Morpheus (VTB)

Morpheus GNC Development and Testing

Dr. Timothy P. Crain / NASA Johnson Space Center
Tye Brady / Charles Stark Draper Laboratory

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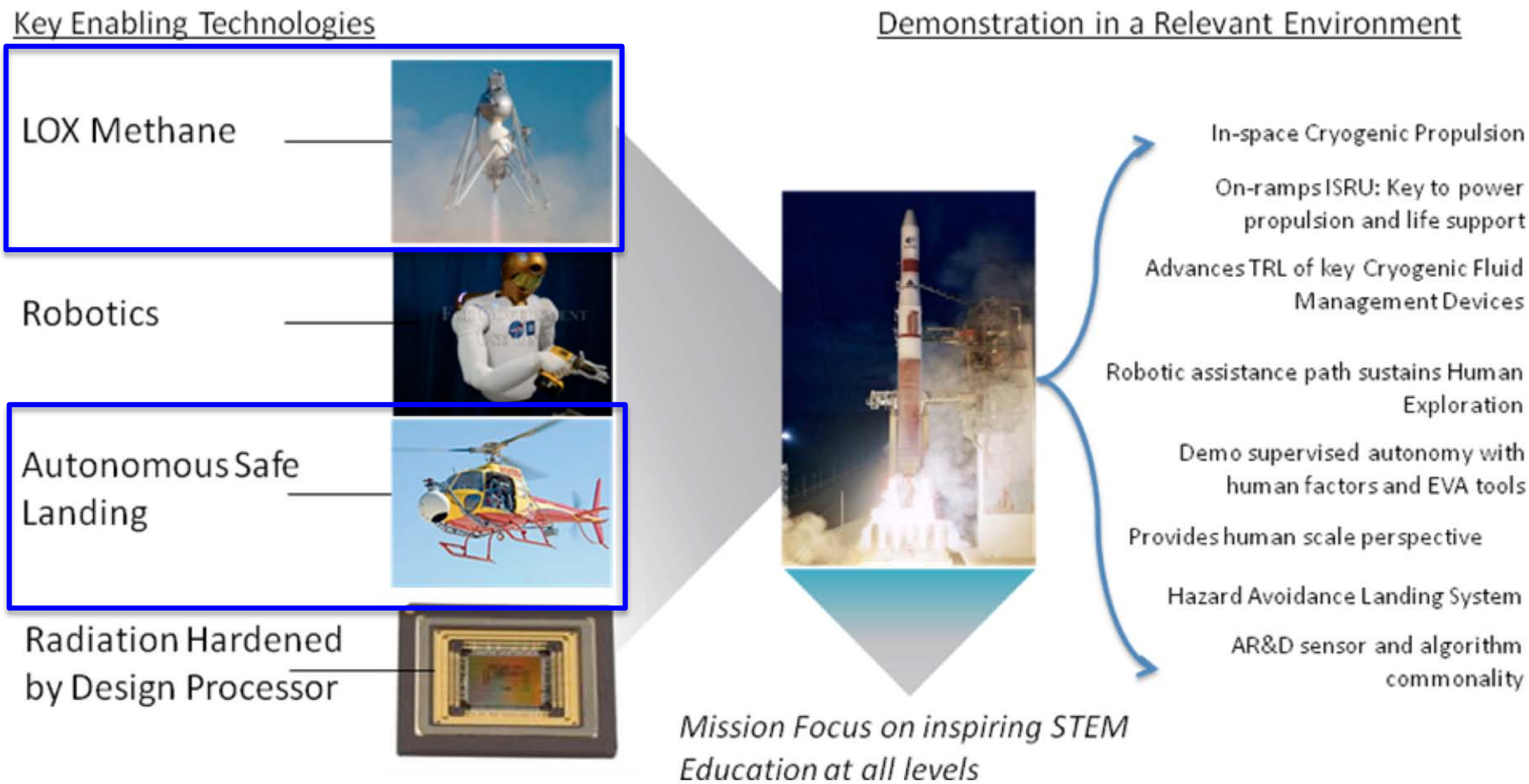
Topics

- Morpheus Background
- Tale of Two Paradigms
- Phase 1: Early GNC Development and Testing
- Phase 2: Vehicle Development and Testing
- Phase 3: ALHAT Testing
- Conclusion

Project M Heritage of Morpheus

- Morpheus evolved from Project M mission application to become a terrestrial vertical testbed (VTB) for LOX/LCH4 and ALHAT technologies



Transition from Project M to Morpheus

Context Feb 1, 2010

- Presidential Budget ends Cx and puts NASA in strategic replanning mode
- Very difficult to get approval for a lunar mission in this environment

- Robonaut2 focuses on ISS deployment and continued terrestrial leg development
- LOX/LCH4 and ALHAT technologies demonstration carry on in the Morpheus VTB

project M

Autonomous Safe Landing

LOX Methane

Vertical Test Bed

MORPHEUS

Advance Exploration Systems

Robotics

ISS Testing

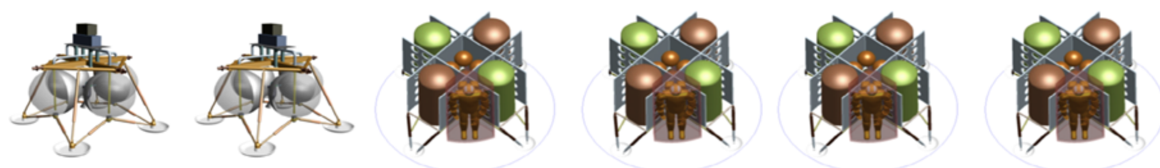
NASA • JSC • GM

R2 - ISS

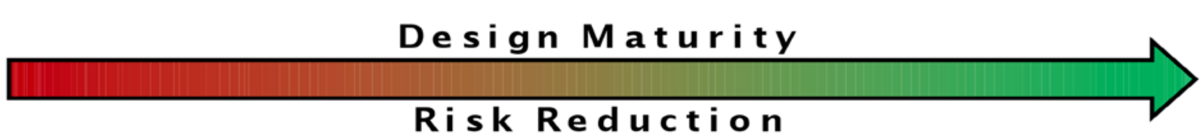
ROBONAUT

Test-early, Test-often

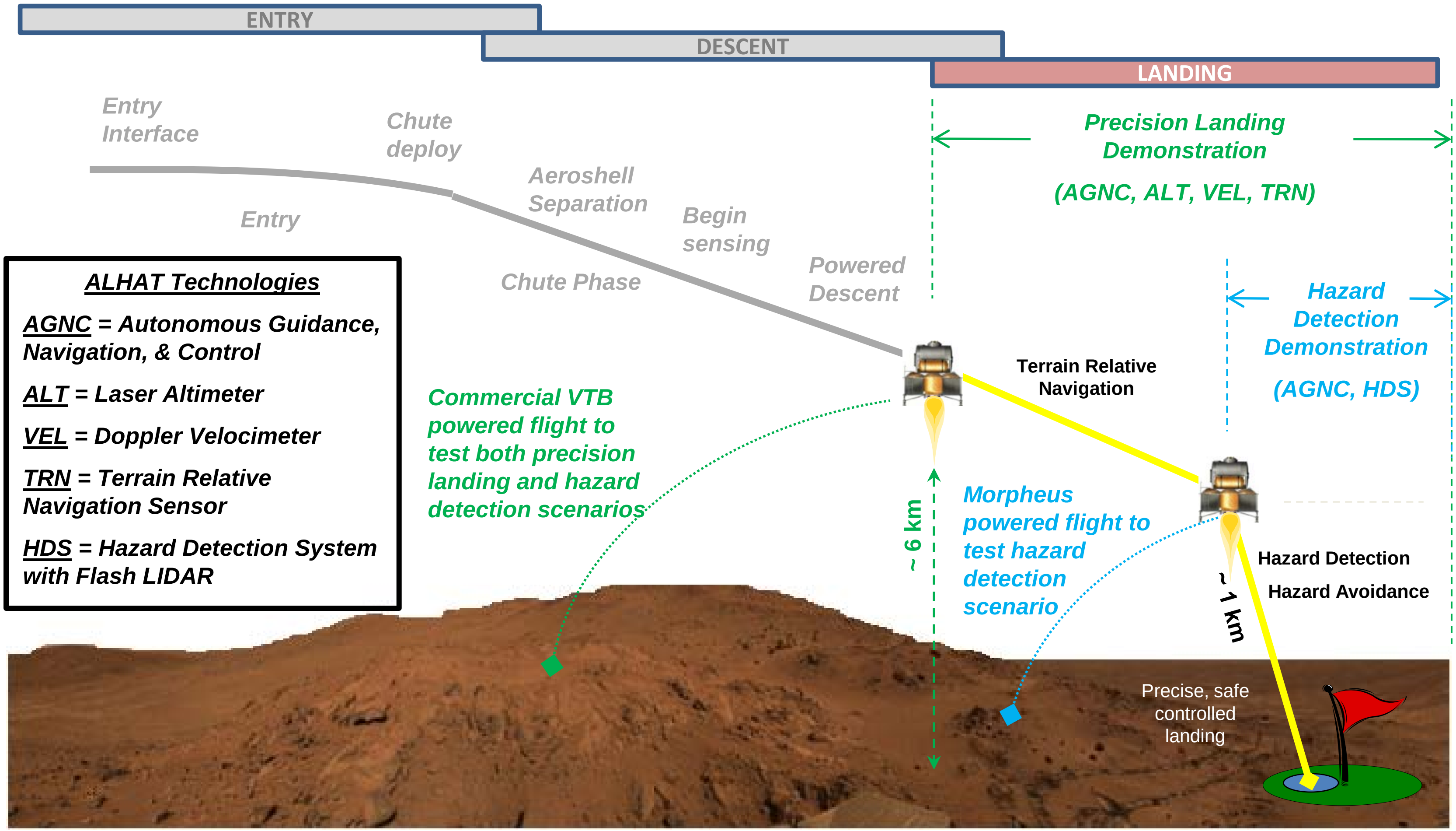
- The Morpheus VTB inherited the test-oriented development approach of ProjectM and is effectively the Project M Risk Reduction 2 (RR2) test vehicle.
- Early GNC and propulsion system development was performed on the RR1 vehicle built by Armadillo Aerospace.



