MAVERIC-II

Vehicle Flight Simulation Software

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Vehicle & Systems Development Dept
GN&C Group
Guidance & Trajectory Team

What is MAVERIC-II ?

- Flight simulation software developed In-house (MSFC)
- Facilitates rapid development of vehicle flight simulations for performance and trajectory analysis
- Any user-defined vehicle configuration
- All phases of flight
- Fidelity from conceptual design through flight
- Combines multiple subsystems and facilitates functional integration of a vehicle design
- It has become NASA's primary tool for simulating space transportation vehicle designs

MAVERIC-II Uses for Space Transportation

- X-33: the only end-to-end simulation used for vehicle design by Lockheed Martin Skunk Works
- X-37 Program's primary insight simulation
- Supported NASA insight for OSP and directly supported both the Lockheed Martin and Boeing vehicle designs
- X-43C (Boeing) used MAVERIC-II for boost phase simulation
- Supported Lockheed Martin directly on 2nd Generation RLV
- The only simulation tool used by SLI and NGLT to test the value of advanced guidance and control methods for improved flight safety
- Chosen as the "general" sim model for Vehicle Integrated Performance Analysis (VIPA) at MSFC
- Exploration Initiative: only sim used for recent Shuttle-derived vehicle analysis for the Exploration Initiative
- Currently adding automated rendezvous capability

Some Other Uses for MAVERIC-II

Because of its design architecture MAVERIC-II is flexible in its uses

MAVERIC-II can simulate any "system" that can be described as a group of subsystems for which force and moment equations can be written

including

- **Anything that flies (e.g. missiles, airplanes, birds, insects)**
- **Other transportation (e.g. Automated cars)**

Other NASA Centers

- Although MAVERIC-II was developed in-house at MSFC, it is attracting more attention throughout NASA.
- JSC personnel suggested using MAVERIC-II to model the Orbital Space Plane launch rather than duplicating effort at the two centers.
- Four centers recently agreed to work with MSFC on further MAVERIC-II development if proposed work was funded (GRC, GSFC, JPL and JSC)

Current / Recent MAVERIC-II Users

Lockheed Martin	LM OSP
bd Systems	Supporting Boeing OSP
Dynamic Concepts	SBIR, Loads Analysis
Barron Associates	SBIR, X-37 TA&L
UAH	Student Launch Initiative
Auburn University	ITAGCT
Iowa State University	ITAGCT
Ohio University	ITAGCT
Universal Space Lines	IDOS
MSFC	OSP, X-37, X-43C, ITAGCT…

Why is MAVERIC-II Unique ?

- Quickly model different vehicle types
- Swap out various models of subsystems quickly
- Model the full range of fidelity from concept to flight
- Model system failures easily
- Provides End-to-end simulation capability
- Monte Carlo Analyses easily performed

We have applied for a Provisional Patent for MAVERIC-II

Email received from Office of Chief Patent Counsel:

From: ***msfc.techtracs@nttsmail.larc.nasa.gov***
To: ***Jim McCarter***
Subject: ***Provisional Serial Number*** ***Sent:*** ***Wed 6/9/2004 11:52 AM***

Information from Office of Chief Patent Counsel:

Technology Case Number: **MFS-31989-1**
Patent Application Title: ***Marshall Aerospace Vehicle Representation In C (MAVERIC-II) Computer Program Provisional Filing Date:*** **05/05/2004**
Provisional Serial Number: **60 / 570,119**

Letters of Endorsement

"The capability for MAVERIC-II to model vehicles in low, medium or high fidelity provides several advantages when performing integrated analyses of space vehicles, including an important but often overlooked role of technical integration. The results from the MAVERIC-II simulation have been used to identify issues and risks much earlier than would have been possible without this capability."

-- **Don Krupp, Vehicle Integrated Performance Analysis (VIPA) Lead**

"MAVERIC-II was instrumental in understanding the adequacy of the X37 OV requirements by applying various guidance algorithms to the early design of the vehicle to evaluate the robustness and capabilities of the vehicle. The rapidity with which a new vehicle can be implemented is of significant benefit in gaining early insight into vehicle designs. It allows the user to easily substitute higher fidelity models (actuators, sensors, etc) to evaluate the adequacy of simpler models used by the contractor. Failure scenarios can also be assessed to understand risk. MAVERIC II greatly enhances our ability to efficiently evaluate guidance, navigation, and control designs, vehicle robustness, and requirements."

-- **Kerry Funston, X37 GN&C Lead Subsystems Engineer**

"The MAVERIC-II simulation program was used by all of the participating technology researchers in the Flight Mechanics Project's NRA8-30 contracted technology development efforts and by NASA technologists in several NASA-led technology research efforts. A number of vehicle simulation tools were considered for these tasks, but it was found that only MAVERIC provided the high fidelity vehicle and flight environment models as well as the program modularity to allow efficient integration, modification and testing of advanced guidance and control algorithms."

-- **Jack Mulqueen, SLI Lead Systems Engineer for Flight Mechanics**

Letters of Endorsement

cont'd

"I have personally used MAVERIC-II to simulate all phases of vehicle flight including launch, ascent, orbital insertion, on-orbit, de-orbit, entry, terminal area energy management (TAEM), approach and landing. The options and flexibility associated with modeling and simulating various complex vehicle configurations, in various flight phases, with various Guidance and Control algorithms are not known to exist in any other available simulation tool."

-- ***Jimmy Compton, Senior Staff Engineer, Dynamic Concepts, Inc.***

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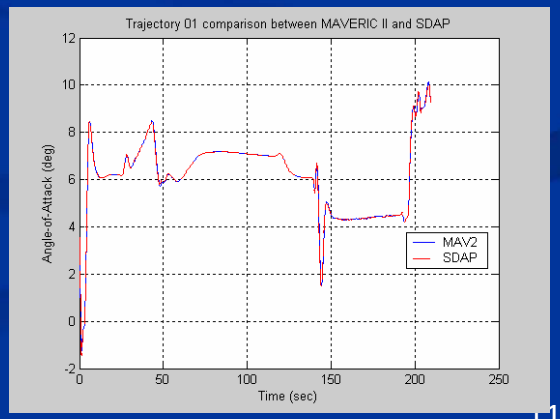
MARSHALL AEROSPACE VEHICLE REPRESENTATION IN "C"

