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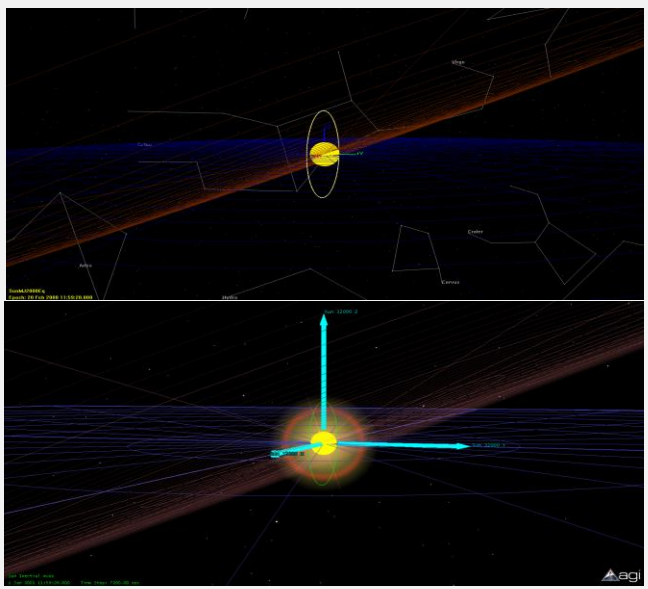
3-D Graphics

- V&V testing for Orbit View:
  - Preliminary testing involved visual inspection of all 3-D graphics behavior
  - Key elements of GMAT's graphics were compared against STK and Celestia benchmarks



GMAT & STK Comparison showing spacecraft trajectory, ecliptic plane, xy plane and sun-centered MJ2000Eq coordinate sys.

GMAT & Celestia showing star constellations comparison

Mathematical Expressions

- Same syntax as MATLAB expressions
- Wrote random generator to generate thousands of valid expressions
- Results validated against MATLAB
- 100 scripts w/ random contents in regression system

Operators	Functions
+ (addition)	sin
- (subtraction)	cos
* (multiplication)	tan
/ (division)	asin
' (transpose)	acos
^ (power)	atan
	atan2
	log
	log10

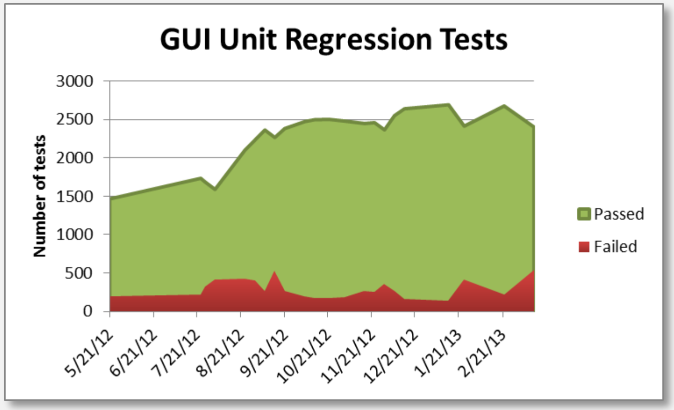
Example operators and functions

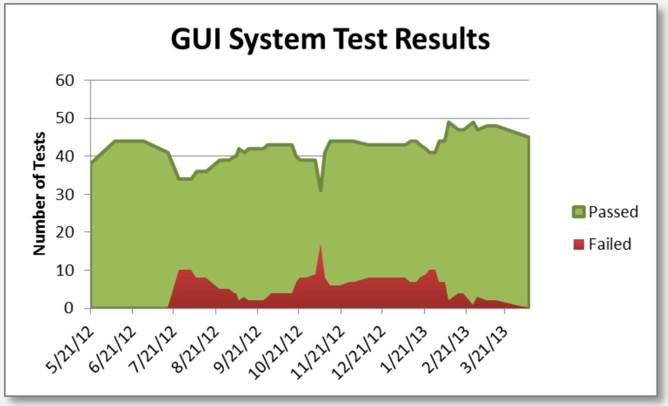
Contents

GUI System Tests and "Unit" Tests

- Unit tests ensure verification and acceptance testing of every button, menu, text box, etc.
  - One unit test project <-> one object (resource, command, script window, mission sequence, etc)
- System tests validates the GMAT GUI by testing the entire application
  - End-to-end test cases
  - Simulating typical end-user interactions
- Tests are implemented using SmartBear's TestComplete GUI testing tool