Risk Reduction 1 (RR-1)	Risk Reduction 2 (RR-2)	Development Article 1 (DA-1)	Development Article 2 (DA-2)	Qual Article 1 (QA-1)	Flight Article 1 (FA-1)
•First flights with LOX/Methane propulsion •First flights with GN&C system	•Updated lander structure •Multiple flights with LOX methane prop system (component development testing) •Testing with preliminary avionics/GN&C	•Structural test article with limited real hardware •Acoustic and vibration test bed to mature structural design	•Mature lander structure •Testing with mature avionics/GN&C •Multiple flights with mature LOX methane prop system •Hot fire testing of the propulsion system in vacuum	•Structural qualification testing (modal, static, pressure testing of tanks) •Avionics/GN&C qualification testing	•Acceptance testing •Functional testing of integrated vehicle

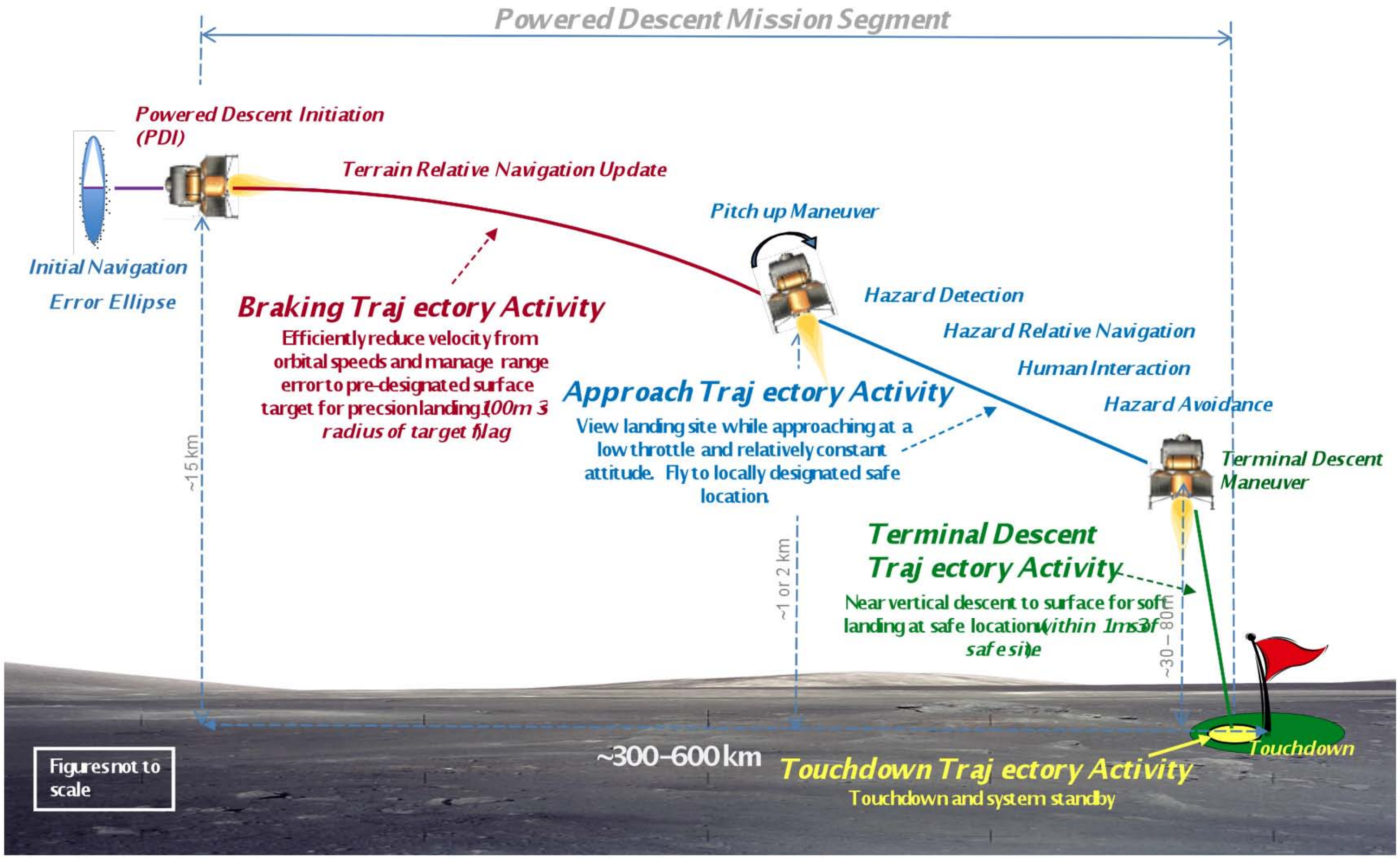


ALHAT Demonstration Description



Trajectories are not to scale and are only illustrations of phases

ALHAT Powered Descent



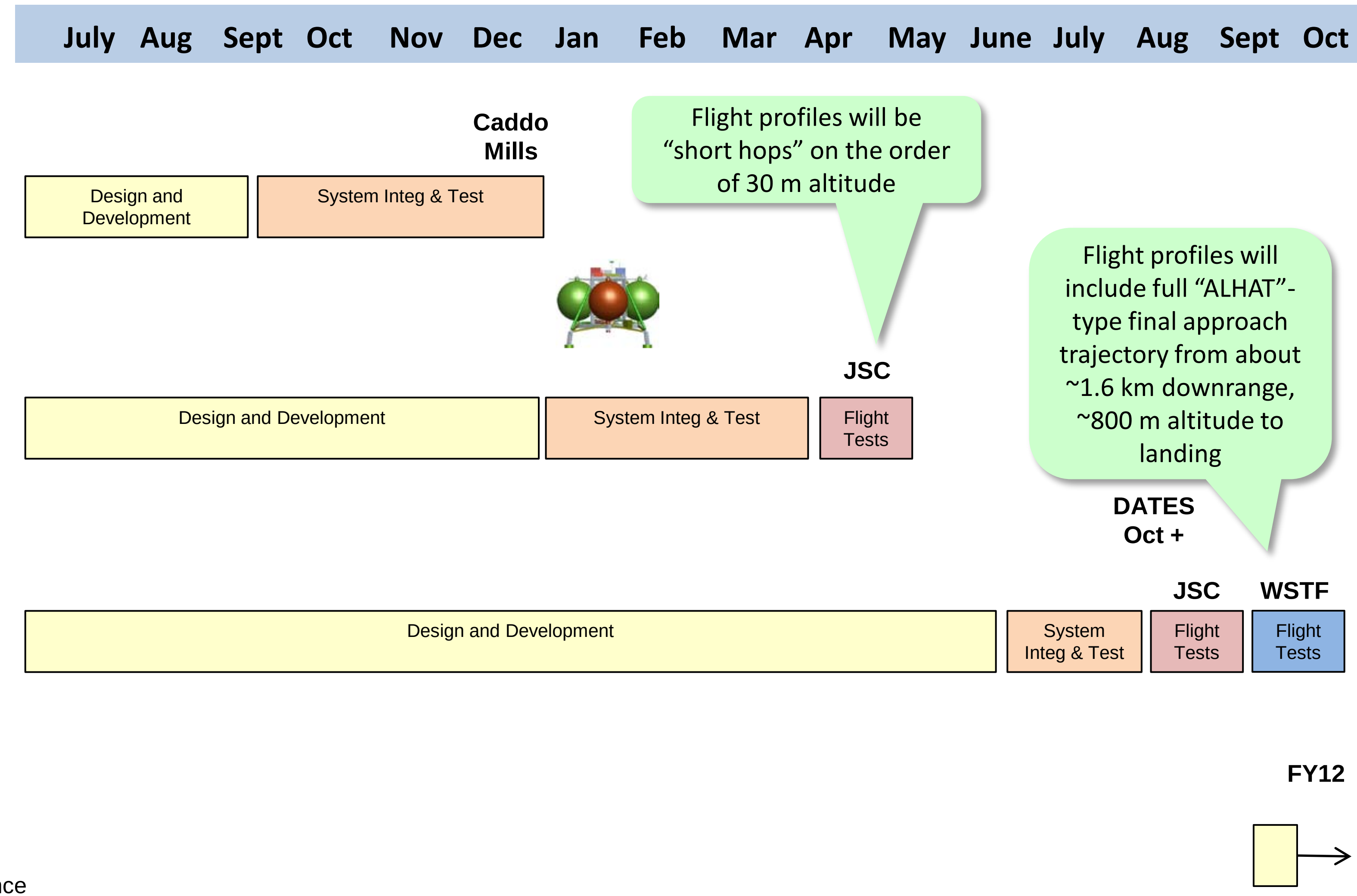
RR-2 (Morpheus) Development Phases

PHASE 1
- New RR-2 Structure
- New RR-2 Engine
- Uses Armadillo's Avionics, Remote Control and Ops

PHASE 2
- Same engine as Phase 1
- Uses NASA's Avionics, Remote Control and Ops

PHASE 3
- Another new engine
- New prop components
- Additions to precision landing sensors

PHASE 4
- Capability for hazard detection and avoidance



ALHAT PROJECT

- ALHAT MISSION STATEMENT
  - Develop and mature to TRL6 an autonomous landing GN&C and sensing system for crewed, cargo, and robotic planetary descent vehicles. The System will be capable of identifying and avoiding surface hazards to enable a safe precision landing to within tens of meters of certified and designated landing sites anywhere on a planetary surface under any lighting conditions.
- The ALHAT Project started in 2006 and has essentially completed the development of software and hardware systems
  - AGNC
  - Terrain Relative Navigation
  - Hazard Detection and Avoidance

