Guidance and Navigation for a Martian Sample Return Ascent Vehicle

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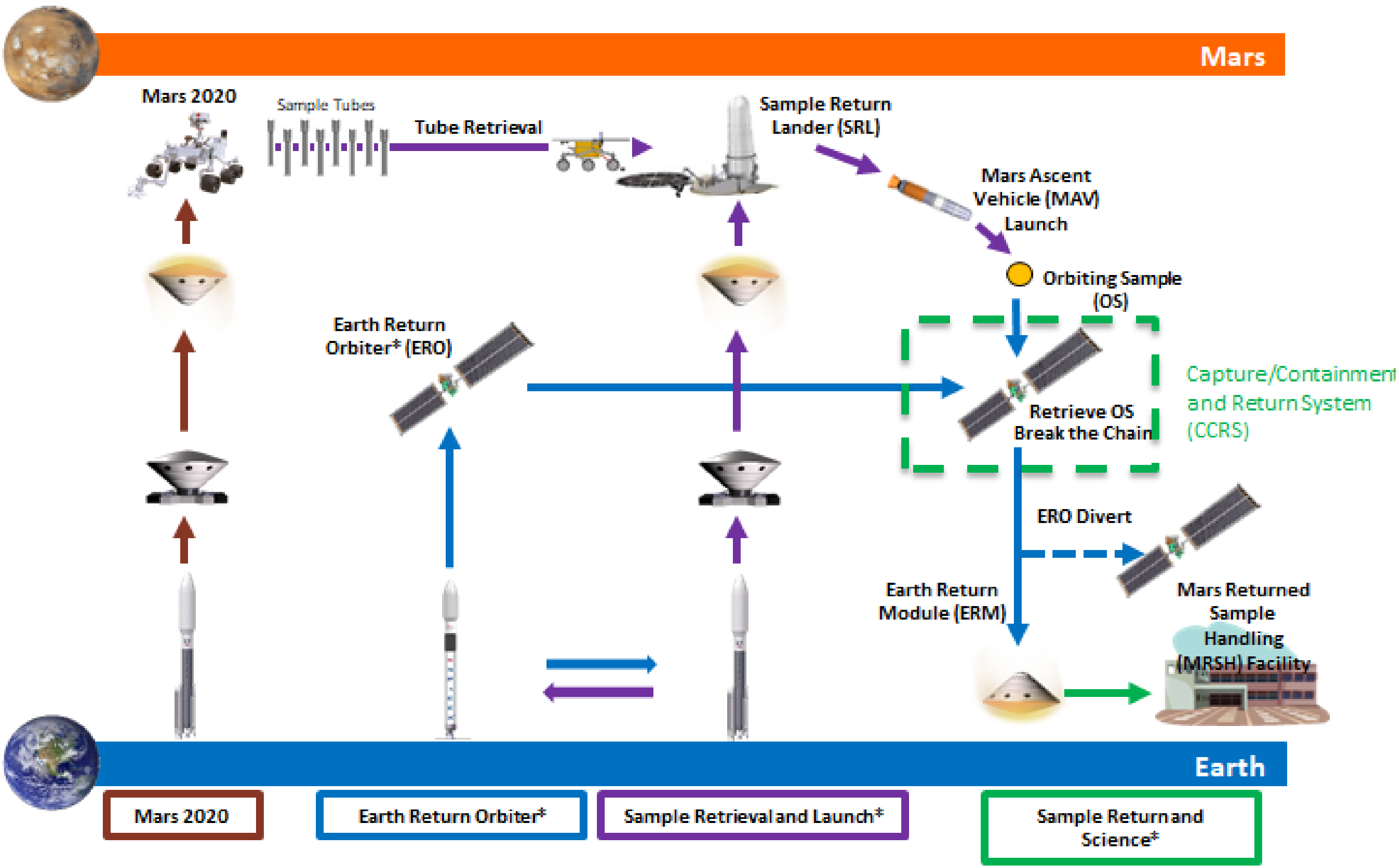
Overview

- Mission Design and Concept of Operations
- Vehicle Concept and System Requirements
- Guidance and Navigation Architecture
- Simulation Architecture
- Guidance Algorithm Development
- Navigation System Design
- Integrated Vehicle Performance
- Continuing Analysis and Trades
- Conclusions