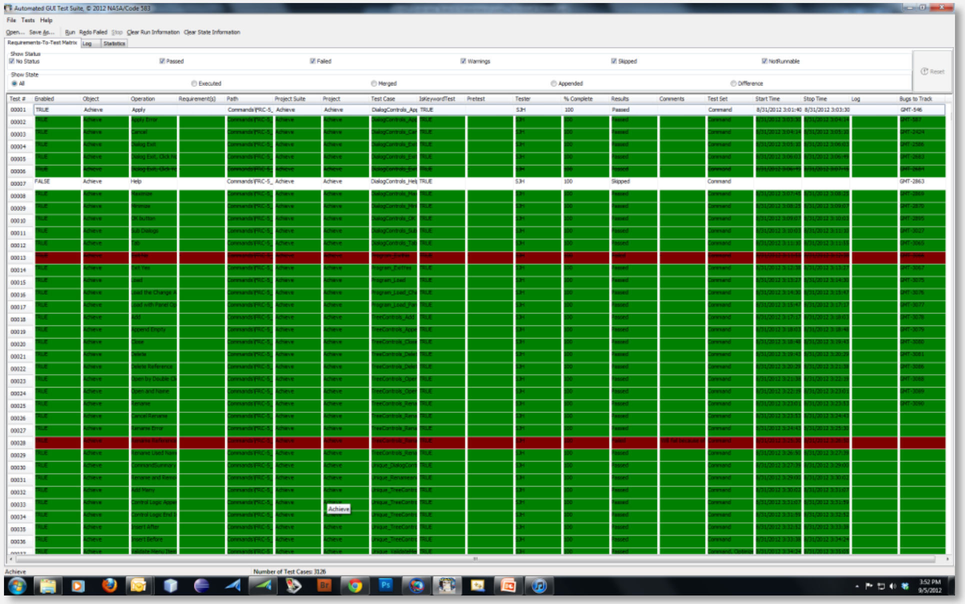
- Test Report History

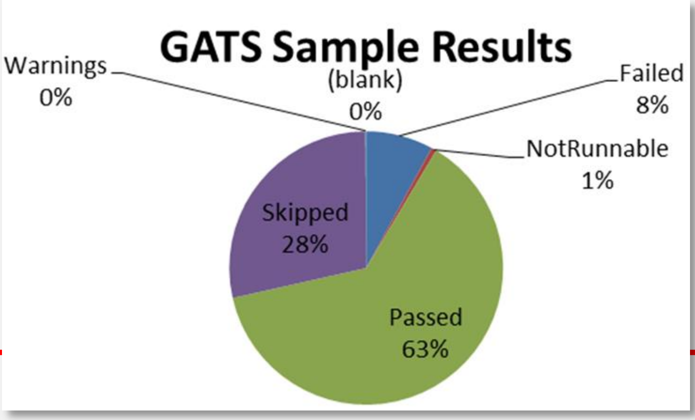




GATS and Requirements To Test Matrix

- GMAT Automated Test Suite (GATS) tool executes RTTM
  - Automate the execution of the GUI tests
  - Map tests to requirements
  - Report results
- ~3400 tests executed in 4 days (biweekly)
  - Smaller subset executed nightly





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Conclusions

- Accomplished technical and strategic goals.
  - Systematically evaluated and validated all models, components, and functionality
  - Fixed nearly all critical system defects
  - Updated working specifications that define system behavior
  - Provided high quality end user documentation and training material
  - Prepared for system maintenance and further development of a NASA Class B flight qualified system
  - Positioned GMAT for larger community adoption
  - Positioned GMAT for flight qualification
- Successful system-wide V&V effort led to release of GMAT R2013a, its first production-quality release.
- Enabled a successful follow-on flight qualification effort.