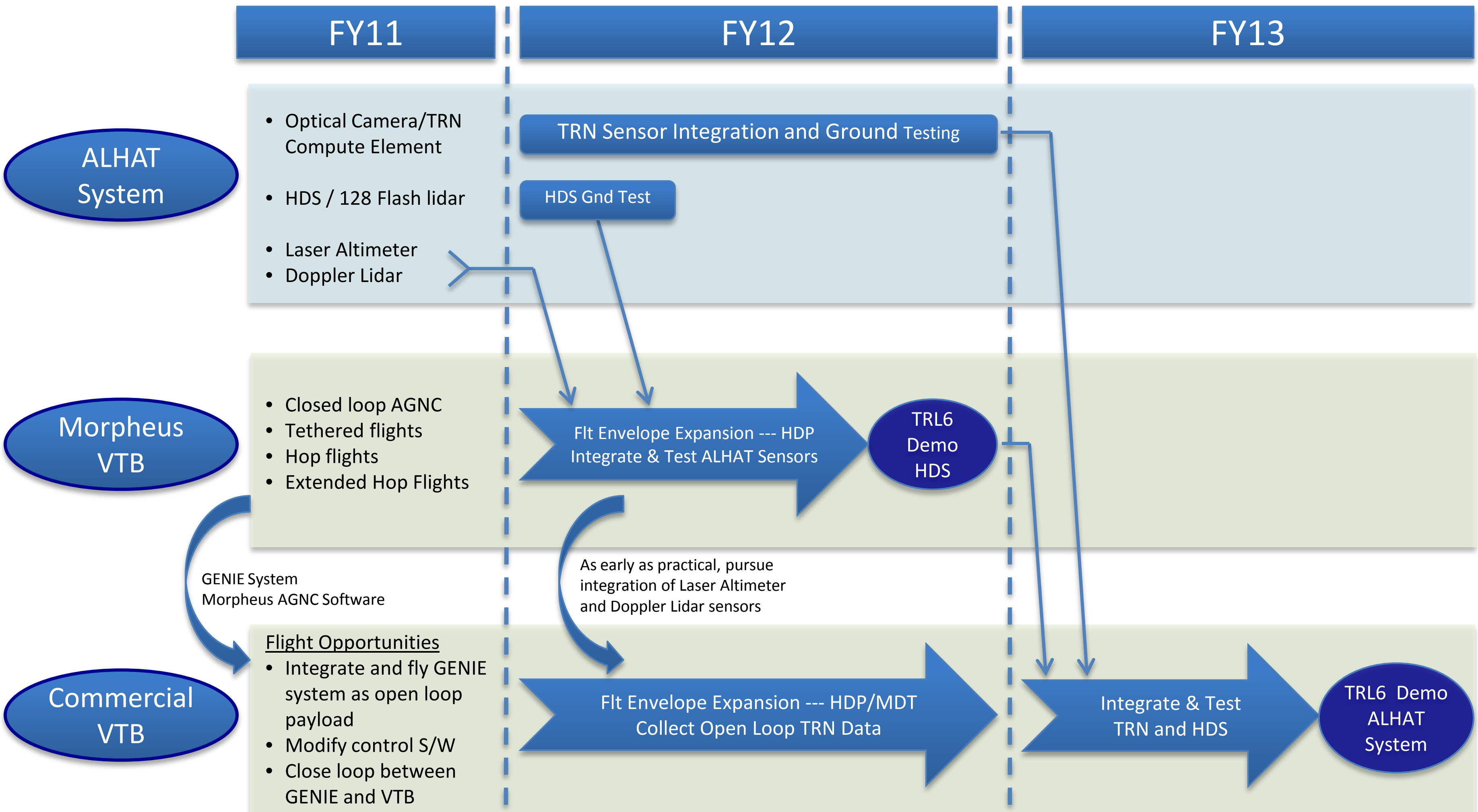
ALHAT DEMONSTRATIONS

- The Project will be ready in FY12 to demonstrate the following capabilities on a Vertical TestBed
  - Autonomous closed loop precision landing from approximately 500m altitude and 1000m slant range with real-time hazard detection and avoidance on the Morpheus VTB
    - Utilizes Hazard Detection System (HDS) which consists of a gimbaled flash lidar with real-time compute element and associated software. Identifies safe landing aim point in less than 10 sec
    - Utilizes Doppler lidar velocimeter and laser altimeter plus COTs navigation sensors such as IMU
    - AGNC with extended Kalman filter navigation which utilizes inputs from all of the above sensors to provide landing precision to within 3m (3σ) of the real-time determined safe landing location
    - Utilizes Hazard Relative Navigation – terrain relative navigation by tracking features and comparing to HDS determined feature location

ALHAT DEMONSTRATIONS

- The Project will be ready in FY13 to demonstrate the following capabilities on a Vertical TestBed
  - Autonomous closed loop precision landing from approximately 6 km altitude using real-time Terrain Relative Navigation (TRN) and hazard detection and avoidance on a commercial VTB
    - Utilizes passive optical TRN from high altitudes to the start of the hazard detection phase followed by hazard detection and avoidance with the HDS for safe precision landing
    - Doppler lidar velocimeter and laser altimeter plus COTs navigation sensors such as IMU
    - AGNC with extended Kalman filter navigation which utilizes inputs from all of the above sensors to give landing precision to within 3m (3σ) of the real-time determined safe landing location and within 90m (3σ) of the prelaunch landing target
    - Demonstrates all of the ALHAT techniques and sensors

ALHAT Project Flow



HDS – Hazard Detection System
TRN – Terrain Relative Navigation
HDP – Hazard Detection Phase
GENIE – Guidance Embedded Navigation Integration Environment
MDT – Mars Descent Trajectory

Morpheus Vehicle Overview

- Vertical Take-off / Vertical Landing
  - Impulse for 60-210 seconds of flight
- Pressure Fed Liquid Oxygen (LOX) and Liquid Methane (LNG) propulsion (235 PSIG)
- Single Film Cooled Rocket engine
  - 2000 or 4000 lbf Thrust
  - Two axes Gimbaled and 4:1 Throttled
- Autonomous Flight Control
  - Nav Base : IMU (2), GPS (2), and Laser Altimeter
  - Ground Command and Telemetry through RF link
- Stand alone Flight Termination System

Tale of Two Paradigms

- Traditional spacecraft development relies on comprehensive requirements development and analysis, varying time in integrated testing early, and late integration of long lead or high value assets into a flght configuration.   This approach is not risk tolerant and experiences significant performance, cost, and schedule impacts when issues are discovered at integration.
- Morpheus adopted a test oriented paradgim where a small set of spacecraft level requirements were developed to guide early subsystem design and development.
  - Metal was cut early and subsystem requirements refined in parallel
  - Integration of subsystems was performed with available/affordable assets.
  - Approach is tolerant of flight failures as test successes

Traditional vs. Test, Test, Test Development

Traditional

- Heavy emphasis on early trades and analysis
- Cost/schedule impacts deferred to late in project
- Serial progression
- Risk averse
- May not flight test
- Spec assets

“Flight” article is well thought out and tested at subsystem/component level. But has no “real-world” exposure.

Planning and Requirements Development | Design and Development | System Integ & Test | Flight Tests

Test, Test, Test

- Emphasis on rapid prototyping
- Cyclic and parallel progression
- Accepts risk early
- Uses available/affordable assets

Planning and Requirements Development | Design and Development | System Integ & Test | Flight Tests | Flight Tests | Flight Tests | Flight Tests

Requirements Refinement

Development, integration, and test cycles or “spirals” lead to a robust design where project energies are focused on issues discovered in testing.

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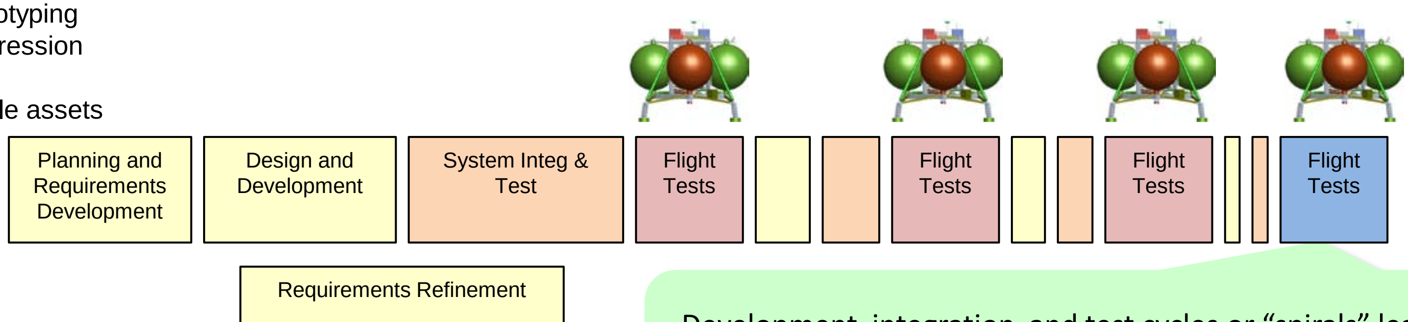
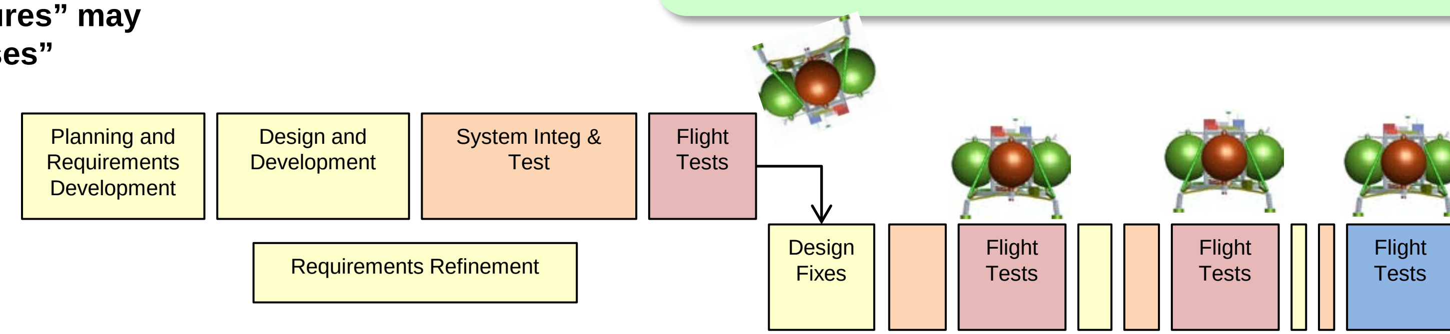


Development, integration, and test cycles or "spirals" lead to a robust design where project energies are focused on issues discovered in testing.