MAVERIC-II provides rapid system analysis capability for X-37

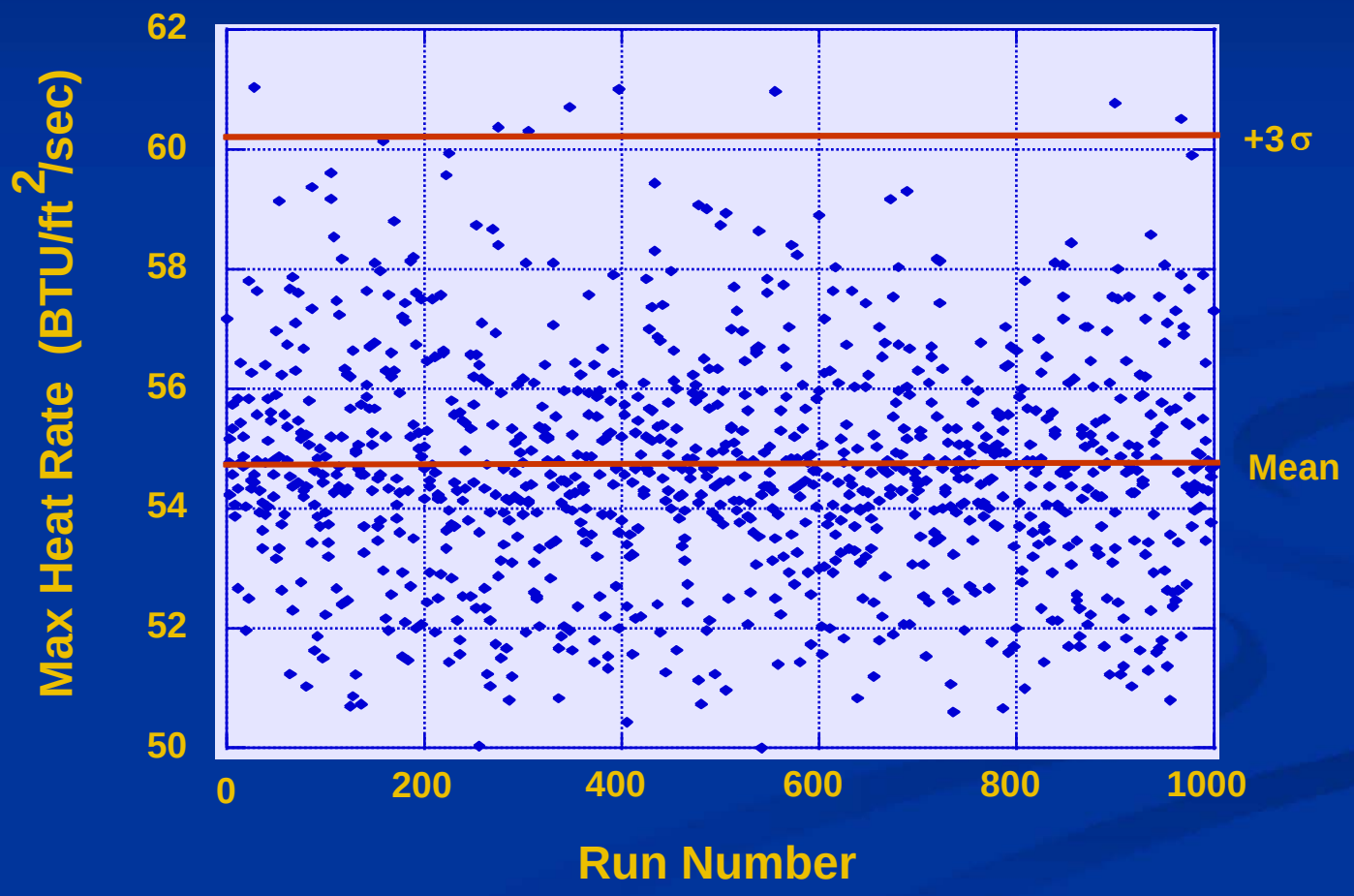
- Independent technical insight into contractor modeling
- Verification of controllability and performance requirements
- B-52 separation analysis
- Monte Carlo simulation capability
- Validation of contractor's simulation (SDAP)

MAVERIC-II offers capabilities not available in SDAP

- Greatly reduced hardware model integration time/effort (open architecture/portable)
- Large Monte Carlo run suites
- Enhanced atmospheric modeling
- Back-end tools to ease data-view and analysis
- Multiple vehicle simulation
- Multiple integration methods/step sizes
- Modeling of avionics data transport lag