BACKUP

Test Types

Test Type	Description
Numeric Tests	Tests of physical and mathematical models. Numeric tests are performed by comparing output to external "truth".
Functional tests	Tests that verify non-numeric functionality, such as plotting styles, file formats, and control flow behavior.
Input validation	Tests that ensure user inputs are validated by the system and the correc user input.
End-to-end tests	Tests that solv as a lunar tran for use" tests a problems
Stress Tests	Test designed system resour
Edge corner tests	Tests designed applicability, in models near n

Test Type	Description
Numeric Tests	Tests of physical and mathematical models. Numeric tests are performed by comparing output to external "truth".
Functional tests	Tests that verify non-numeric functionality, such as plotting styles, file formats, and control flow behavior.
Input validation	Tests that ensure user inputs are validated by the system and the correct error messages are provided for invalid user input.
End-to-end tests	Tests that solve an end-to

We performed

POWERED FLIGHT

Example Tank Configuration

Tank	Description	Mass (kg)	Pressure (kPa)	Temp (C)	Ref Temp (C)	Volume (m^3)	Fuel Density (kg/m^3)	Pressure Model
A	Baseline	725	1200	20	12	0.8	1029	PR
B	High Mass	820	1200	20	12	0.8	1029	PR
C	High Pressure	725	2500	20	12	0.8	1029	PR
D	Low Pressure	725	725	20	12	0.8	1029	PR
E	High Temp	725	1200	200	12	0.8	1029	PR
F	Low Temp	725	1200	2	12	0.8	1029	PR
G	High Ref Temp	725	1200	20	100	0.8	1029	PR
H	Low Ref Temp	725	1200	20	2	0.8	1029	PR
T	High Volume	725	1200	20	12	80	1029	BD
U	Low Density	725	1200	20	12	8.0	101.325	BD
V	High Density	725	1200	20	12	0.8	2500	BD

Example Thruster Configurations

Coordinate System	Designation	Description
MJ2000Eq	CS0	J2000-based Earth-centered Earth mean equator inertial
Earth VNB	CS1	Earth Velocity-Normal-Binormal (VNB) is a non-inertial coordinate system based upon the motion of the spacecraft with respect to the Earth. The X-axis of this coordinate system is along the velocity of the spacecraft with respect to the Earth, the Y-axis is along the instantaneous orbit normal (with respect to the Earth) of the spacecraft, and the Z-axis completes the right-handed set.
Earth LVLH	CS2	Earth Local Vertical Local Horizontal (LVLH) is a non-inertial coordinate system based upon the motion of the spacecraft with respect to the Earth. The X-axis of this coordinate system is the position of the spacecraft with respect to the Earth, the Z-axis is the instantaneous orbit normal (with respect to the Earth) of the spacecraft, and the Y-axis completes the right-handed set.
SpacecraftBody	CS3	SpacecraftBody is the attitude system of the spacecraft. Since the thrust is applied in this system, GMAT uses the attitude of the spacecraft, a spacecraft attribute, to determine the inertial thrust direction.
Custom Designed Earth VNB	CS4	Same coordinate system as Earth VNB. (created using a different user interface)

Summary of Impulsive Maneuver Results

Orbit	Position RSS Error (m)	Velocity RSS Error (m/s)	Mass Error (g)
Earth	0	0	2.27374E-10
Moon	2.59206E-08	0	2.27374E-10
Mars	5.96083E-06	1.7764E-12	2.27374E-10

Coordinate System	Position RSS Error (m)	Velocity RSS Error (m/s)	Mass Error (g)
Earth Mean Equator J2000 (CS0)	0	0	2.27374E-10
Earth VNB (CS1)	0	0	2.27374E-10
Earth LVLH (CS2)	0	0	2.27374E-10
SpacecraftBody (CS3)	0	0	2.27374E-10
Custom Designed Earth VNB (CS4)	0	0	2.27374E-10

Test Category	Position RSS Error (m)		Velocity RSS Error (m/s)		Mass Error (g)	
	Low	High	Low	High	Low	High
Orbit	0	6.0e-6	0	1.8e-12	2.3e-10	2.3e-10
Maneuver Coordinate System	0	0	0	0	2.3e-10	2.3e-10
Tank Configuration	0	0	0	0	0	2.3e-10
All	0	6.0e-6	0	1.8e-12	0	2.3e-10

Mission Data Parameters

- Parameters are calculated on request
- Can be read-only or read-write
- One of three types:
  - Standalone
  - Central-body dependency
  - Coordinate system dependency
- Truth sources:
  - STK
  - custom MATLAB
  - custom GMAT scripting

Parameter	Access	Dependency
Spacecraft		
Cartesian position	RW	Coordinate system
Keplerian elements	RW	Coordinate system, celestial body
Epoch	RW	(None)
Attitude quaternion	RW	(None)
Duty cycle	RW	(None)
Thrust scale factor		
Fuel tank		
Fuel mass	RW	(None)
Fuel density		
Impulsive maneuver		
Cartesian maneuver direction	RW	(None)

