AES FY14 Review

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Morpheus Introduction

While <u>technologies</u> offer promise, <u>capabilities</u> offer potential solutions with application for future human exploration beyond LEO. Morpheus provides a bridge for evolving these technologies into capable systems that can be demonstrated and tested – in a <u>relevant flight environment</u>.

- Morpheus is a Full Scale Robotic Lander (500kg payload) built as a risk reduction test article
  - Morpheus system includes the vehicle, ground systems, operations
  - Developed, tested and operated in-house at Johnson Space Center and KSC
- Technologies:
  - Liquid oxygen/methane propulsion (cryogenic, green, safe for ground handling and crew)
  - Precision landing and hazard detection Sensors
  - Leverages GSFC's modular, reusable Core Flight Software
  - Technology incubator for advanced development efforts
- Tests complete: 12 hot fire, 34 tethered, and 14 free flights to date
- Lean Development Approach
- Forward Leaning towards Human Spaceflight

Morpheus Project Goals

- **Technology Advancement**
  - Liquid oxygen/liquid methane propulsion system
  - Precision landing and hazard avoidance
- **Lean Development**
  - In-house design & build focus
  - Test early, test often
- **Innovative Partnerships**
  - Collaborations with other NASA centers
  - In-kind agreements with commercial partners
- **Education/Outreach**
  - Student involvement at every level
  - Social media use to depict engineering development process

Morpheus Timeline

2010	2011	2012	2013	2014

Project M

Pixel

Morpheus 1.0 Development

Testing

- Built and operated by Armadillo Aerospace manual control
- Proof of concept
- LOX/Methane engine

- JSC built & operated
- Autonomous vehicle
- 48” tanks
- HD3 engine

Morpheus 1.5A Development

Testing

- APU redesign
- HD4 engine
- Addition of ALHAT
- Stable hover under tether
- Methane roll jets

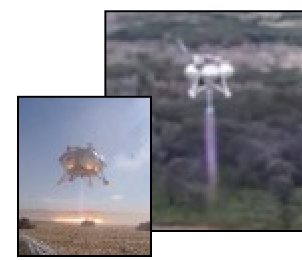
Morpheus 1.5B Development

JSC Testing

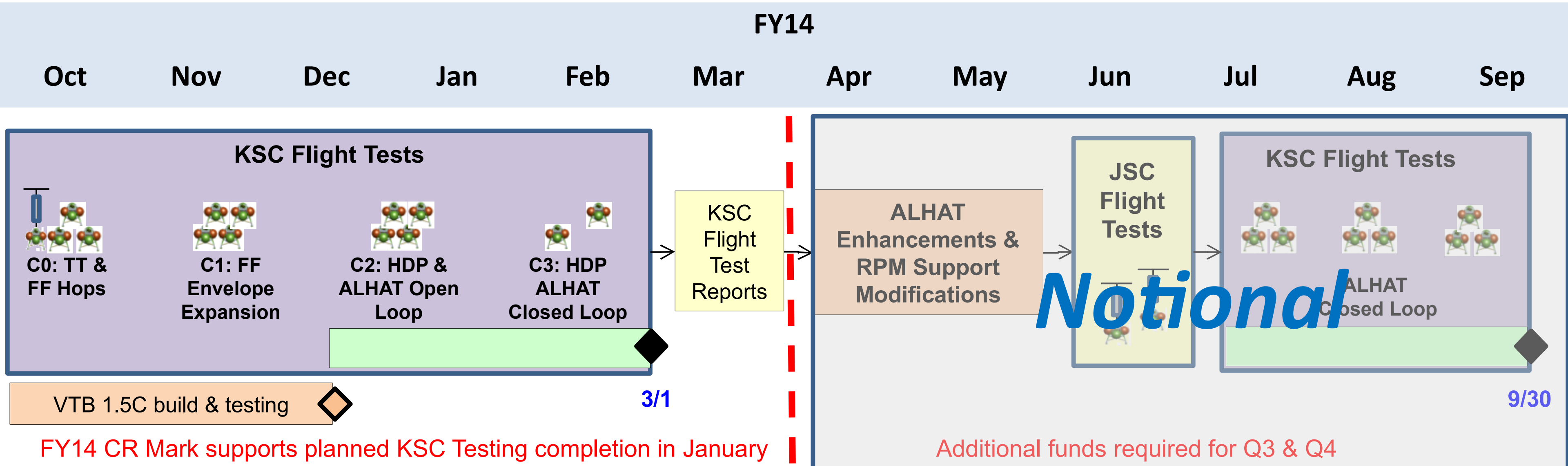
- Reliability upgrades
- Stable hover
- Precision translation
- Ground takeoff and landing under tether
- Engine stability