Heat Rate Dispersions During X-37 Entry



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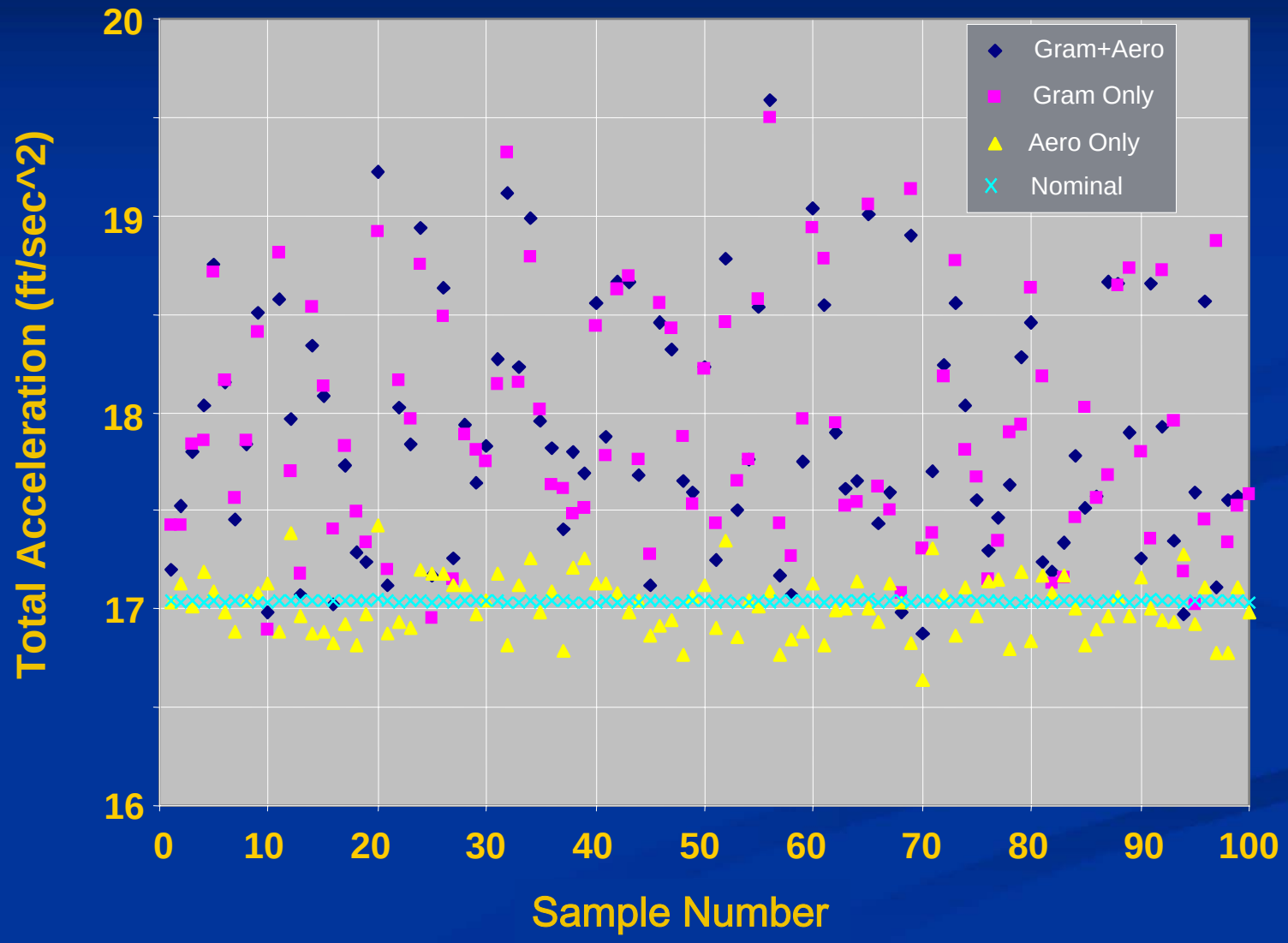
Offloaded Propellant Trajectory - Worst Abort Time Dispersions



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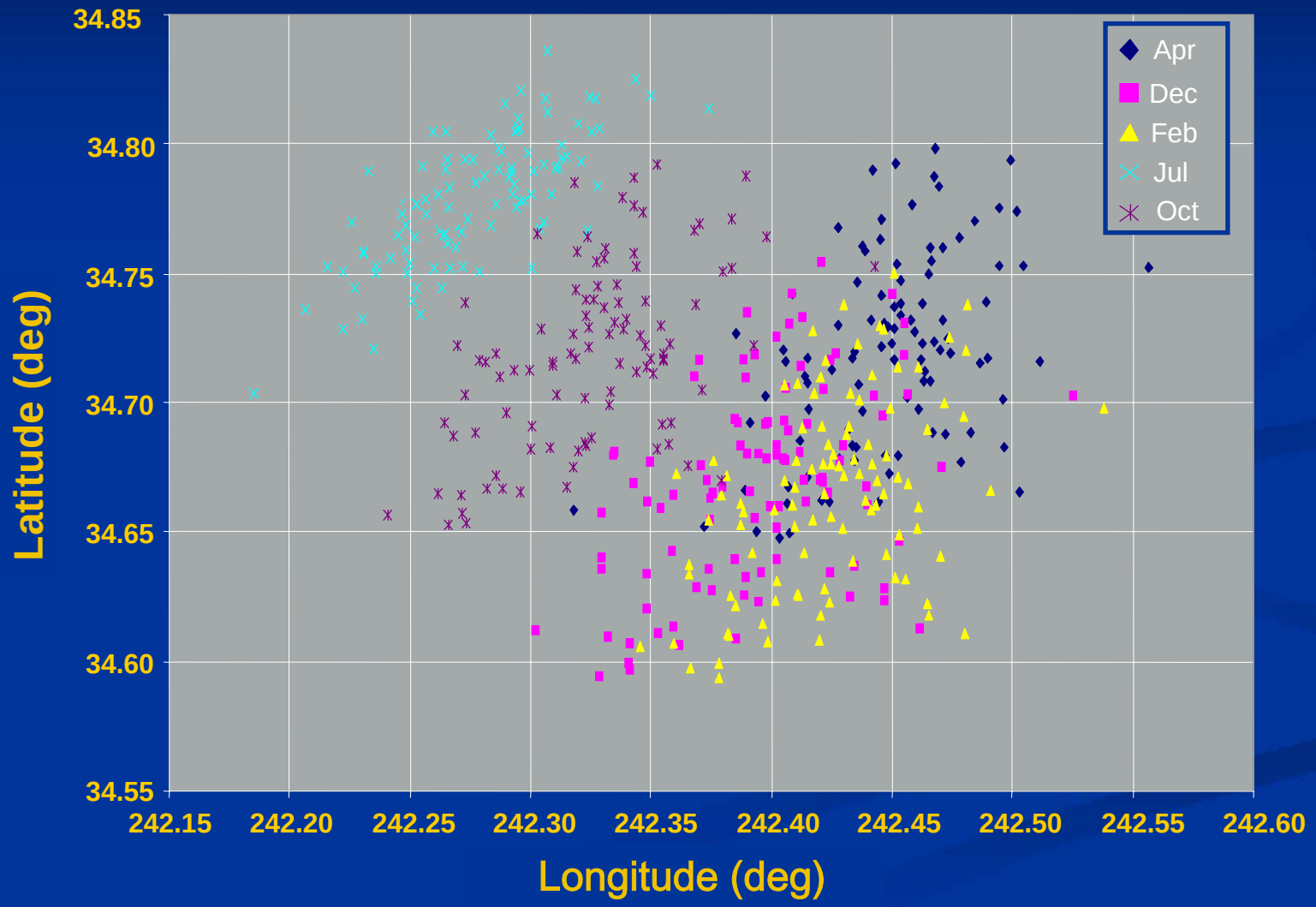
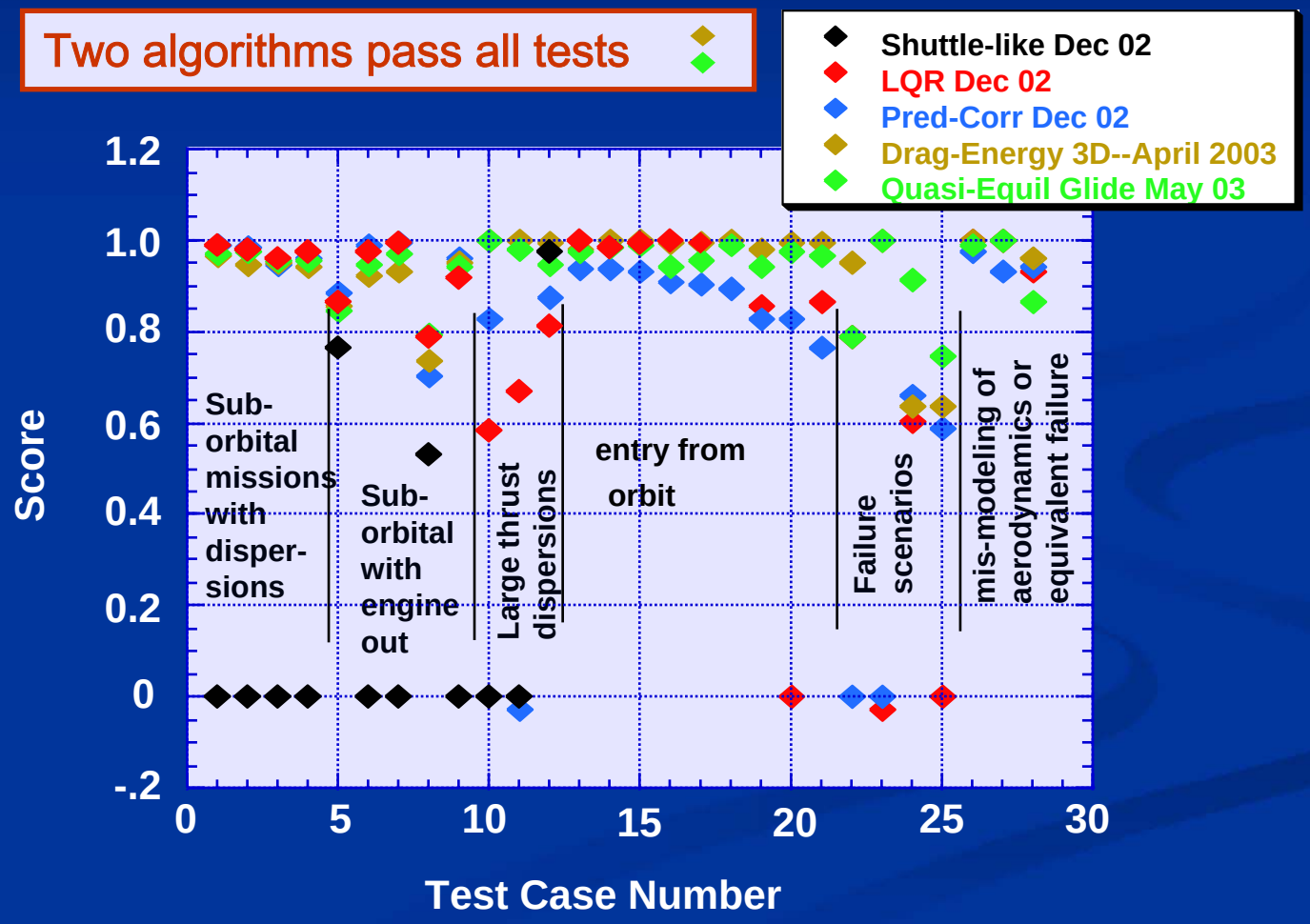
Touchdown Footprint