Example parameters

Results: Coordinate-System Parameters

Orbit	Coordinate system	Velocity magnitude	RAAN	Declination	Right ascension of velocity
GEO	Earth J2000	4e-12	5e-14	5e-14	2e-9
	Saturn Fixed	8e-12	2e-5	8e-13	2e-5
Hyperbolic	Earth J2000	3e-8	1e-13	4e-9	4e-9
	Saturn Fixed	6e-13	2e-6	7e-13	2e-5
Mars	Mars J2000	5e-9	2e-11	2e-5	9e-7
	Saturn Fixed	6e-13	6e-6	3e-13	6e-6
Luna	Moon J2000	5e-10	6e-13	2e-6	3e-7
	Saturn Fixed	4e-13	3e-6	4e-13	2e-5

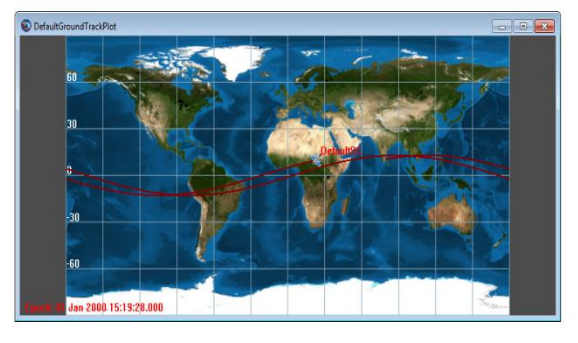
- Parameter calculations tested for multiple orbit types, with multiple coordinate-system dependencies
- Results compared against STK/Astrogator
- Selection of results shown
- Results are percent difference between GMAT and truth solution
  - 1 = 100% error
  - 1e-12 = 11 digits of agreement

Output/Utilities Methodology and Results

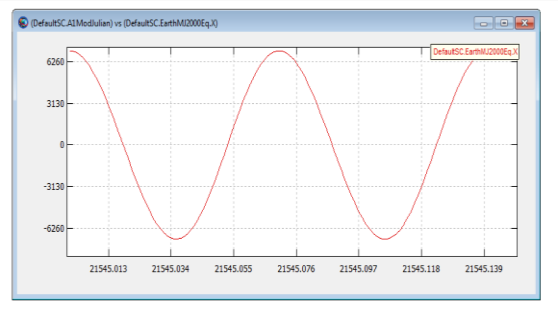
- Extensive & Systematic testing of all components in Output/Utilities feature area was done:
  - OrbitView
  - Spacecraft Visualization
  - GroundTrackPlot
  - XYPlot
  - ReportFile
  - EphemerisFile
  - Report
  - Toggle On/Off
  - ClearPlot
  - MarkPoint
  - PenUp & PenDown
- Only test results for 2-D, 3-D graphics and Ephemeris File are presented

2-D Graphics: Ground Track & XY Plot

- V&V testing methodology for Ground Track Plot employed standard GMAT GUI testing plans/procedures:
  - Testing involved visual inspection of each functional element
  - Compared graphical output to expected results from external tools
  - Prepared data for automated GUI regression tests that are run using the GUI regression test environment



- V&V testing methodology for XY Plot:
  - Initial testing involved visual inspection of all XY plot functional elements
  - Compared XY Plot output with MATLAB as the external benchmark tool
    - Equivalent XY data plots generated in MATLAB and GMAT and overlaid plots for visual comparison
  - For more rigorous & automated GUI testing, test scripts were written to test each XY plot element. Test scripts are used by the GUI regression test environment



Ephemeris File

- V&V testing methodology for EphemerisFile:
  - Extensive automated testing of ephemeris file component was conducted through GMAT's script test system
  - Test scripts for all functional elements were written
  - For CCSDS ephemeris format, we compared interpolation to MATLAB and STK implementations
  - For SPK ephemeris format, we tested SPK ephemeris output comparing the results to STK and MICE toolbox