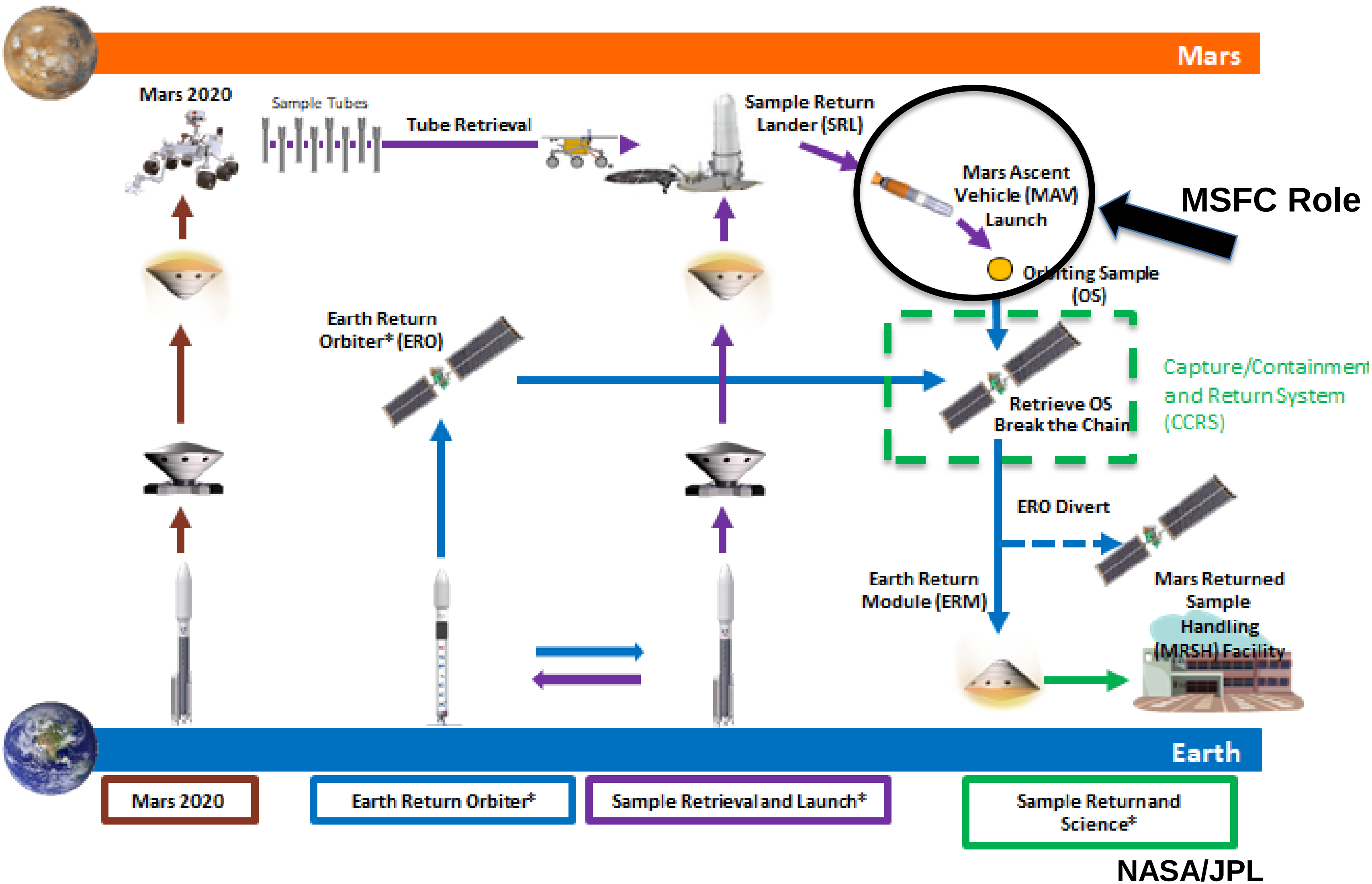
Mission Concept of Operations



NASA/JPL

[NOTIONAL, CONCEPTS UNDER STUDY]

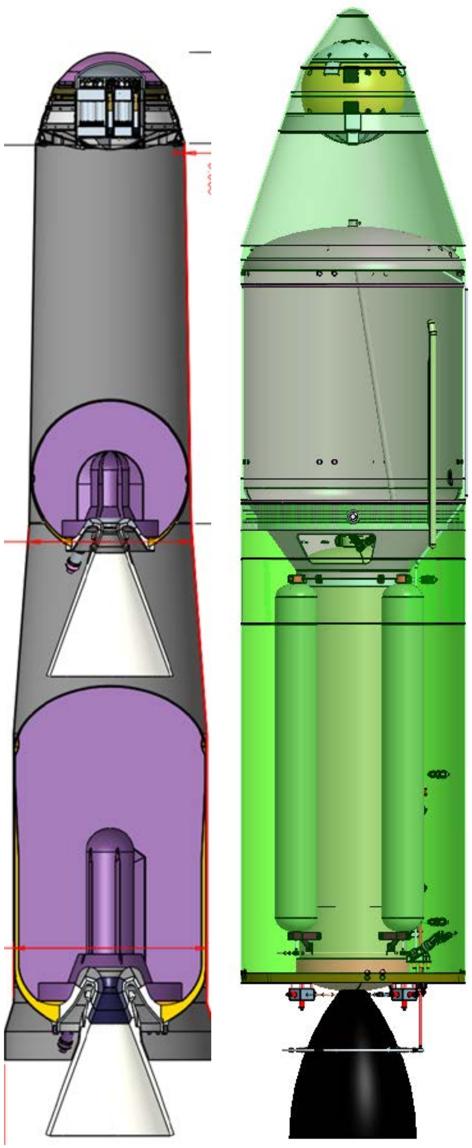
Mission Concept of Operations



[NOTIONAL, CONCEPTS UNDER STUDY]