Entry Guidance Advanced Algorithm Test Results



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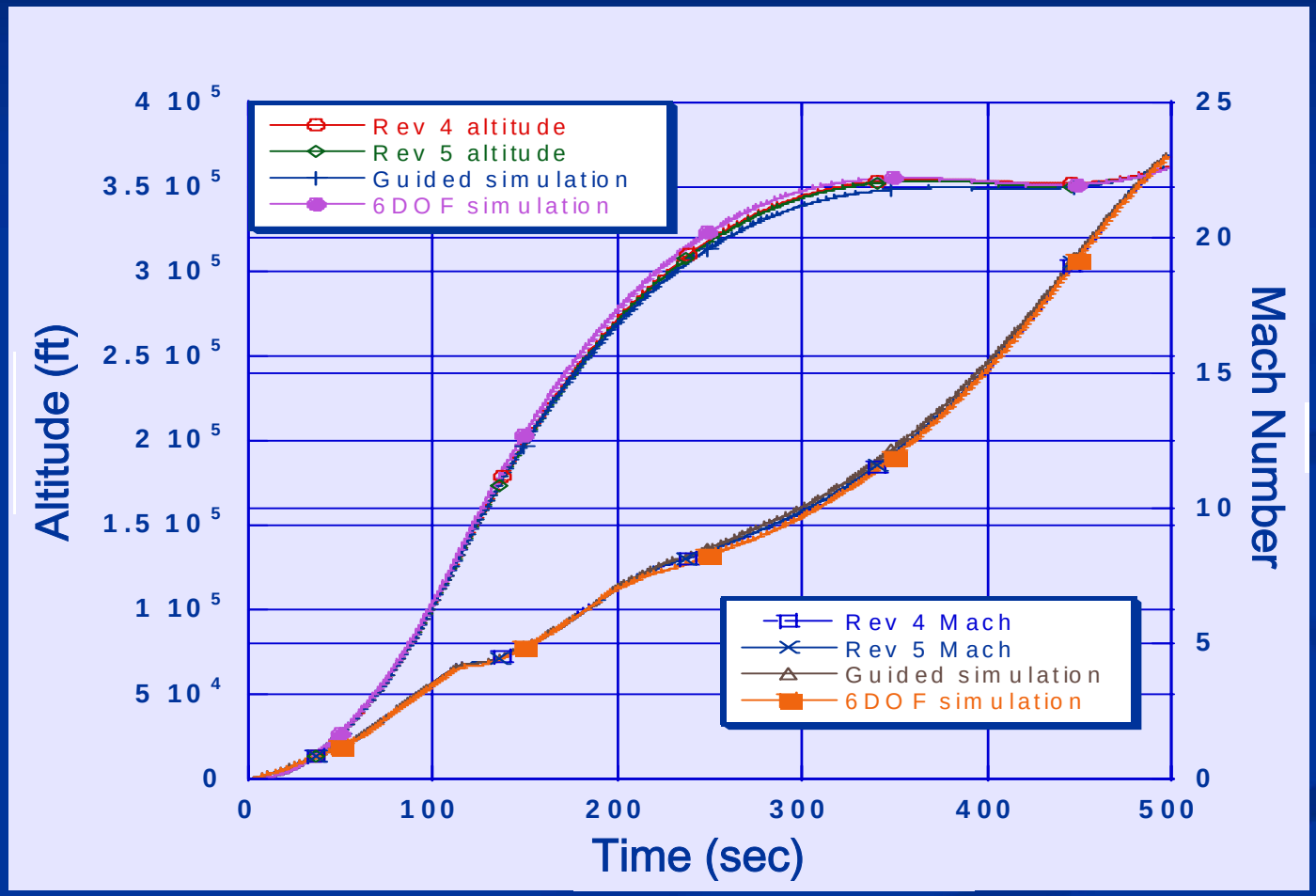
Shuttle-derived Cargo Vehicle