Early flight "failures" may be test "successes"



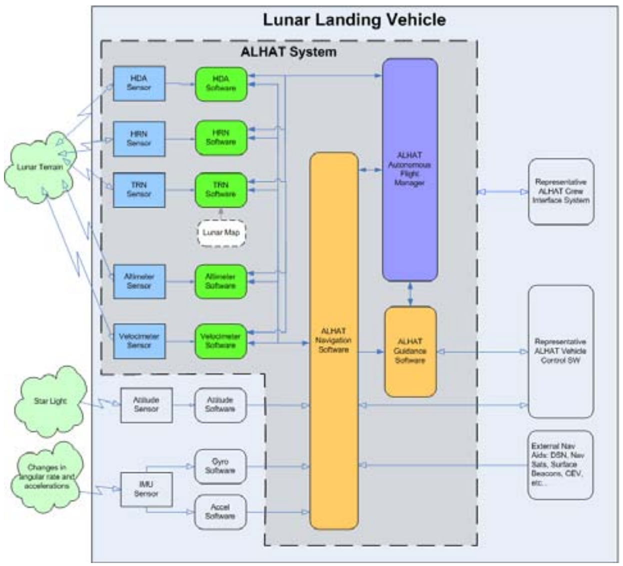
Morpheus Lean Management

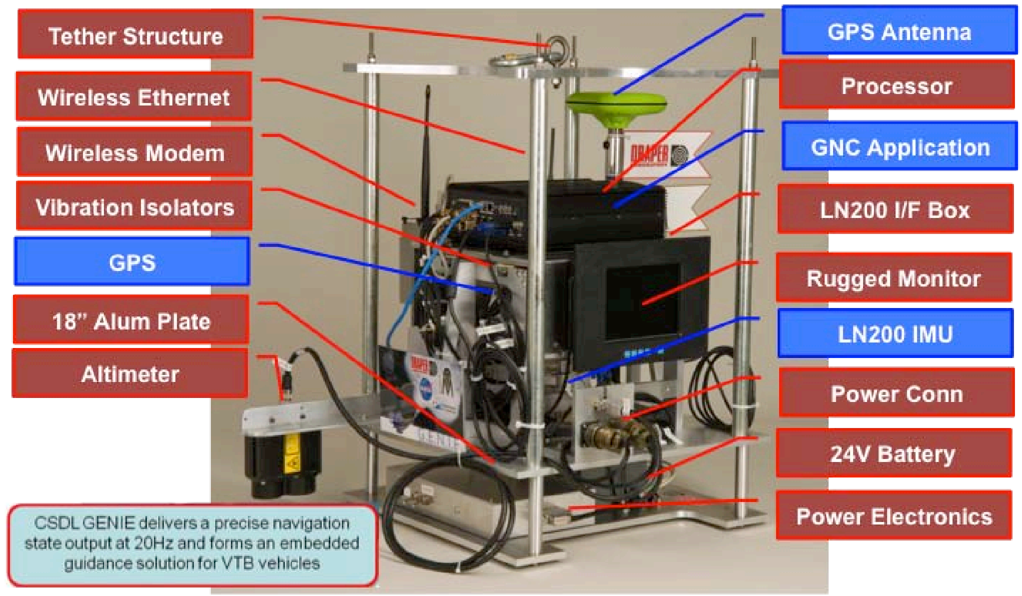
- Flat organization
- Small teams / co-location
- Open source tools
- Available/affordable asset re-use and utilization
- Online collaboration through Sharepoint
- Engagement of safety/qa early as part of team
- Incremental and tangible test milestones - genie, mast demos, cold flow, hot fire, tether, vertical, hops, high energy

Phase 1: Early GNC Development and Testing

- 2-3 charts
- ALHAT analysis GNC package start background description and rationale
- Letting the genie out of the bottle.....genie overview, purpose to test realtime feasibility of basic guidance and nav approach with basic sensors
- Commonality with ft4
- Flight details and results
- Successful distributed team collaboration
- Cart testing
- Sim development with laptop, realtime, flight processor etc support (technology simulation levels?)
- Cool pictures, movie?

ALHAT GN&C System





Autonomy (AFM) – *Combines precise navigation, surface imaging, adaptive vehicle maneuvering outside the nominal profile, and human input to enable safe and precise lunar landing.*

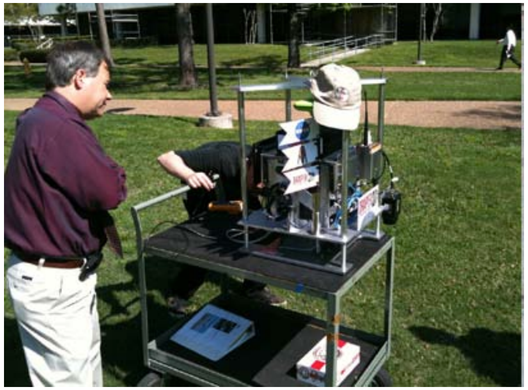
Guidance – *Provides burn targeting & maneuver guidance for end-to-end lunar landing mission. Supports precision landing (dispersion correction) and hazard avoidance.*

Navigation – *Estimates vehicle states for end-to-end lunar landing mission. Dual-state filter architecture for precise vehicle delivery.*

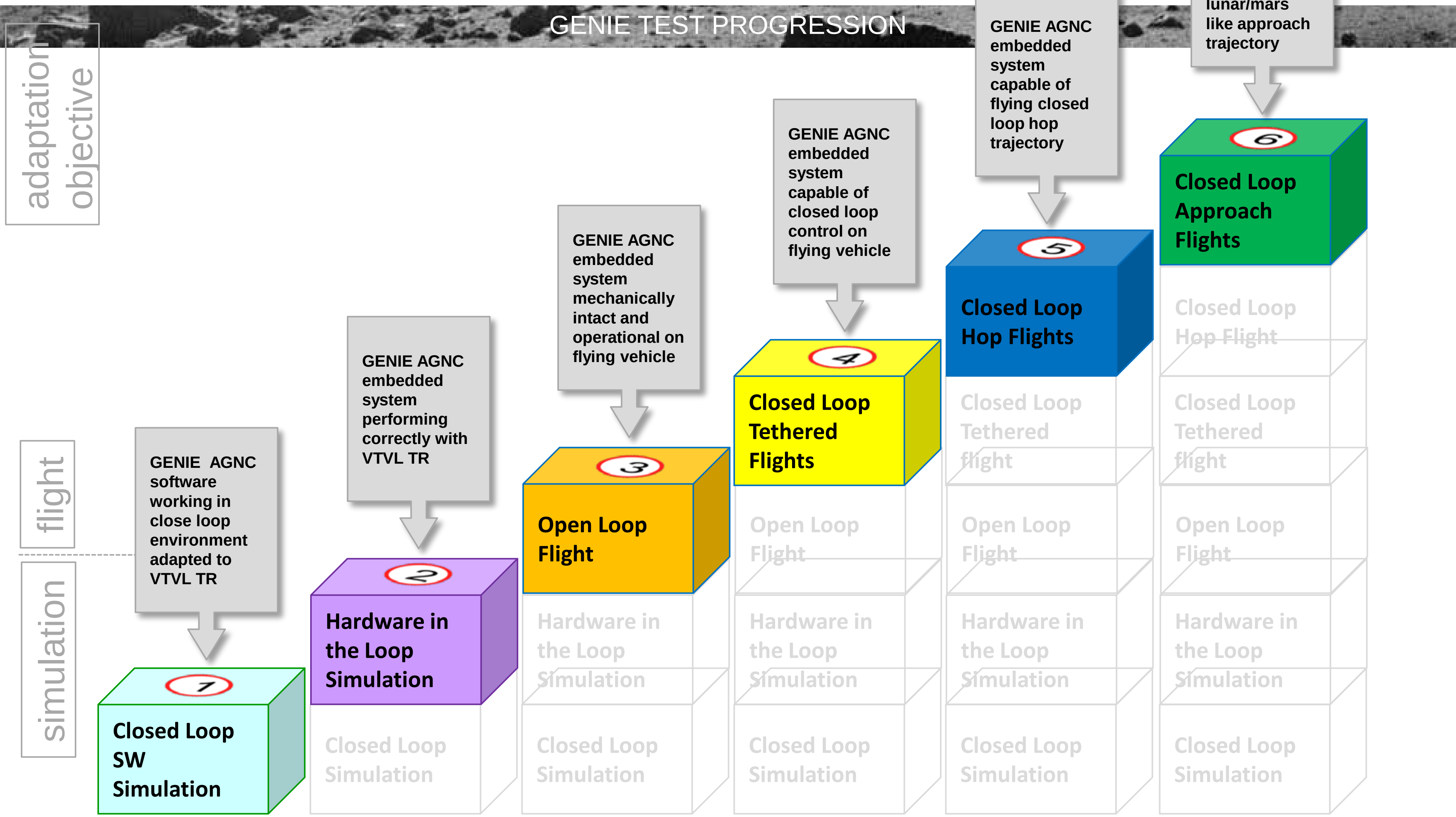
Control – *Provides 6DOF control (RCS and main engine) for Crewed lunar landing vehicle.*