Mission Design and Concept of Operations

- **Goal of Mission:**
  - To return ~5 kg sample from Mars back to Earth
- **Goal of Ascent Vehicle:**
  - Receive sample from surface rover, and insert sample into desired orbit (accuracy TBR) with long lifetime (12+ months)
- **Other Constraints:**
  - Launch vehicle propellant must be stable for 5+ years
  - Entire ascent platform and vehicle must fit within volume and mass requirements to land on Mars
  - Autonomous pre-launch procedures and operations during flight
  - Synchronization with orbital relays for detailed flight telemetry and reconstruction (to aid in rendezvous with sample rendezvous spacecraft)
- **Two Vehicle Configurations in Parallel Development**
  - 2-stage Solid Motor with actuator TVC + RCS
    - HTPB + AP (NH_4ClO_4)
  - 1-stage Hybrid with LI-TVC + RCS
    - Re-startable (2-burns)
    - MON25 + SP7

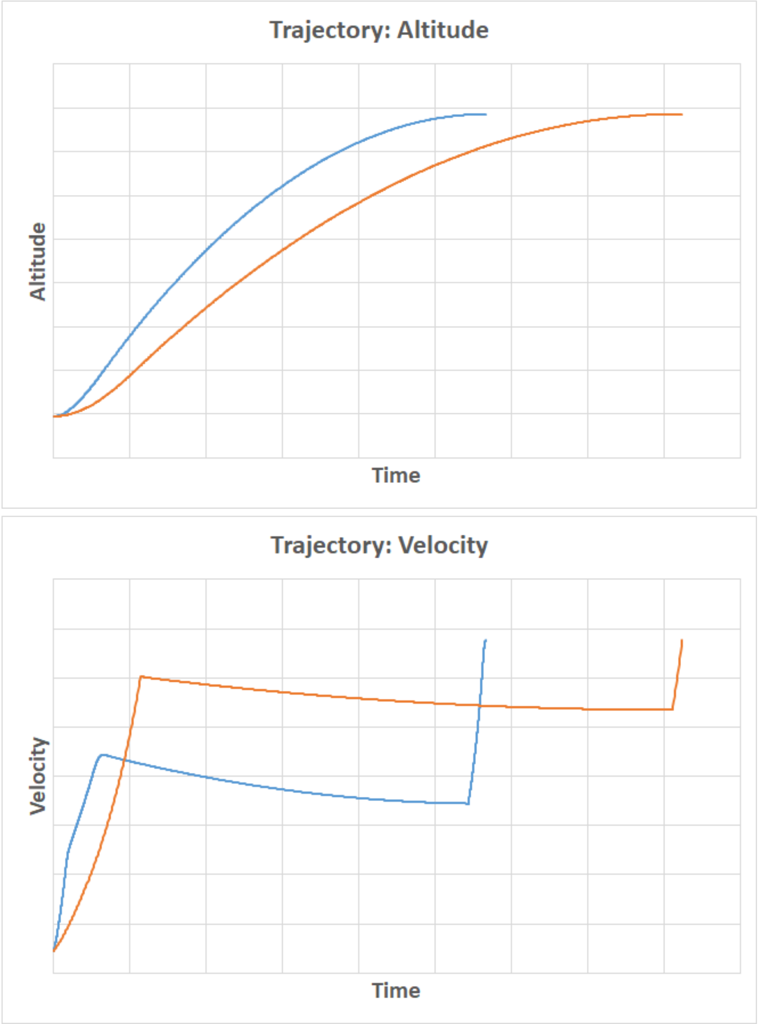


Vehicle Concept and System Requirements

- **Mission Objectives**
  - 23.06 [kg] payload, 343 x 343 [km] 25° inc. orbit, 400 [kg] GLOM limit
- **Requires dV ~ 4000 m/s**
- **Vehicle Design**
  - GLOM, payload goals drive compact, energy-dense propulsion design
  - Coupled propulsion design with trajectory design and optimization to produce dV split, burn times, thrusts, other specs to meet mission
  - Iterative design process for vehicle closure
- **Trajectory Design**
  - 3DOF vehicle trajectory optimized with both OTIS and POST
  - Resulting trajectories and vehicles for hybrid and solid differ