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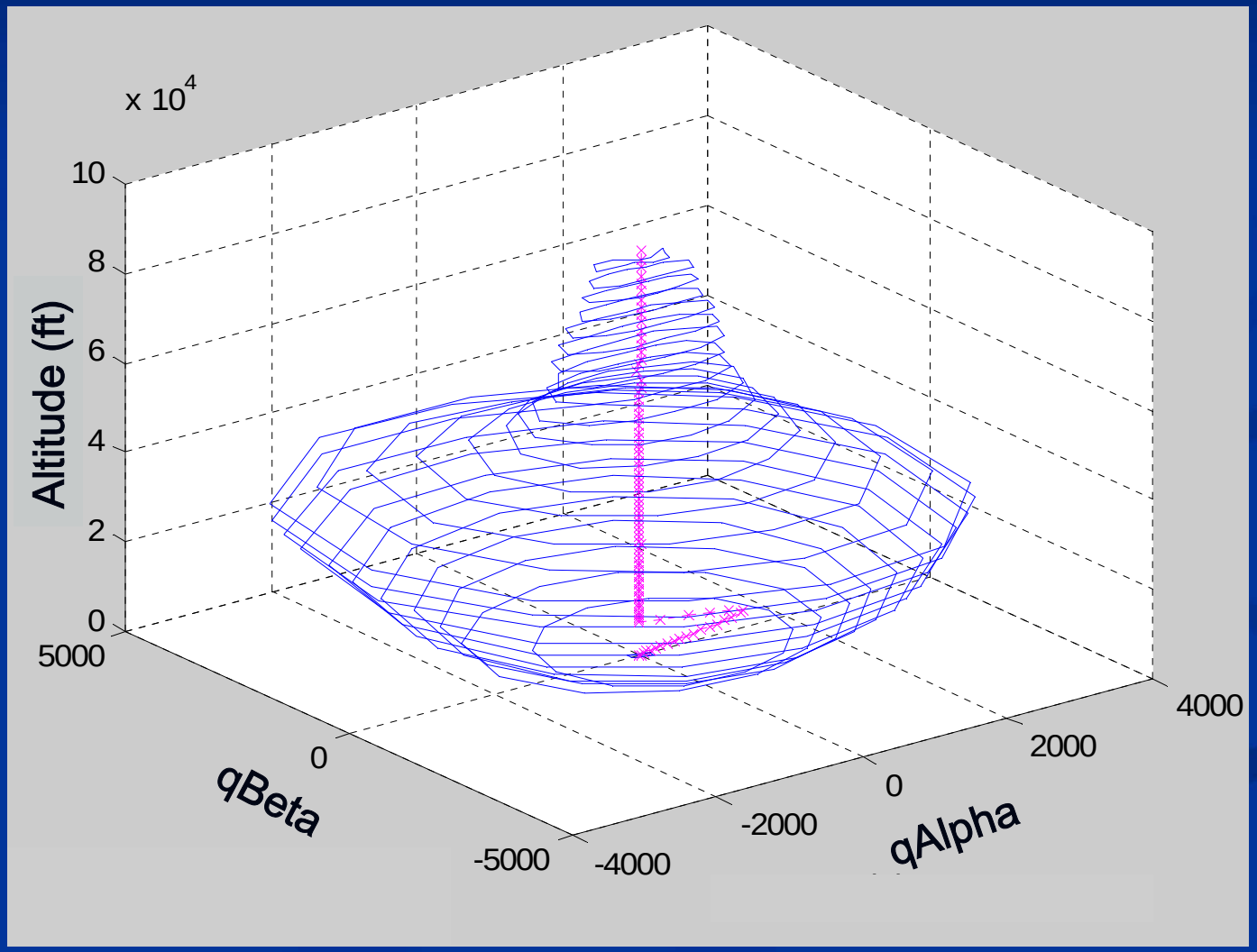
Side-Mounted Shuttle-Derived Vehicle – Ascent Squatcheloids