KSC Testing

- Precision landing
- Free flights
- ALHAT flights
- HDP 1 trajectory



FY14 Plan & Milestones



Milestone	Date
Complete KSC flight tests of ALHAT on Morpheus lander to demonstrate closed-loop control of vehicle and autonomous Hazard Detection and Avoidance (HDA)	2014-Mar-01
Complete Morpheus/ALHAT/RPM Free Flight tests at KSC (Notional)	2014-Sep-30

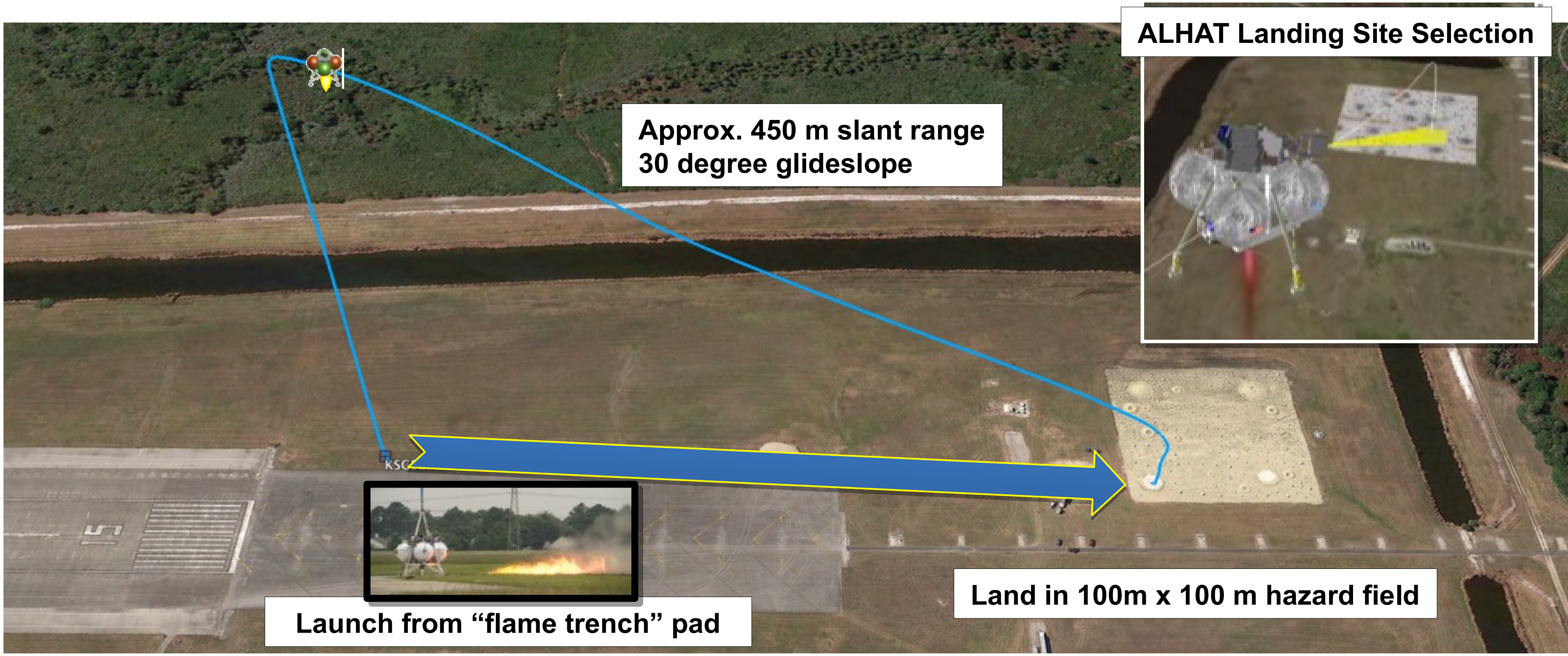
Center	Interaction/Collaboration
JPL & LaRC	ALHAT
KSC	Test Flights, RESOLVE
GSFC	Flight & Ground Software
SSC	Engine Testing
MSFC	Propulsion Development, DMSL nozzle testing, Lander Partnership
ARC	Resource Prospector Mission