Ascent Profile

Blue = Solid Propellant
Orange = Hybrid Propellant



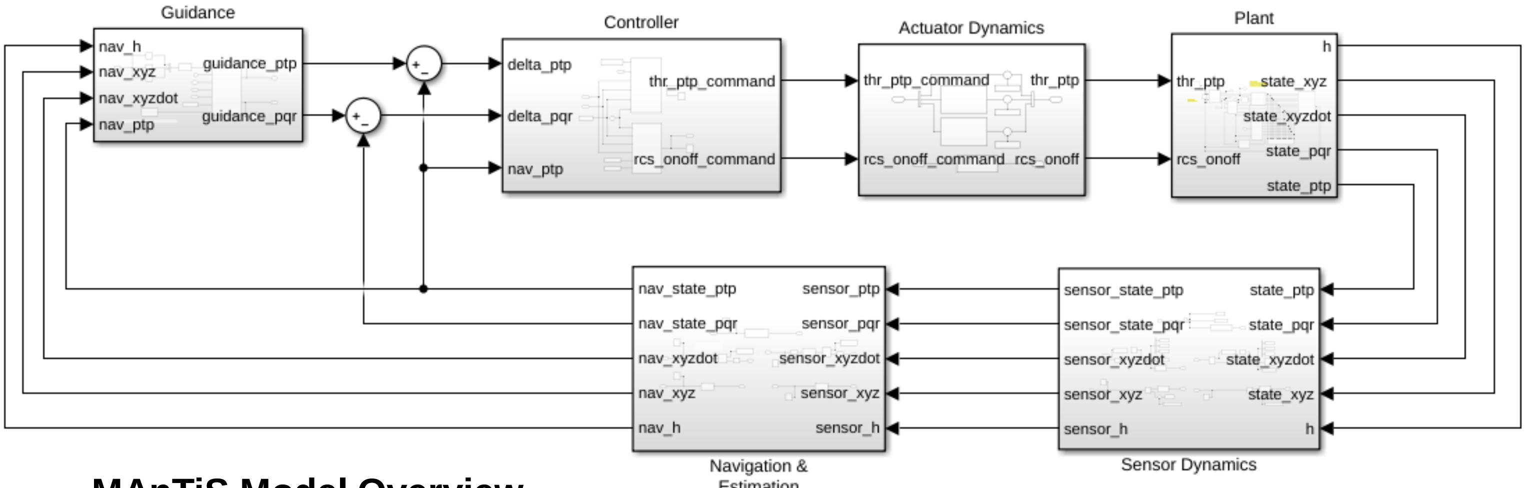
OTIS: Optimal Trajectories by Implicit Simulation – NASA Glenn Research Center
POST: Program to Optimize Simulated Trajectories II (POST2) – NASA Langley Research Center

Guidance and Navigation Architecture

- **Strapdown inertial navigation during flight**
  - Inertial measurement unit supplying acceleration and angular rate
  - Comparing variety of platforms from MEMS to Navigation-grade
  - Trade between mass/volume and performance
  - Additional IMU and sun sensor on lander platform potential for initialization
- **Onboard actuators**
  - Thrust vector control on 1st stage
  - Roll Control System on 2nd stage
- **All software resides on upper stage of vehicle for operation during flight**
- **Staging design principles**
  - First stage to quickly gain altitude
  - Coast to apogee
  - Second stage to circularize orbit
- **Autonomous sequence for initialization, countdown, and ascent**
- **Guidance Options**
  - Must be robust to propulsion architecture (liquid and solid)

Simulation Architecture and Tools

- **Mars Ascent Vehicle (MAV) Analysis Tool in Simscape (MAnTiS)**
  - Plant: Aero, Gravity, Atmosphere, Thrust, Mass
  - Sensor Dynamics (state model ~ Markov Bias and noise)
  - GNC: Two Stage Guidance, State Estimation, TVC and RCS commands
- **Other internal standalone tools**
  - Guidance Implementations in MATLAB
  - Mars Ascent Vehicle Navigation (MAN) Toolkit in Python
  - Generalized Lunar Lander Simulation in Simscape (GLASS)
- **MAN + GLASS share same parent code base**
  - Developing standardized inertial navigation toolkit with PYTHON, MATLAB, and C/C++ wrappers
  - Updated common navigation model being integrated into MAnTiS
  - Validation planned against verified and validated SLS INS model
  - Moving towards integrated/common code-based for GNC analysis for landers/small launch vehicles
- **Functionality: Variance-based Sensitivity Analysis, Monte Carlo Simulations, 1/2/X-D Trades**