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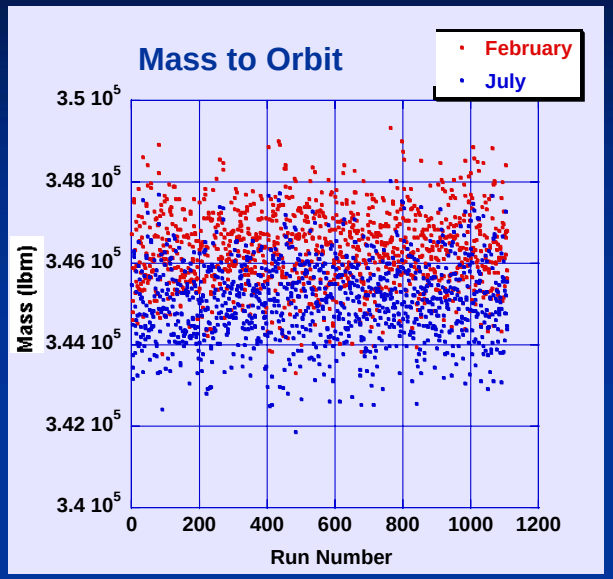
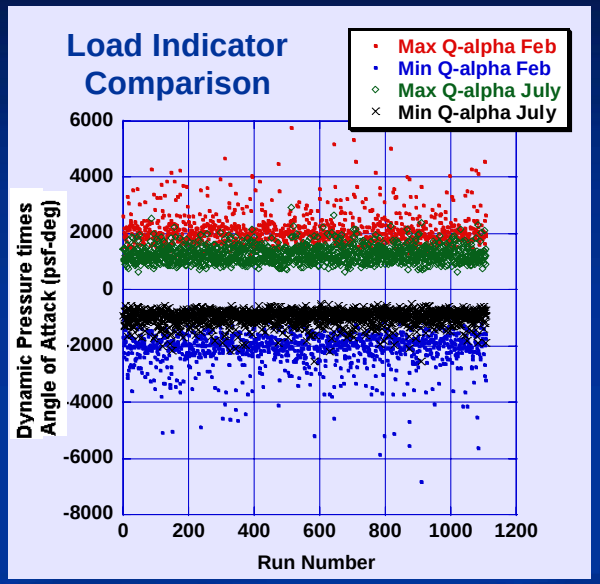
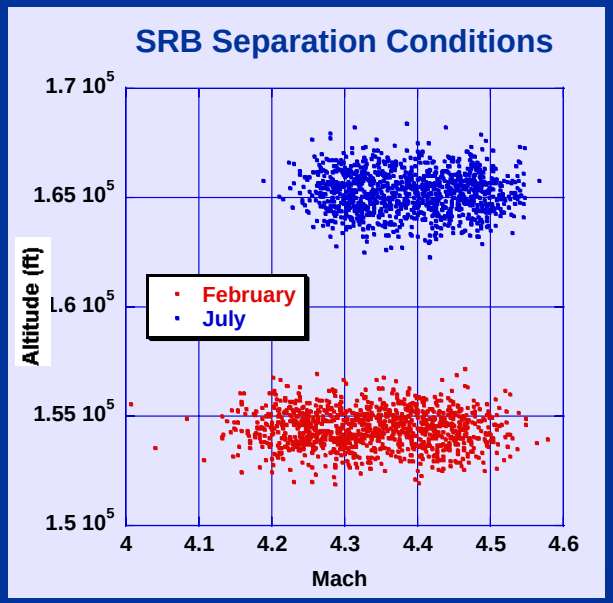
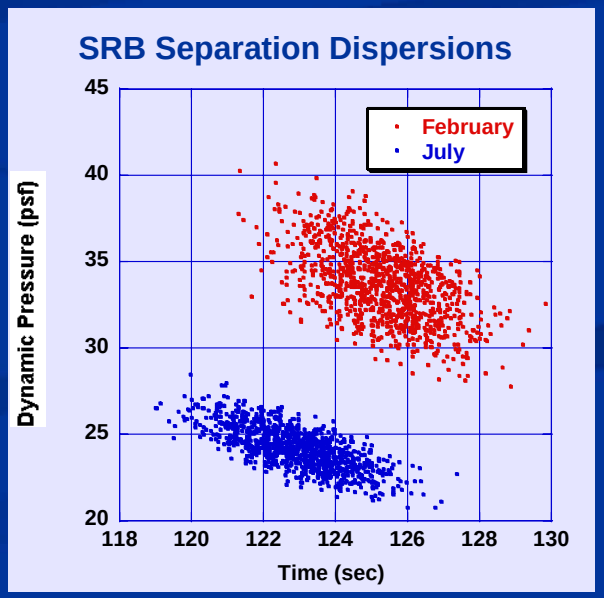


Dispersion Comparisons: February vs. July Environments





MAVERIC-II provides leverage for finding vehicle design issues early in a vehicle development program



Why is MAVERIC-II Important ?

- **MAVERIC-II fulfills the need for a versatile and comprehensive simulation tool.**
  - **Complex, high-fidelity simulations.**
  - **Any vehicle configuration and mission scenario**
  - ***Rapid simulation development.***
  - **Easy to learn and use.**

- **MAVERIC-II provides a *crucial design tool***
  - **Trajectory prediction**
  - **Vehicle flight behavior evaluation**
  - **Functional Integration of SW and subsystems**

- ***Early insight* of flight behavior in unexpected environments**
  - **An essential part of the vehicle design process.**
  - **Ensures that all flight regimes can be flown safely**

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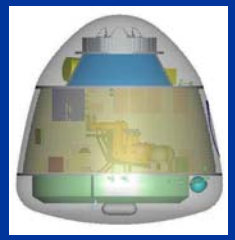
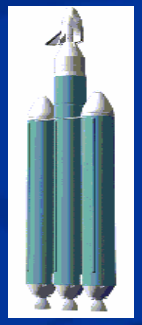
X-37 program selected MAVERIC-II as the primary insight simulation.

- **Approach and Landing test vehicle**
- **Orbital vehicle**
- **Examine alternative guidance and control**

X-43C program used MAVERIC-II to simulate its boost phase



OSP program used MAVERIC-II to support both Lockheed Martin's and Boeing's vehicle designs.



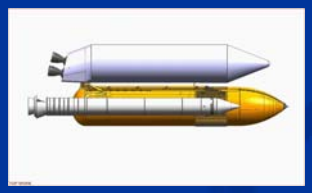
NGLT is using MAVERIC-II for testing advanced guidance and control methods.

Existing MAVERIC-II Simulations

X-33
Lockheed Martin Skunk Works

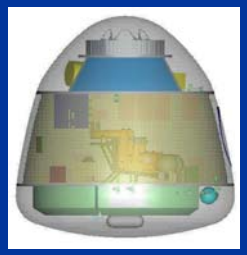
Saturn V
MSFC VIPA Activity

X- 43C
Orbital Sciences



Shuttle-Derived Cargo
MSFC VIPA Activity

X- 37
Boeing



OSP
Lockheed Martin

OSP
Boeing

Others: TSTO (LM), UAH 2-stage, Generic 2-stage (ITAGCT)

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MAVERIC-II can provide *realistic, high-fidelity* simulations which include effects such as:

- Atmospheric uncertainties.
- Onboard software communication delays.
- Hardware delays and response.
- Dispersions in navigation sensor readings.
- Behavior of Guidance and Flight Control software.
- Mass uncertainties (e.g. propellant loads).
- Wind uncertainties.
- Engine performance degradation / dispersions
- RCS and aero-surface actuator failures (other subsystems)
- Multiple gravitational sources.
- Propellant slosh forces and moments.
- High-Fidelity subsystem models.