Hazard Detection System – *Provides hazard detection sensors and algorithms/software*

GENIE Field and Flight Testing



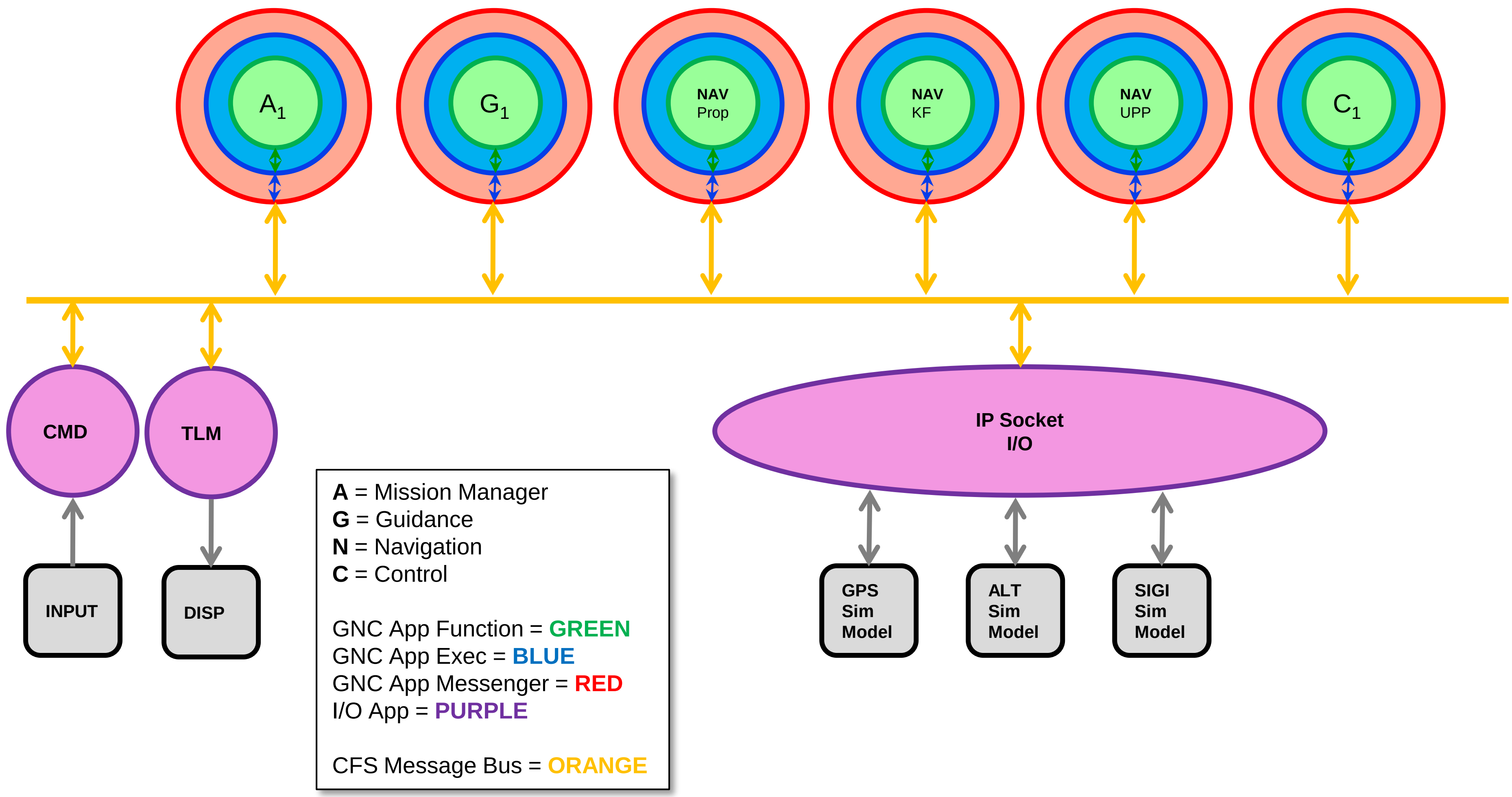
Six GENIE Adaptation Steps to High Performance Flight on a VTVL Terrestrial Rocket



Adaptation Step Completion Number

RR2 Rev1 Build2 GNC FSW Architecture

"Core AGNC FSW" retains only the blue and green layer



GNC App Function, Executive, and Messenger

"Core AGNC FSW" retains only the blue and green layer

CFS SW Message Bus

a GNC *app messenger* handles the CFS specific messaging and executes the GNC app executive

The place where the CFS message subscribe, CFS message send occurs along with other CFS specific detail

a GNC *app executive* calls the GNC app function and extracts necessary data for the function call

Literally calls the GNC app function

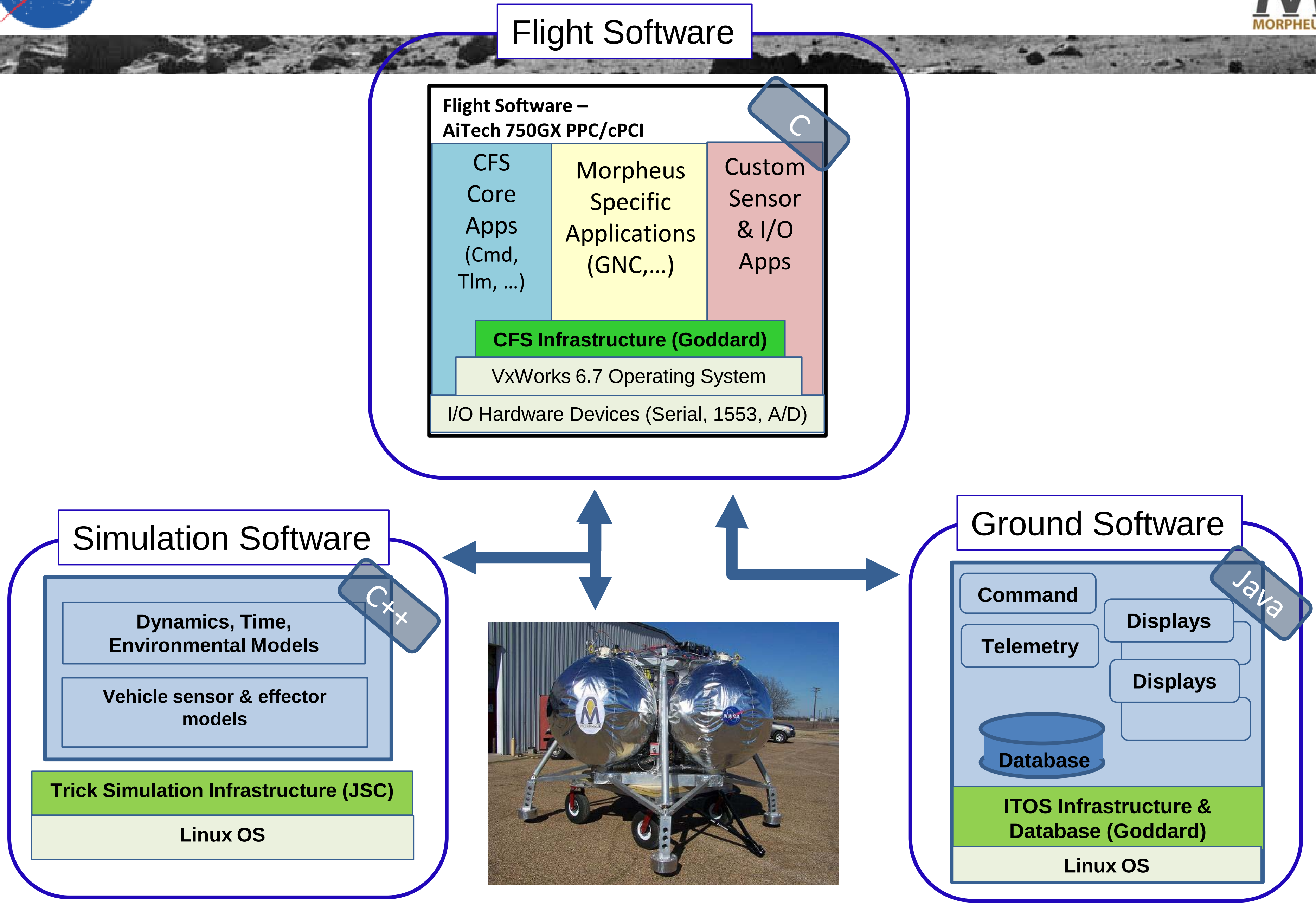
a GNC *app function* performs the GNC algorithm

Isolating the functions from particular architecture allows for extensible and reusable GNC SW development