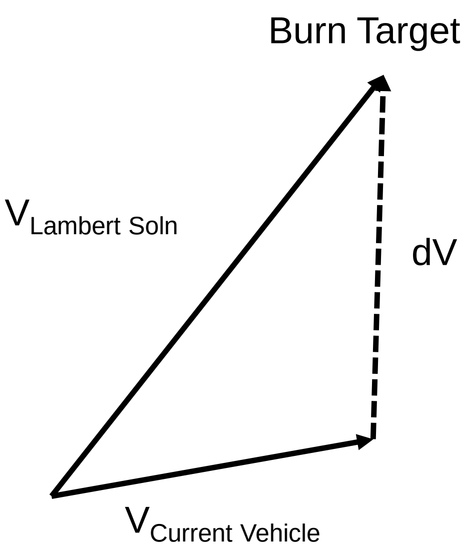
MAnTiS Model Overview

Guidance Algorithm Development

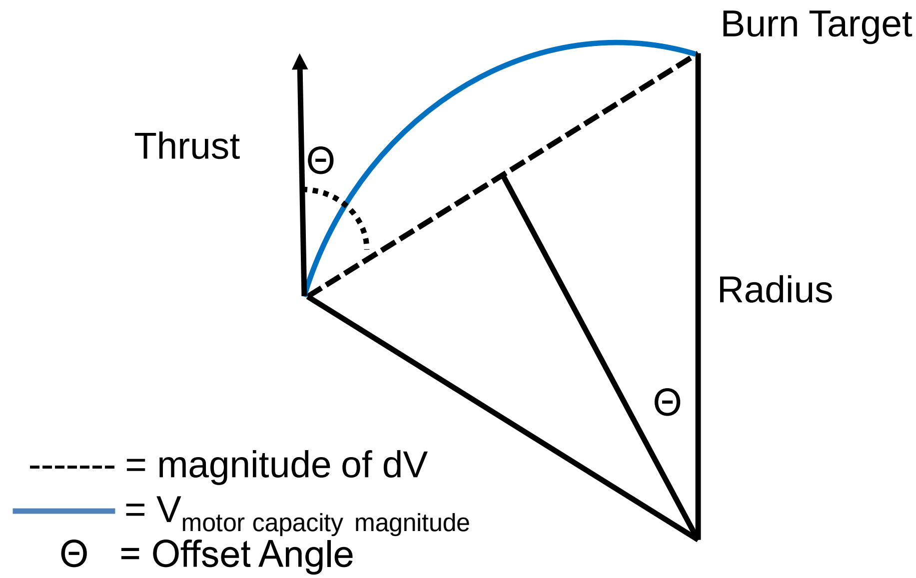
- **Primary Problem:** Design guidance to allow for excess energy in solid motors which must be burned, and which is applicable for use in hybrid motor
  - Typical large vehicle solutions (solid: blow-out panels, liquid: PEG, IGM) are either too heavy or do not apply to both solid and hybrid motors
- **Algorithm Options for 1st Stage:** Open Loop, Lambert, GEM
- **Algorithm Options for 2nd Stage:** Open Loop, Lambert, GEM, Inertial Hold
- **Open Loop:** Fly commanded launch inertial pitch from simulated trajectory
- **Closed Loop Lambert:**
  - Calculate lambert solution to burn target every 1 second
  - Pitch at a preset rate until current velocity vector matches Lambert solution
- **Closed Loop GEM:**
  - Energy wasting technique to ensure thrust terminates at burn target
  - Requires accurate estimate of remaining motor dV capacity
  - Pitch off from lambert solution until dV capacity matches lambert solution, then employ lambert
- **Inertial Hold:**
  - Align thrust with velocity vector and burn to circularize the orbit

Lambert & GEM Guidance

Lambert Guidance



GEM (General Energy Management)



As the motor burns, the delta-V capacity of the motor reduces. As that magnitude of the delta-V capacity of the motor approaches that required by the Lambert guidance, the offset angle approaches zero. This ensures zero dV capacity and target accuracy at the end of the burn.

Figures redrawn from: Zarchan, P., “Tactical and Strategic Missile Guidance,” *Chapter 14. Lambert Guidance,* 2nd ed., Vol 157, AIAA, Washington DC, 1994, pp. 292-298

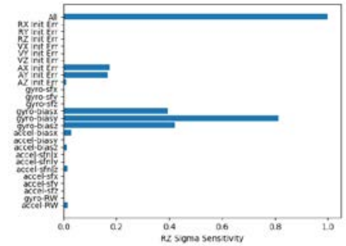
Navigation System Design

- **Sensor options**
  - STIM3000, LN200S, HQ, MQ, HG1930, HG9900
- **Inertial navigation approach**
  - Integrate measurements at 200Hz
  - Assuming IMU coning-sculling compensation
  - 2-body gravity model
  - Use of launch-fixed inertial frame
- **Approaches to initialization**
  - Onboard gyrocompassing
  - Transfer alignment from platform
  - Sensitivity analysis for position and attitude initialization requirements
- **Performance along 3DOF trajectory with generated 6DOF attitude dynamics to match commanded pitch profile**