ALHAT flight tests

HQ Tracked Milestones

KSC Testing Objective:
Hazard Detection Phase (HDP) Trajectory

Simulated lunar approach profile that exercises ALHAT sensors and navigation, GOAL: Closed-Loop ALHAT Navigation



Shuttle Landing Facility at KSC with Simulated Lunar terrain

Summary of Morpheus 1.5B Testing

JSC Testing

Hot fire
(static engine tests,
ground interaction)

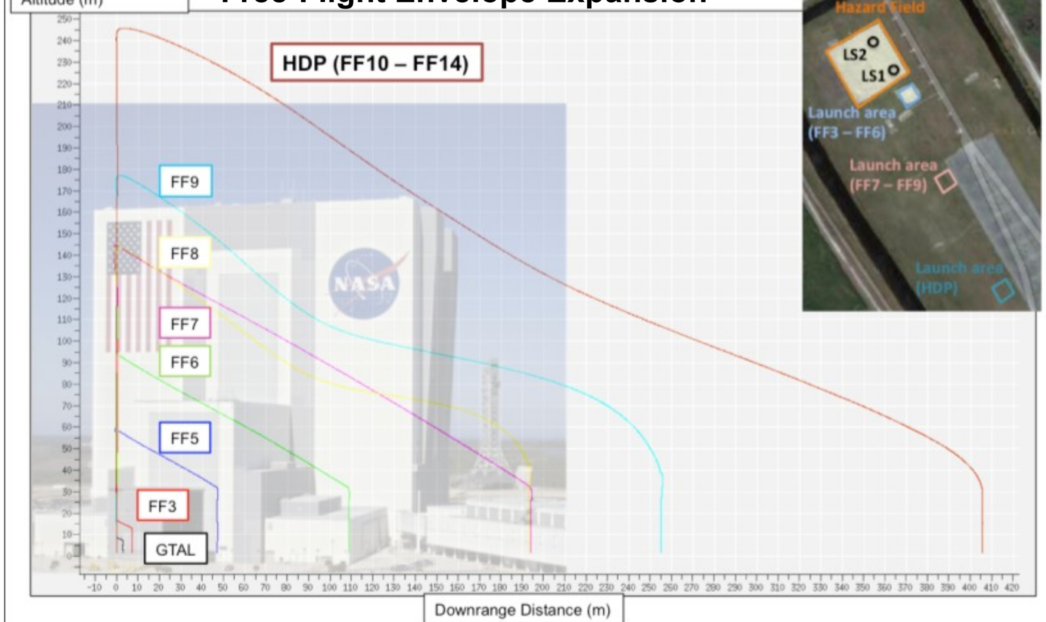
Tether tests

Ground Take-off and Landing (GTAL)

KSC Testing

Free-Flight Tests

Free-Flight Envelope Expansion

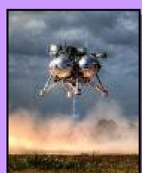


Morpheus 1.5B Testing - KSC

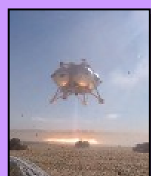
Started Dec 6, 2013

Morpheus 1.5B (2013-2014)

Tether 33
Dec 6
54 sec



FF3
Dec 10
54 sec
15 m x 7 m



FF4
Dec 17
82 sec
50 m x 47 m

Free Flight 5
Jan 16
57 sec
57 m x 47 m

Free Flight 6
Jan 21
64 sec
93 m x 109 m

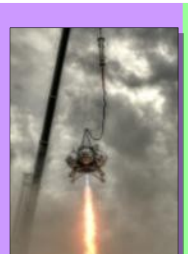
Free Flight 7
Feb 10
68 sec
144 m x 194 m