Features and Creative (✓) Elements of MAVERIC-II

- ✓ Generic, modular program design
- ✓ Accommodates any vehicle configuration
- ✓ Propagates branching trajectories
- • Simple interface between integration "engine" and vehicle models
- ✓ Algorithm "plug-in" feature requiring no source code revisions
- • Generic models for mass properties, propulsion, aerodynamics
- ✓ Computes mass properties "on-the-fly"
- ✓ Dispersion (Monte Carlo) analysis capability
- ✓ Parametric study capability
- ✓ Parameter "out-of-bounds" tracking
- • Easily mixes discrete and continuous models
- • Low overhead and Fast execution with ANSI "C" coding
- • Accommodates C, C++, FORTRAN and MATLAB models
- • Simulates 3 or 6 Degrees-of-Freedom
- ✓ Flexible method of describing mission events and flightphases

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Generic Code Never Modified by User

Numerical Integration Engine

Libraries
- math
- sim models
- input
- output

Vehicle Flight Simulation Executive Routines

Global Variables are defined here

Set_simulation

Input and other one-time operations are performed here

Set_initial_values

Parameters are initialized here

Derivatives

Force and moment models and equations of motion are called from here

Report_results

Screen and File output routines are called from here

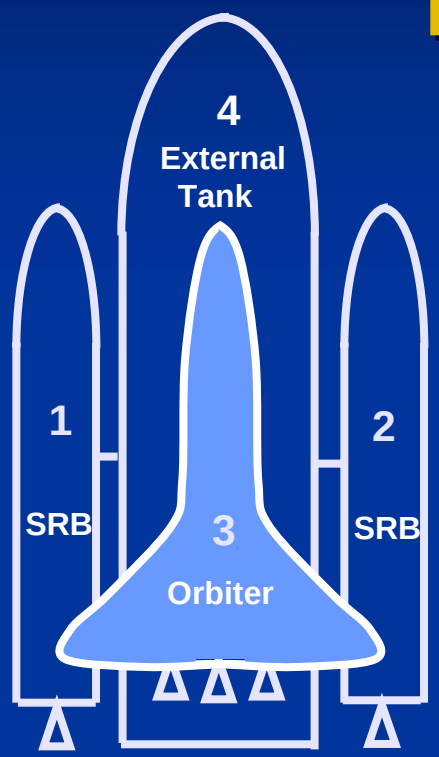
multi -run loop (Monte -Carlo)

Integration time loop

Flight simulation executive routines are called in the correct sequence by logic in the integration engine

```
Integrator_v ( accel,  &vel );
Integrator_v (   vel,   &pos );
```

Defining Vehicles to be Propagated



Vehicle	Stages	Enable Propagation	Start Propagation	End Propagation	
A	1 2 3 4	YES	Liftoff	SRB_sep	$
B	3 4	YES	SRB_sep	ET_sep	$
C	3	YES	ET_sep	ORB_meco	$
D	1	NO	SRB_sep	SRB_impact	$
E	4	YES	ET_sep	235.	$

A "Vehicle" is a group of one or more attached stages that is to be propagated.

Defining Flight Events

Event Flag	Condition that Toggles Event Flag ON or OFF
Liftoff	ON: time == 0. //
BST_meco	ON: oxRem.1 <= unuOx.1 || fuelRem.1 <= unuFuel.1 //
Stage_sep	ON: DT_BST_meco >= 1.25 //
ORB_meco	ON: oxRem.2 <= unuOx.2 || fuelRem.2 <= unuFuel.2 || time >= tCutoff.B //
Insert_LEO	ON: ORB_meco == 1 //
firstApogee	ON: time < 7200. && fpa.A < 0.
Circ_burn	ON: firstApogee.A == 1 OFF: speed.A >= circOrbitSpeed.A //
Sim_stop	ON: Orb_meco == 1 //
$	

Defining Flight Phases

```
VEHICLE_A_PHASES
        BST_ascent    START:  Liftoff  == 1       //
        $

VEHICLE_B_PHASES
        ORB_ascent    START:  Stage_sep  == 1   //
        Coast_100nm   START:  Orb_meco  == 1   //
        OMS_burn_1    START:  Alt_100nm  == 1 //
        Coast         START:  speedFps.B  >=  circSpeedFps.B   //
        ORB_entry     START:  alt_Ft.B  <=  400000.   //
        $

VEHICLE_C_PHASES
        BST_post_sep  START:  Stage_sep  == 1       //
        BST_descent   START:  fpaDeg.A  <  0.       //
        BST_brake     START:  speedFps.A  <=  88.   //
        $
```

Setting the Gravitation Options

Flight Phase	Central Body	Cent. Body Gravity Model	Degree x Order	Additional Gravity Fields
Ascent	EARTH	KEPLER		
Insertion	EARTH	Hi-Fi	20 20	
TransLun	EARTH	Hi-Fi	5 5	SUN MOON
Lun_orbit	MOON	Hi-Fi	50 50	EARTH SUN
Landing	MOON	Hi-Fi	100 100	