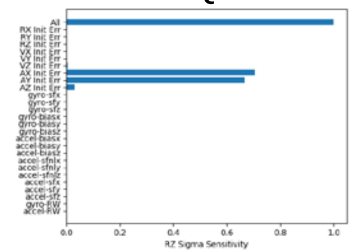
Inertial Z Position Error 1-Sigma

<u>10m, .1 m/s, .5 deg</u>

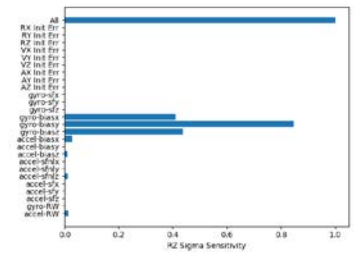
STIM3000

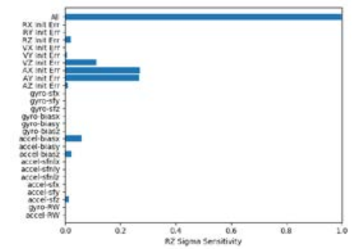


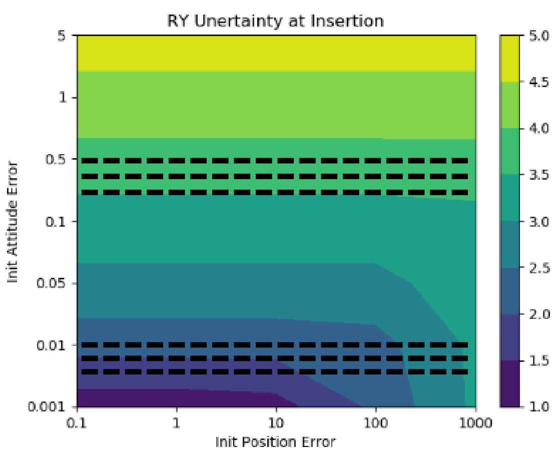
HQ

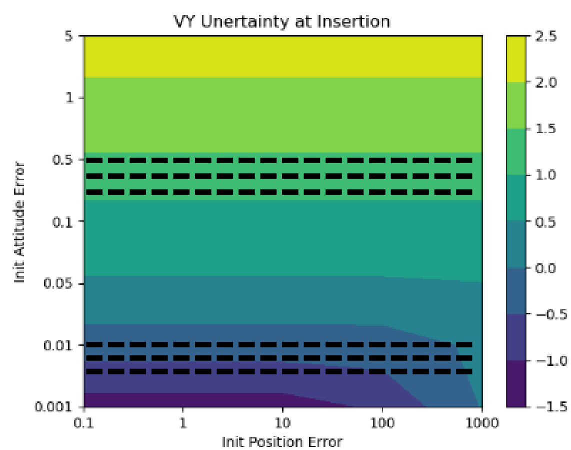


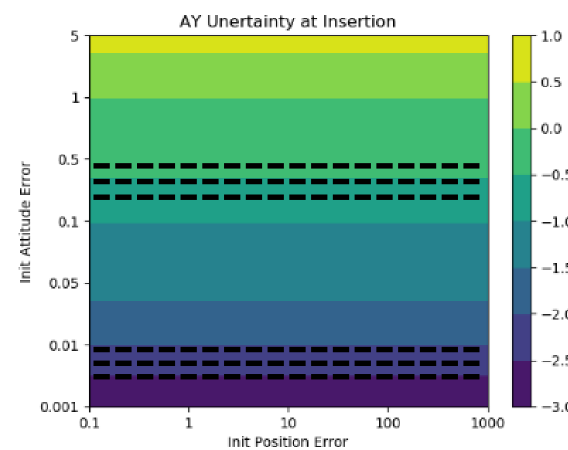
<u>10m, .1 m/s, .01 deg</u>







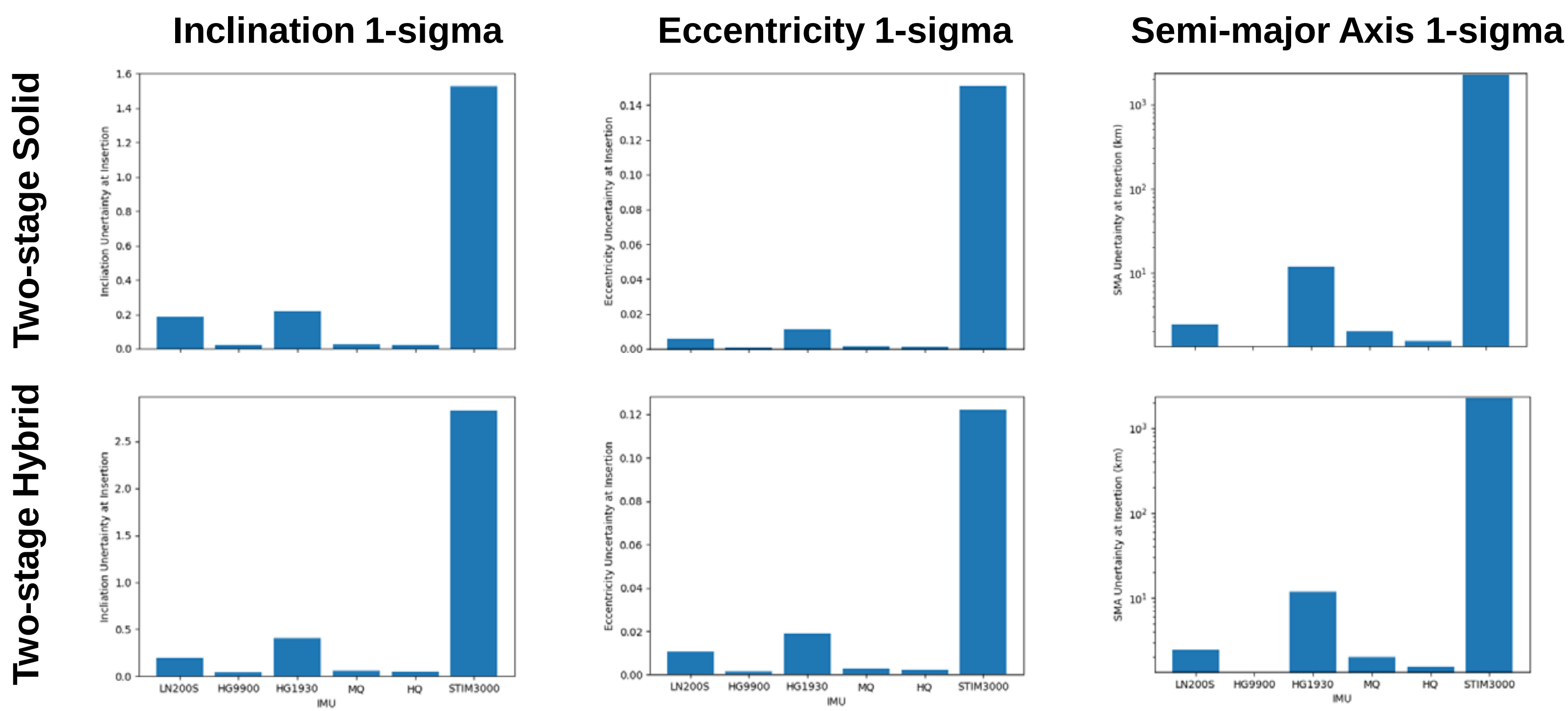




Effects of Initial Position and Attitude Error on Insertion Uncertainty

Navigation Capability

- **Navigation Performance**
  - Assumed external initialization errors: 10m, .1 m/s, .1 deg
  - Performed Monte Carlos for each sensor type
  - Errors captured in inertial, RTN, and orbital elements
  - Comparing external initialization vs. gyrocompassing