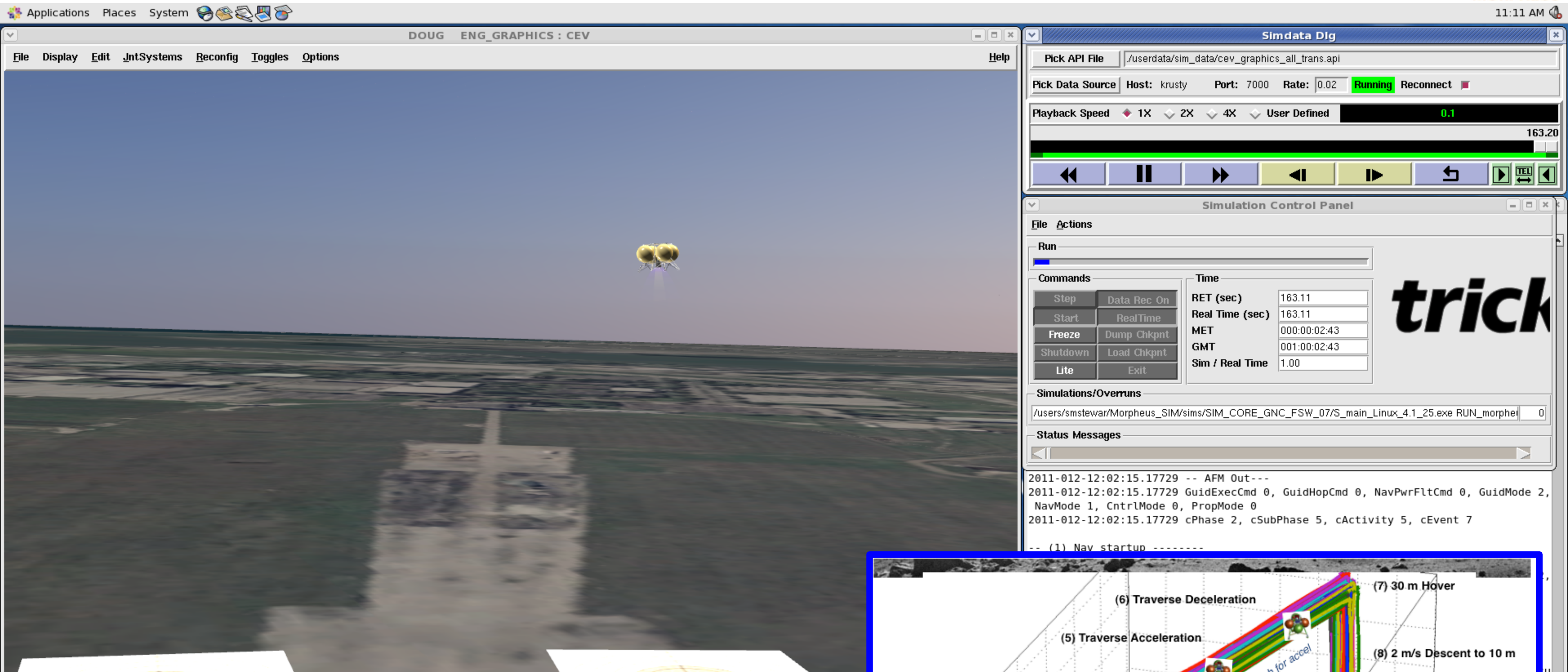
Phase 2: vehicle development and testing

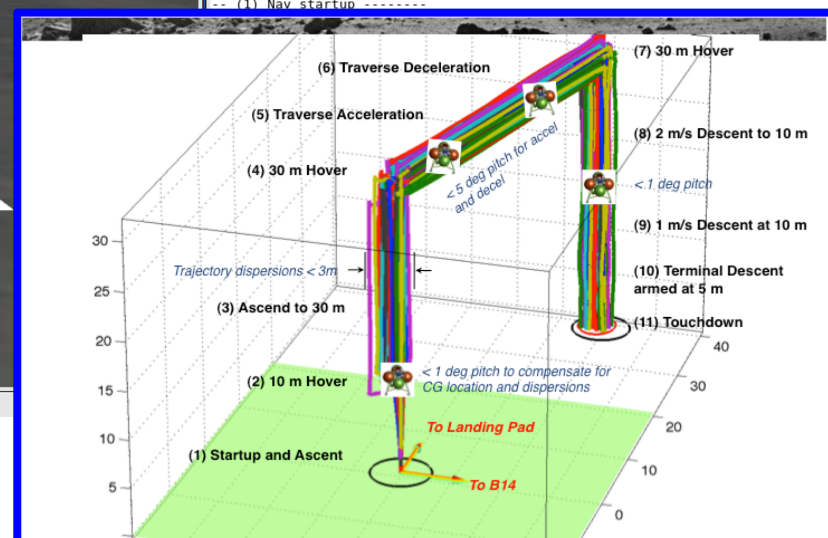
- 3-4 charts
- Integration with CFS and flight processor, ported from genie...but maintaining genie
- Breaking up nav into rate groups
- Simplified guidance
- Added flight control
- Added AFM
- Added sigi as prime imu
- Display development
- GNC bunker, mast demo 1 ("failure"), mast 2 demo (Ethernet sim), mast demo 3 (socket sim), flat sat testing, cold flow, hot fire, tether timelines pictures and some details

Morpheus Software Components



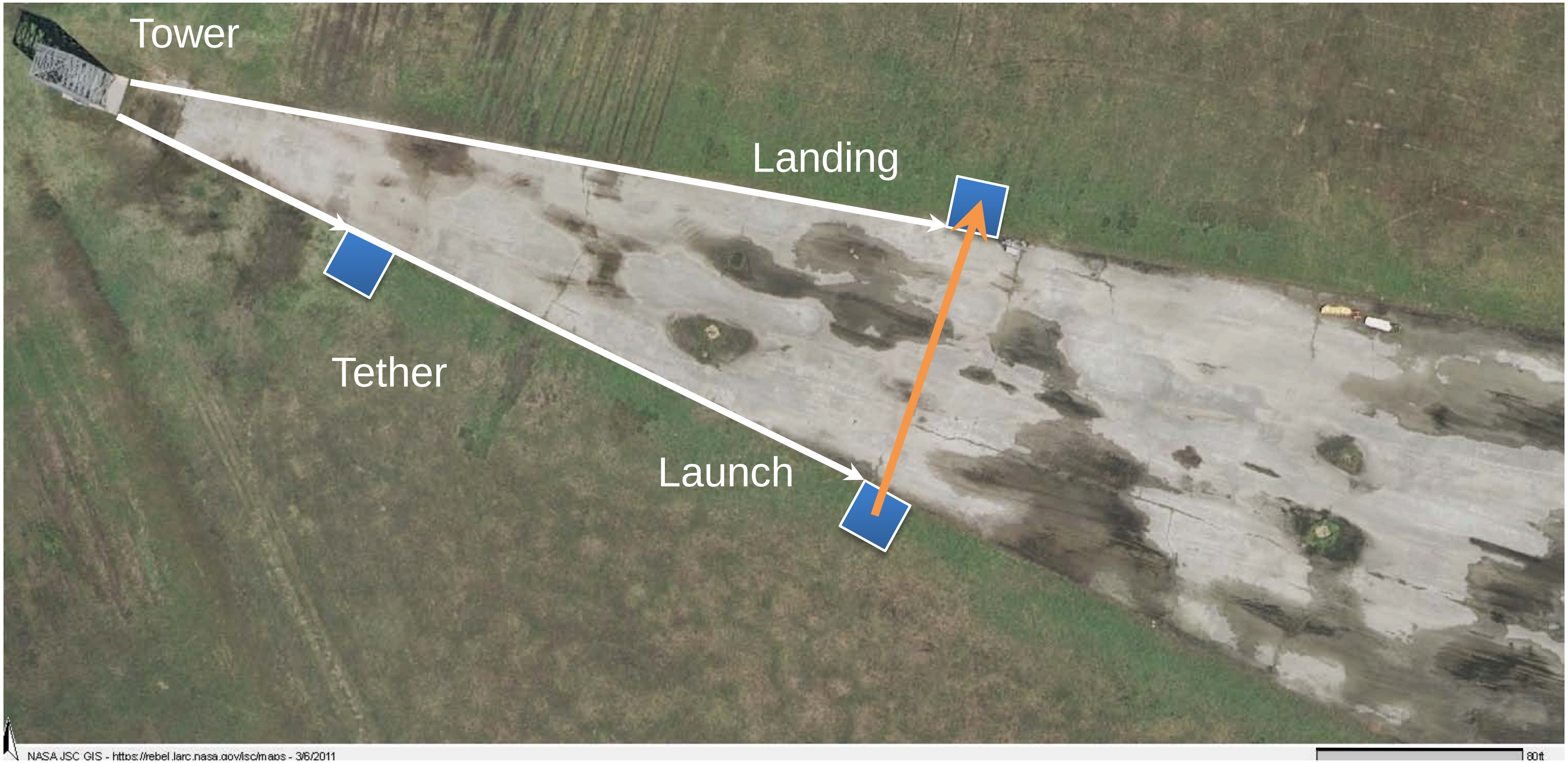
Morpheus Embedded Simulation





Phase 2 Vehicle Testing at JSC

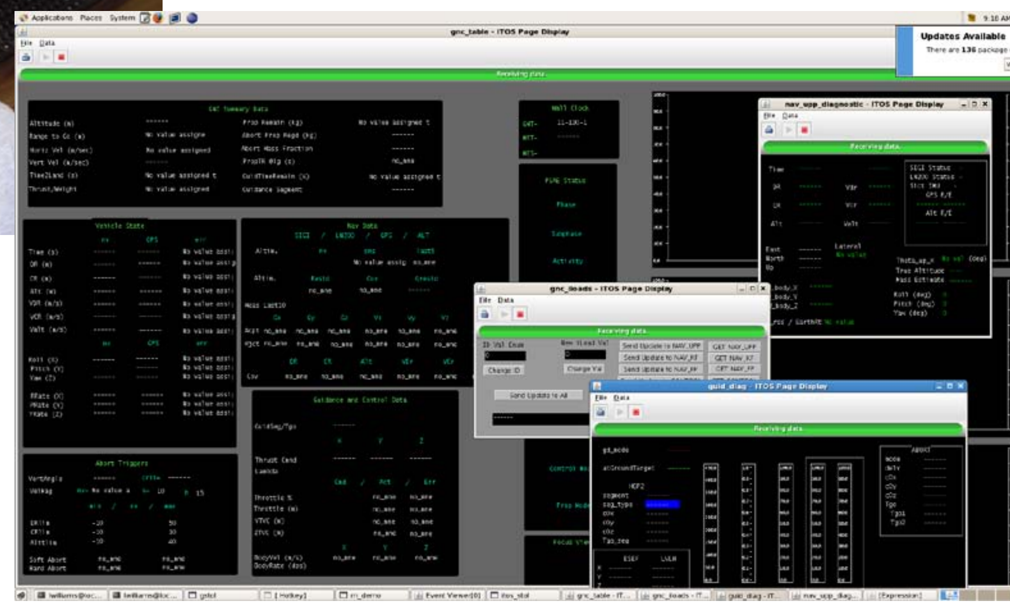
Extensive non-realtime and realtime simulations in the Morpheus Avionics/Software Testbed (MAST)
Completed Hotfire and Tether testing at the JSC VTB Flight Complex
Continuing Tether testing at the JSC VTB Flight Complex
Planned Free Flight Vertical and Hop Trajectories at JSC VTB Flight Complex