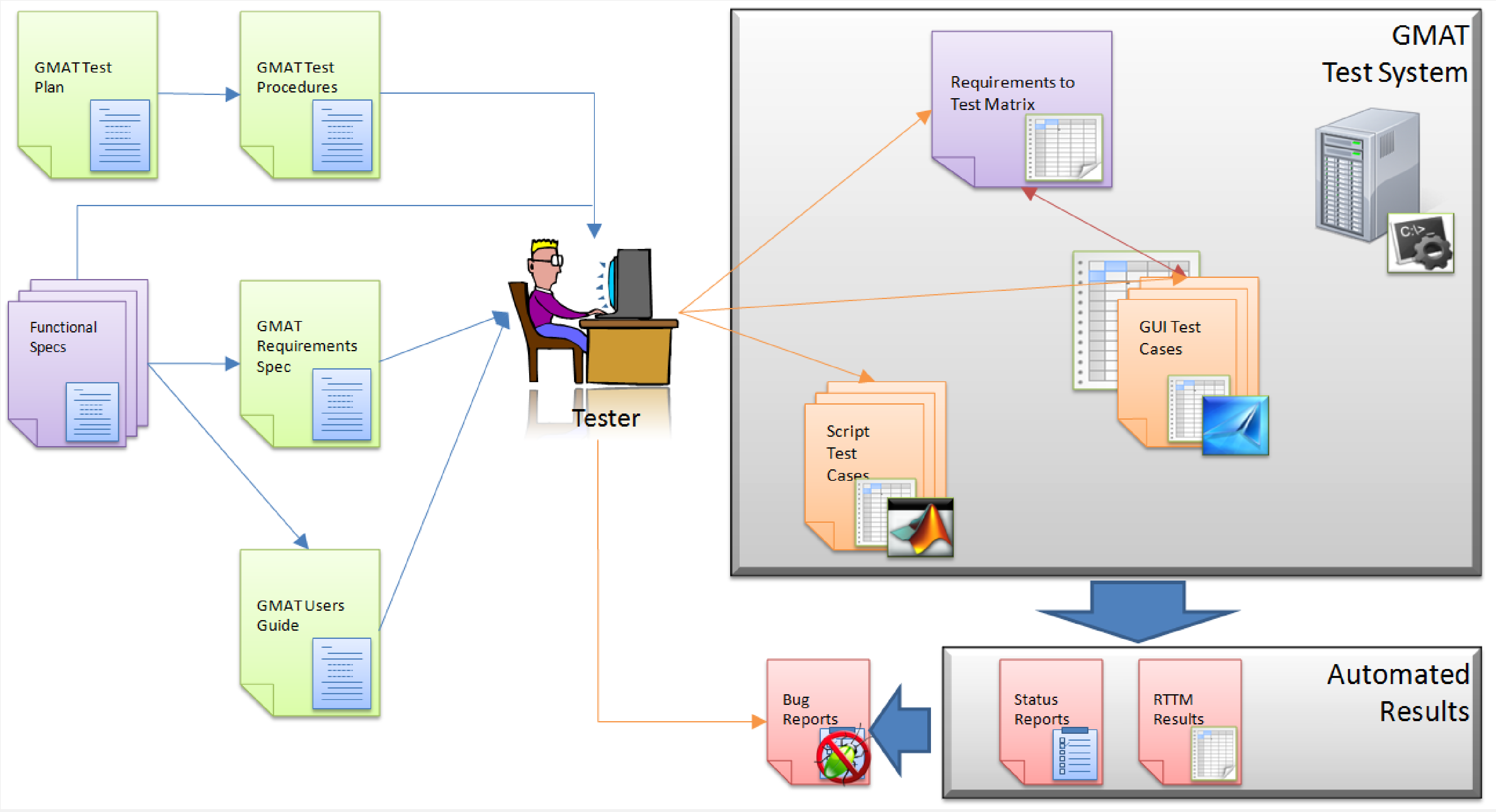
Programming Infrastructure

- Two testing areas
- Script Language: functional testing
  - Variables, arrays
  - Assignment, mathematics
  - Control flow, logical operators
  - External interfaces
- Mission Data Parameters: numeric testing

Script Language

- All features were tested with all applicable input and output types:
  - literals: numeric, strings
  - resources: variables, arrays, array elements, string variables, calculated parameters
  - mathematical expressions
- Special testing for:
  - Logical operators: all data types w/ all operators
  - MATLAB interface: all data types as input/output
  - Mathematical expressions

GMAT Test Processes



Goals of GUI Testing

- **Reasonable confidence that GMAT is user-ready**
- 100% coverage of GUI – every widget in the GUI gets exercised at least once
- 100% requirements fulfillment – every GUI-related requirement is fulfilled by the GUI
- Repeatable
- Maintainable