- **Longer trajectory with liquid propulsion exhibits greater error growth**



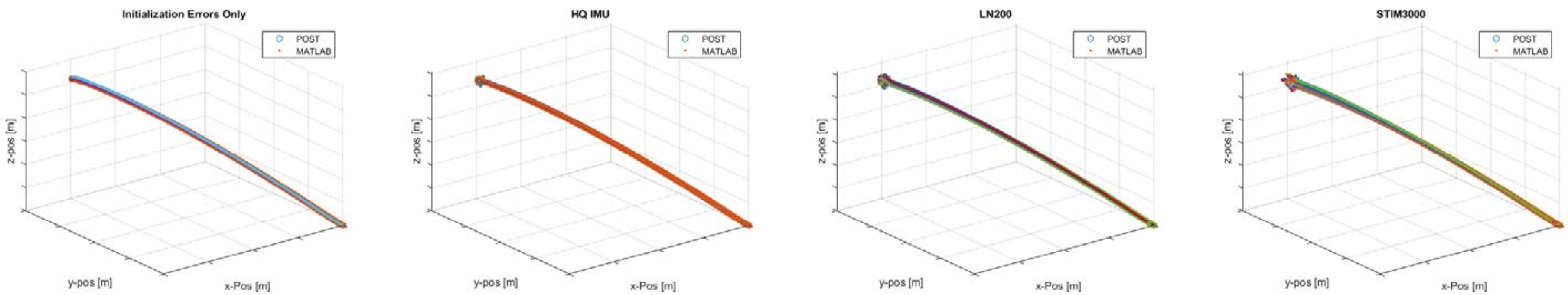
Integrated Vehicle Performance

- **Open loop attitude commanding (pitch) as function of altitude (or time)**
- **Running 3DOF simulation with attitude errors for effect on pitch command**
  - Assessing impact of initial attitude uncertainty and error growth
  - Applied attitude errors as rotation to thrust vector
  - Includes thrust trace and mass flow matching POST optimization
- **Assess against variety of IMUs**
- **Next steps: continued analysis of GEM vs. Lambert for both vehicles, integration into 6DOF simulation framework**

1-sigma Insertion Uncertainty with 0.1 Deg.