*Scale, 1.24" = 80' = 24.384 m

= Pads are 6m x 6m (20' x 20')

Morpheus Control Room

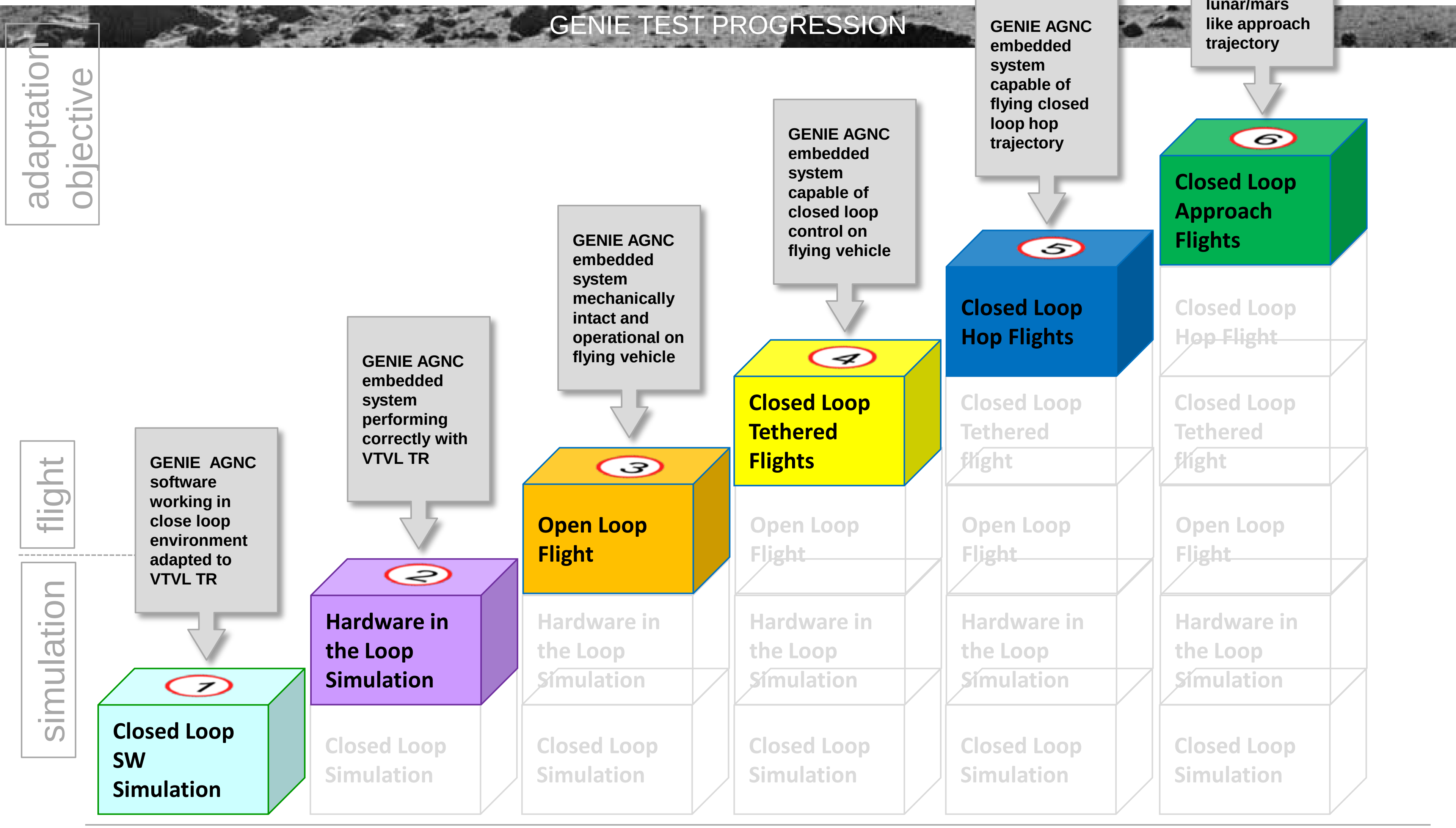


Morpheus Tethered Flight

Phase 3: ALHAT testing

- 1-2 charts
- Future tether test, vertical free flight, hop free flights
- Transition to high energy testing, trajectory plot?
- Integration with ALHAT
- Integration with Masten for commercial ALHAT demo

Six GENIE Adaptation Steps to High Performance Flight on a VTVL Terrestrial Rocket



Adaptation Step Completion Number

Big Picture – 2010 in review

11/09
Team Formed (EA, DA, KA, NA, JA, LE, BA, MA, AD)

Mar 2010
GENIE ground testing

May 2010
Leg Prototype in ARGOS

Jun 2010
Pixel Lander Free Flight #1

Jul 2010
Second Lander Morpheus start

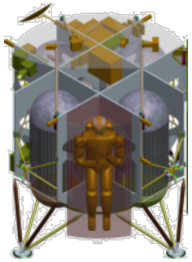
Sep 2010
GN&C Bunker

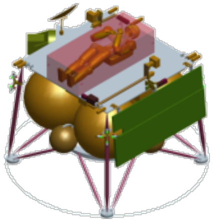
Dec 2010
Morpheus Complete

JPL Team X
Jan 2010

Robot Env. testing
Feb 2010

Design Analysis Cycle #1 complete
May 2010





Project transition to Morpheus
Jul 2010

NASA HD Engine test
Oct 2010

Morpheus FF at JSC
Apr 2011

Pixel Lander:
Armadillo Aerospace hardware with LOX/LCH4 engine
NASA GN&C collecting data
~20 tethered flights, 3 free flights

Morpheus Lander:
All NASA design
Constructed, assembled, and tested by AA and NAS
Flying at JSC will be all NASA team

Video Link: 2010-10-21-VerticalTestBedProgress-PowerPoint WMV - episode-.wmv

Big Picture – 2011 in review













Jan 2011

More GN&C & Software Bunker

Energy Absorber testing

Tank cycle testing

B220 Set-up

Vehicle Arrives at JSC

Propulsion System Assembly

NASA HD Engine test(s)

End to End Wiring Checks

Feb 2011

Software Talks to the Vehicle Avionics for the First Time

Power GSE plugged to Vehicle for the First Time

Mar 2011

N2 Cold Flow

Conclusion

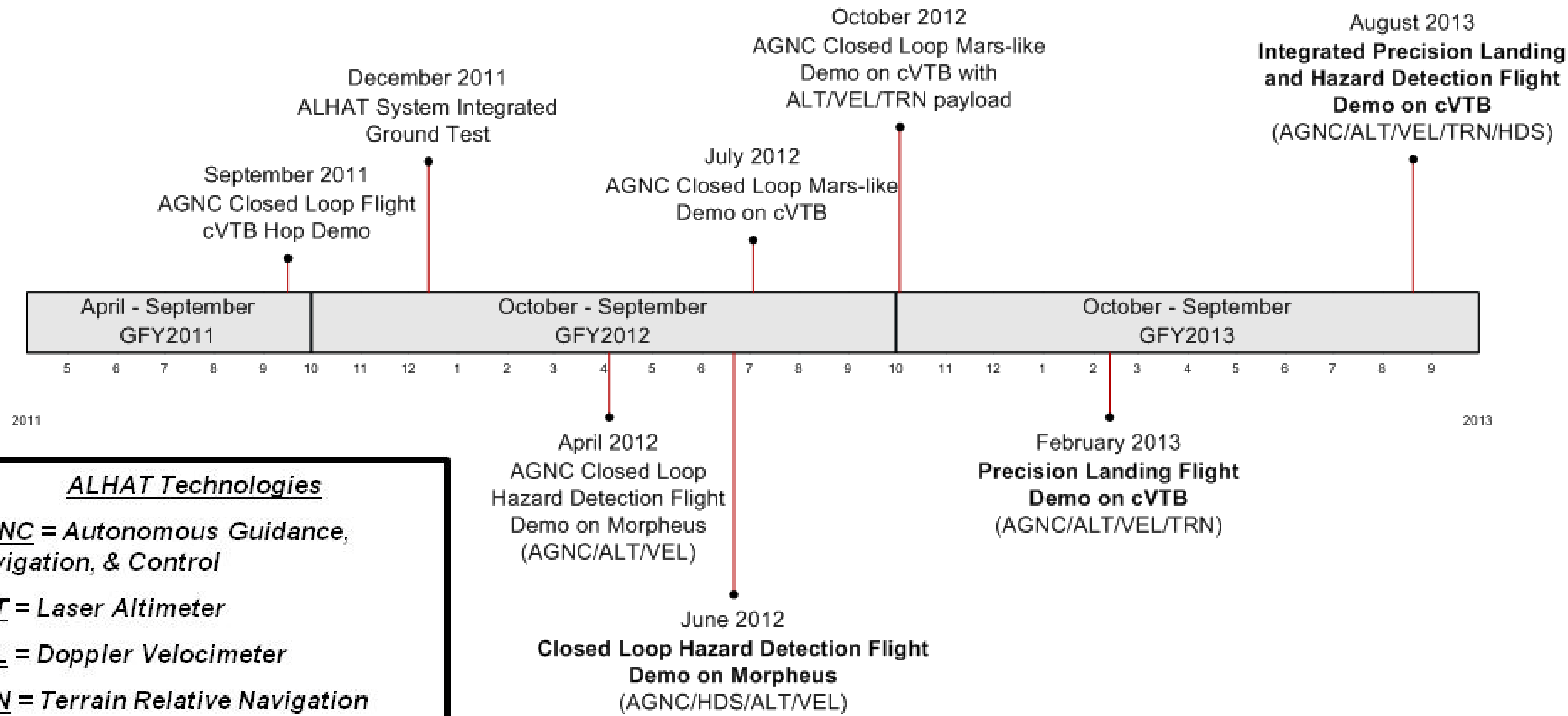
– 1 chart

– Rate of progress to date

- Test paradigm with lean management
- Forward plans with ALHAT
- Could be right back on track for lunar mission with little loss of pace…i.e. We needed to do this testing anyway!