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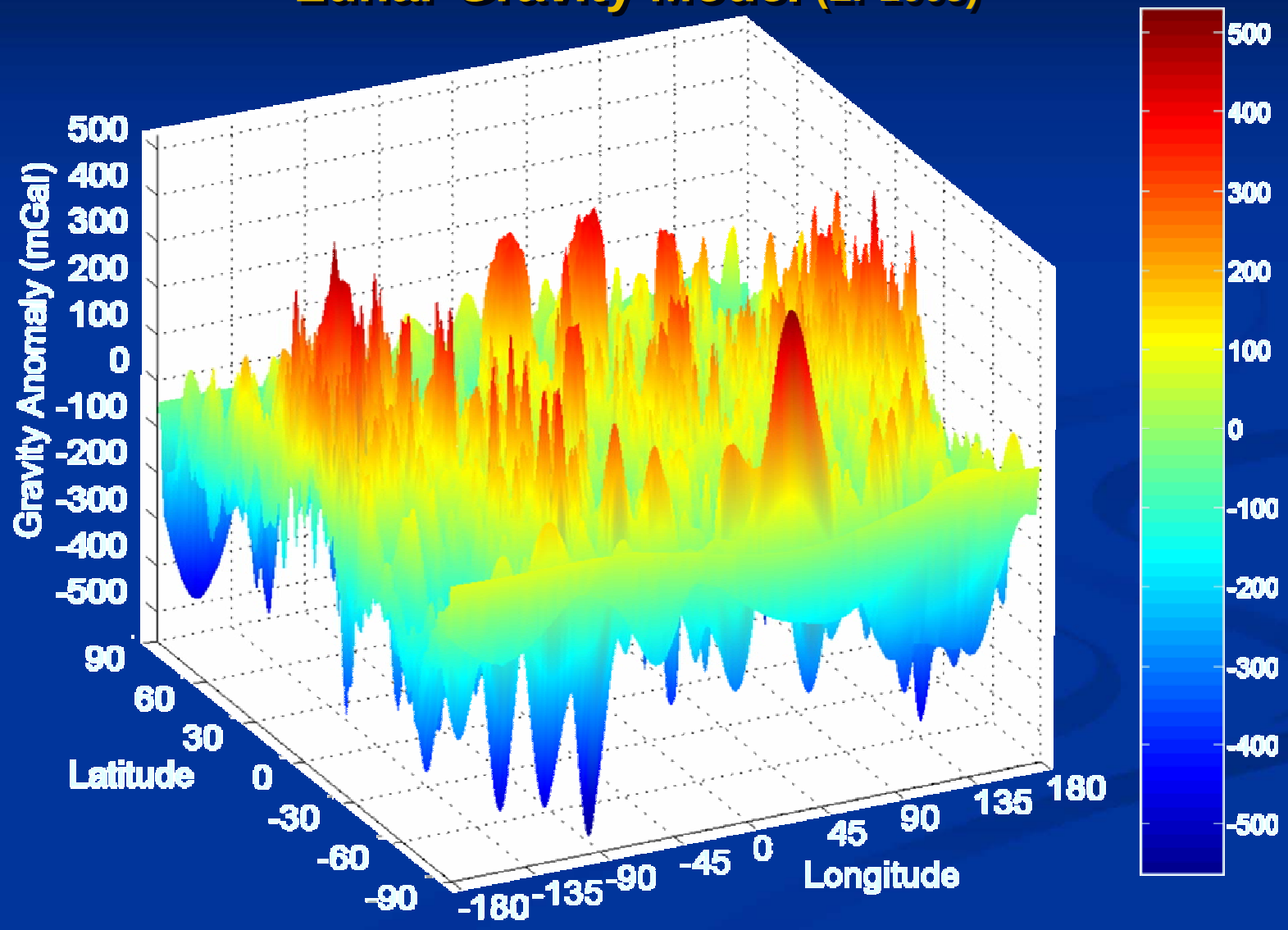
Lunar Gravity Model (LP100J)



Parameter Out-of-Bounds Detection

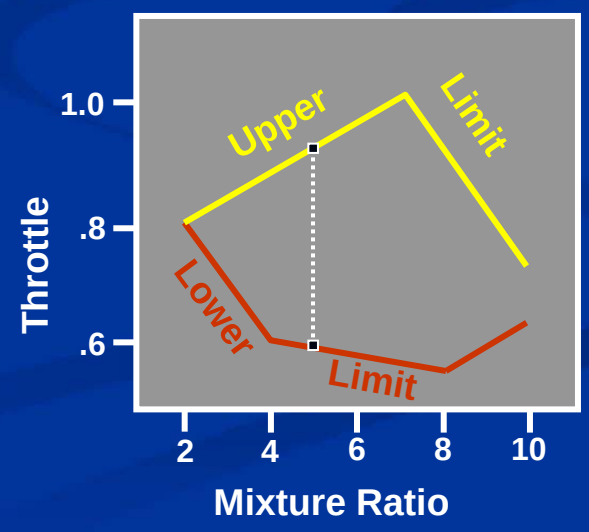
Parameter	Independent Variable	Lower Limit Value/Table	Upper Limit Value/Table	Start Event	End Event
fpaDeg.A	*	*	*	*	ORB_meco
alphaDeg.A	time	-.5	10.2	0.	ORB_meco
throttle	mixRatio	Throt_LL_tbl	Throt_UL_tbl	Liftoff	ORB_meco
⋮					

Lower Limit Table

Throt_LL_tbl	
mixRatio	throttle
2.	.8
4.	.6
8.	.55
10.	.62

Upper Limit Table

Throt_UL_tbl	
mixRatio	throttle
2.0	.8
.71	1.0
10.	.7



Propulsion System Input Data

```
ENGINE_1_OF_STAGE_1
   engine_type          1                  #  1-Bi-Prop   2-Solid Prop   3-Mono-Prop
   nozzle_exit_area    20.5   (in2_to_ft2) #  ft^2

   #                   Stage   Tank
   propellant_source     1       1
                         1       2

   location             17.87   0.   0.   (m)      #  Position vector of engine in
                                                    #   structural frame (ft)
   yaw_cant_angle        1.8    N   .12            #  N for Normal distribution
   pitch_cant_angle      2.3    U   2.   %         #  U for Uniform distribution

   #                          ENGINE_GIMBAL_ANGLE_LIMITS
   #    Flight Phase     Min Pitch     Max Pitch     Min Yaw     Max Yaw
        BST_ascent        -6.           6.            0.          360.
        ORB_entry          0.           0.            0.            0.
        Drogue             0.           0.            0.            0.
        Main_chute         0.           0.            0.            0.
           .
           .
```

Conclusions

- Prior to MAVERIC-II, high fidelity vehicle sims were complex tasks requiring many people to produce a one-of-a-kind, vehicle-specific simulation.
- MAVERIC-II was designed to be a generic, reusable simulation tool to be easily learned and used by engineers involved in vehicle design.
- In-house development of MAVERIC-II has resulted in cost savings of millions of dollars.
- MAVERIC-II represents a significant vehicle design and trajectory analysis capability that has made it possible to provide simulation support to the RLV, TSTO, SLI, OSP, NGLT and CEV programs.
- MAVERIC-II is positioned to provide support to Code T in using simulation-based acquisition to make smart architecture choices, potentially saving billions of dollars by identifying issues earlier in the design process.

MAVERIC-II is a significant addition to NASA's space transportation engineering capability

The End