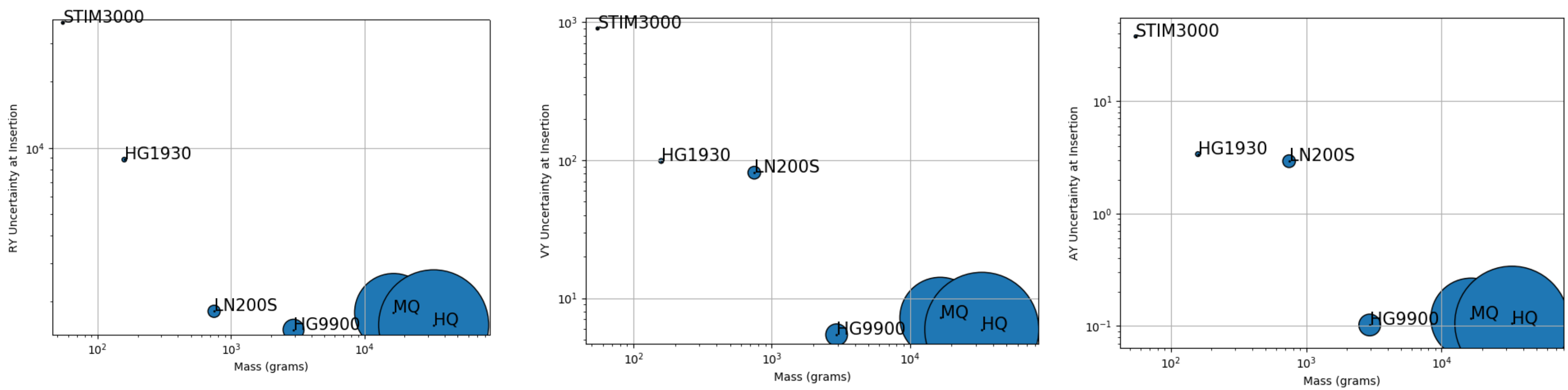
	ALT (m)	Vmag (m/s)	Ha (m)	Hp (m)	Inc (deg)
Init. Error Only	940	2.4	1500	1900	0.08
HQ	930	2.25	1500	1800	0.08
LN200	1300	3.1	2000	2500	0.11
STIM3000	2000	4.7	3100	3800	0.17
HQ w/ .01 Deg	93	0.22	150	180	0.01

Dispersed Trajectory with Initial Attitude Error 1-Sigma of 0.1 Deg.



Continuing Analysis and Trades

- **Simulation Maturation and Continued Development**
  - Integration of updated GN algorithms into MANTISS framework for dispersed 6DOF
  - Sync with latest thrust trace/trajectory design
- **Need for improved Sensors**
  - Technology pull, integration opportunity
  - Order of magnitude mass/volume increases for uncertainty decreases
  - Level of redundancy/internal systems
- **Incorporation of other measurements**
  - Ground tracking from launch platform
  - Support from orbital assets
  - Star tracking for attitude solution during coast
- **Post-flight reconstruction challenges**
  - Limited data and external measurements



Sensor Performance as a Function of Sensor Mass (Size = Relative Volume) (10,.1,.1 init)

Conclusions

- **MSFC developing Ascent Vehicle to support JPL-led Martian Sample Return effort**
  - In-house propulsion, structures, GNC design
  - Tightly constrained system due to need for autonomous operation, transportation to Mars, and long delay between integration and flight
- **Developing Guidance and Navigation architecture early to feed into sensor selection and vehicle trades**
- **Overall design in iteration between disciplines as individual elements continue to mature**
  - Propulsion, thermal, structures, mission design, GNC
- **Continuing work to feed into PDR-level analysis in early/mid 2019**
  - Final sensor selection
  - Guidance algorithm robust to propulsion options
  - Integrated GN with C in detailed 6DOF simulation tools
  - Continued assessment of external disturbances (i.e. atmosphere)
  - Proposed approach to state initialization with available sensors

Thank you!

Co-authors: Dane Erickson NASA/MSFC, Carlos Montalvo/Univ. South Alabama

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