Hot Fire12
Feb 14
RCS Only

Hot Fire13
March 3
RCS Only

FF8
March 5
82 sec
144 m x 194 m
>300,000 views

FF 9
March 11
83 sec
177m x 255 m

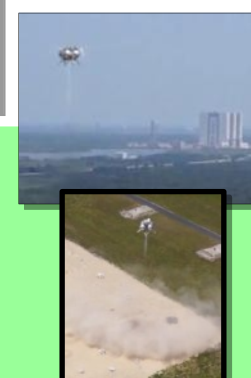


Tether 34
March 27
ALHAT

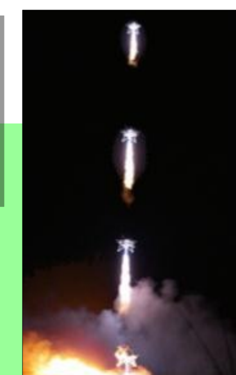
FF10
April 2
96 sec
ALHAT OL
245 m x 406 m

FF11
April 24
98 sec
ALHAT OL
245 m x 406 m

FF12
April 30
94 sec
ALHAT OL
245 m x 406 m



FF13
May 22
95 sec
ALHAT CL
245 m x 406 m



FF14
May 28
98 sec
ALHAT CL
245 m x 406 m

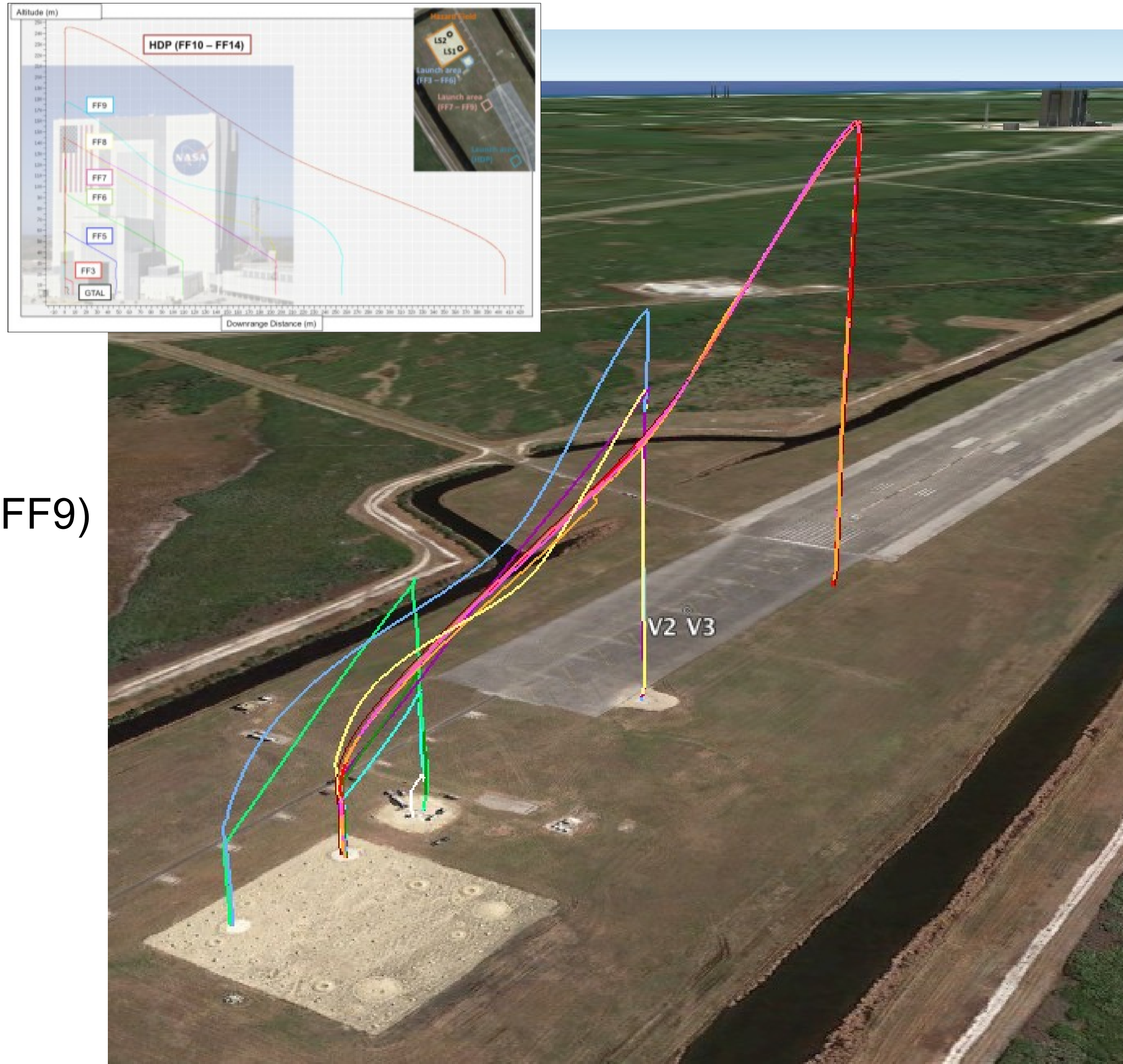
Flight Test Highlights

Completed 12
tremendously awesome
free-flight tests, including
5 full HDP Trajectories