Backup Material

SCHEDULE SUMMARY



ALHAT Technologies

AGNC = Autonomous Guidance, Navigation, & Control

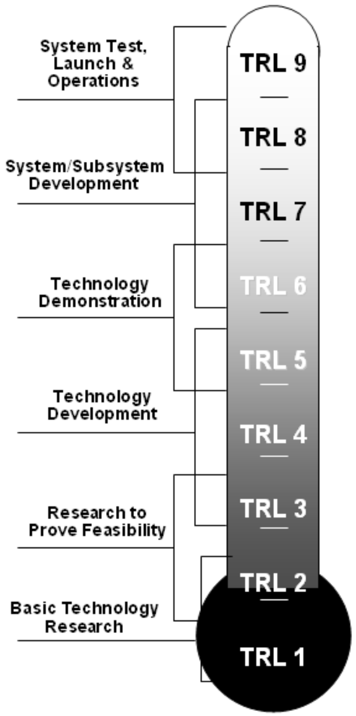
ALT = Laser Altimeter

VEL = Doppler Velocimeter

TRN = Terrain Relative Navigation Sensor

HDS = Hazard Detection System with Flash LIDAR

cVTB = Commercial Vertical Test Bed



TRL 9: Actual system "mission proven" through successful mission operations *Thoroughly debugged software readily repeatable. Fully integrated with operational hardware/software systems. All documentation completed. Successful operational experience. Sustaining software engineering support in place. Actual system fully demonstrated.*

TRL 8: Actual system completed and "mission qualified" through test and demonstration in an operational environment *Thoroughly debugged software. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. V&V completed.*

TRL 7: System prototype demonstration in high-fidelity environment (parallel or shadow mode operation) *Most functionality available for demonstration and test. Well integrated with operational hardware/software systems. Most software bugs removed. Limited documentation available.*

TRL 6: System/subsystem prototype demonstration in a relevant end-to-end environment *Prototype implementations on full scale realistic problems. Partially integrated with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.*

TRL 5: Module and/or subsystem validation in relevant environment *Prototype implementations conform to target environment / interfaces. Experiments with realistic problems. Simulated interfaces to existing systems.*

TRL 4: Module and/or subsystem validation in laboratory environment *Standalone prototype implementations. Experiments with full scale problems or data sets.*

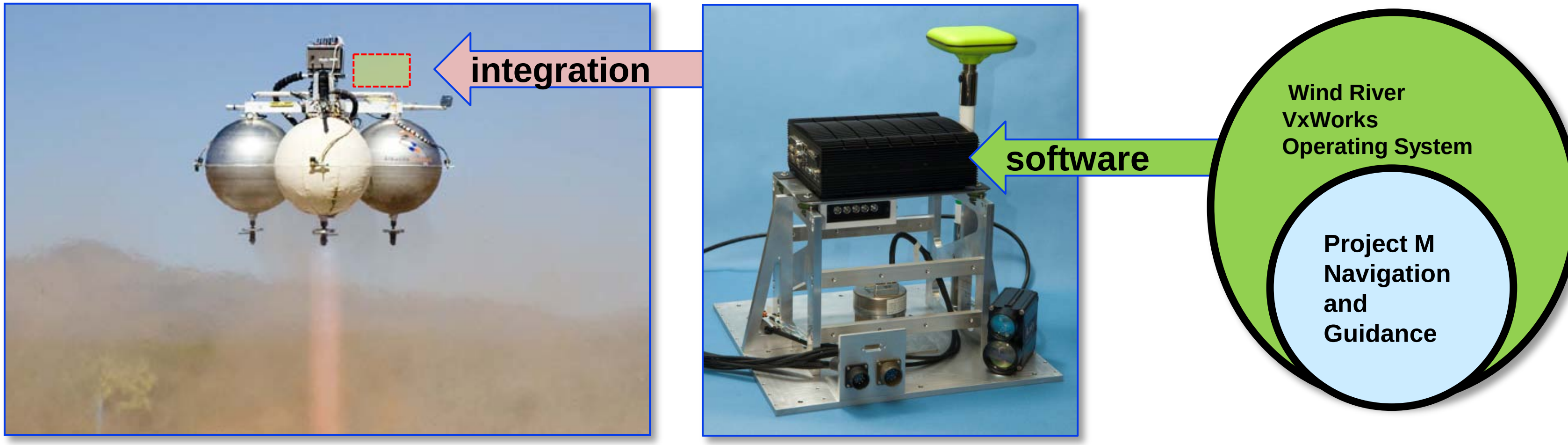
TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept *Limited functionality implementations. Experiments with small representative data sets. Scientific feasibility fully demonstrated.*

TRL 2: Technology concept and/or application formulated *Basic principles coded. Experiments with synthetic data. Mostly applied research.*

TRL 1: Basic principles observed and reported *Basic properties of algorithms, representations & concepts. Mathematical formulations. Mix of basic and applied research.*

About Project M RR-1

First in a series of specially developed field tests for Project M



Armadillo Aerospace Vertical TestBed (AA-VTB) Pixel Vehicle

NASA/Draper Developed GNC HW Solution

NASA/Draper/UT Developed SW Solution

MISSION STATEMENT

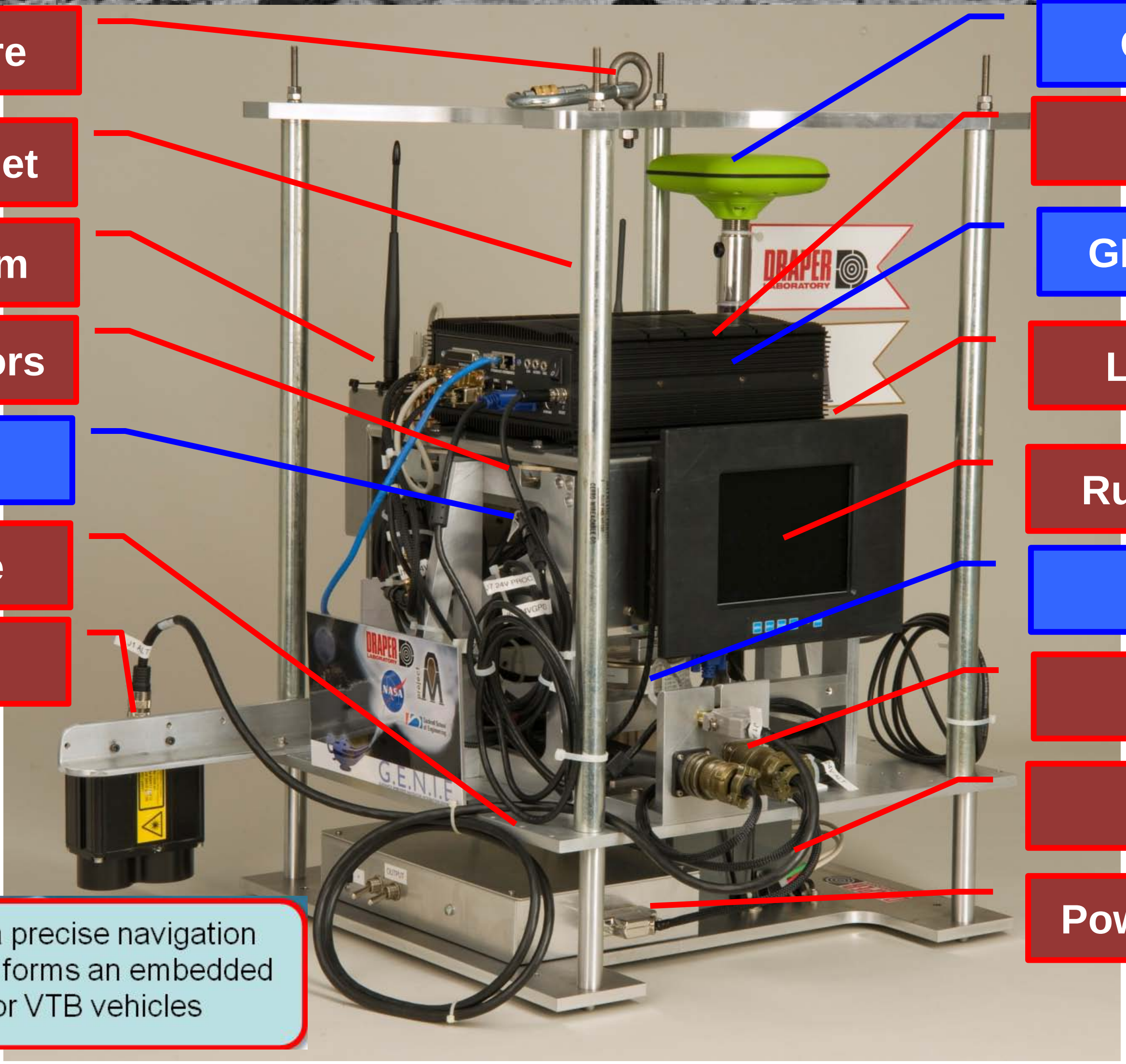
- The Project M Field Test effort aims to demonstrate high rate inertial Guidance, Navigation, and Control (GNC) with low rate representative Kalman filter updates in a free-flying terrestrial lander environment.

AA-VTB-FT1 OBJECTIVE

- The primary objective of the Project M Tier 1 FT is the open loop navigation demonstration of Project M Autonomous GNC (M-AGNC) using data from a tactical grade IMU, GPS, and altimeter with telemetry and data recording on the AA-VTB.

CSDL GENIE

GENIE shown with additional power plate and tether structure



CSDL GENIE delivers a precise navigation state output at 20Hz and forms an embedded guidance solution for VTB vehicles