Max speed:
36 mph vertical (15.9 m/s)
30 mph horizontal (13.4 m/s, FF9)

Total vertical height:
1905 m (6250 ft, 1.2 miles)

Total horizontal distance:
2883 m (9450 ft, 1.8 miles)

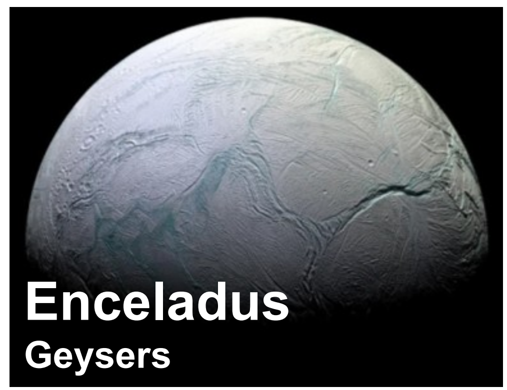


Project Success Criteria

AES Objectives	Project Success Criteria	Met?	Description
Rapid development and demonstration of prototype systems	Did the project complete its annual milestones?	✓	• Completed *ambitious* KSC FF test milestone schedule
Pioneer innovative approaches to improve affordability	Did the project implement innovative approaches to improve affordability?	✓	• MS SharePoint electronic documentation for PM, SE&I, T&V, CM, etc. • Using expensive HW from other Programs (e.g., Orion SIGIs) • Used low-cost vendors on MFG.com for some structural elements • Low-cost COTS components bought online & locally with P-Cards
Create opportunities for the NASA workforce to gain hands-on experience and learn new skills	• Was most of the work performed in-house by civil servants instead of being outsourced to contractors? • Did people learn new skills?	✓	• 73 FTE (85%) in FY12 and 55 FTE (68%) in FY13 performed most work • Team members learned many new skills with hands-on design, manufacturing and flight test experience, e.g., SE&I and T&V; wiring; design, manufacturing, testing and operation of rocket engines and Vertical Test Beds (VTB), and Flash LIDAR & Doppler LIDAR sensors
Multi-disciplinary, highly-collaborative project teams working across organizational lines	• Did the project interact with other AES projects? • Did the project involve multiple NASA centers?	✓	• See “Collaborative Partnerships” and “FY14 Plan, Milestones & Interactions” slides • Interaction with RESOLVE, SRP and other AES projects • 8 NASA centers involved in Morpheus vehicles, ALHAT sensors, and ground and flight testing
Infuse new technologies and capabilities into exploration missions	• Did the project incorporate new technologies? • Has the project identified a customer or end user?	✓	• New technologies include first known flight test of integrated LOX/methane RCS and main engine propulsion systems, and autonomous landing with hazard detection and avoidance (ALHAT) • Customers include all projects with lunar/planetary landers
Leverage partnerships to amplify investments	Did the project establish partnerships with external organizations or other NASA programs?	✓	• See “Collaborative Partnerships” slide • External partnerships with commercial aerospace (Armadillo, Masten), universities (Marquette, Purdue, UT), ESA, ULA, etc.
Outreach	Did the project engage the public through outreach activities?	✓	• Morpheus web site includes blog, videos, live streaming, & links to… • Twitter (“Vehicle” Tweets during tests), Facebook page & YouTube ch. • FF8 had > 450K views; most since FF2 • Morpheus & ALHAT personnel visit schools for outreach • Morpheus is VERY popular with co-ops and interns for work tours!

Mission-Enabling Capabilities

The mission of the ALHAT team is to develop, demonstrate, and infuse autonomous, real-time, 3-D terrain mapping and surface-relative navigation technologies promoting safe, precision landings on any solid planetary body under any lighting conditions.



Fundamental ALHAT Functions

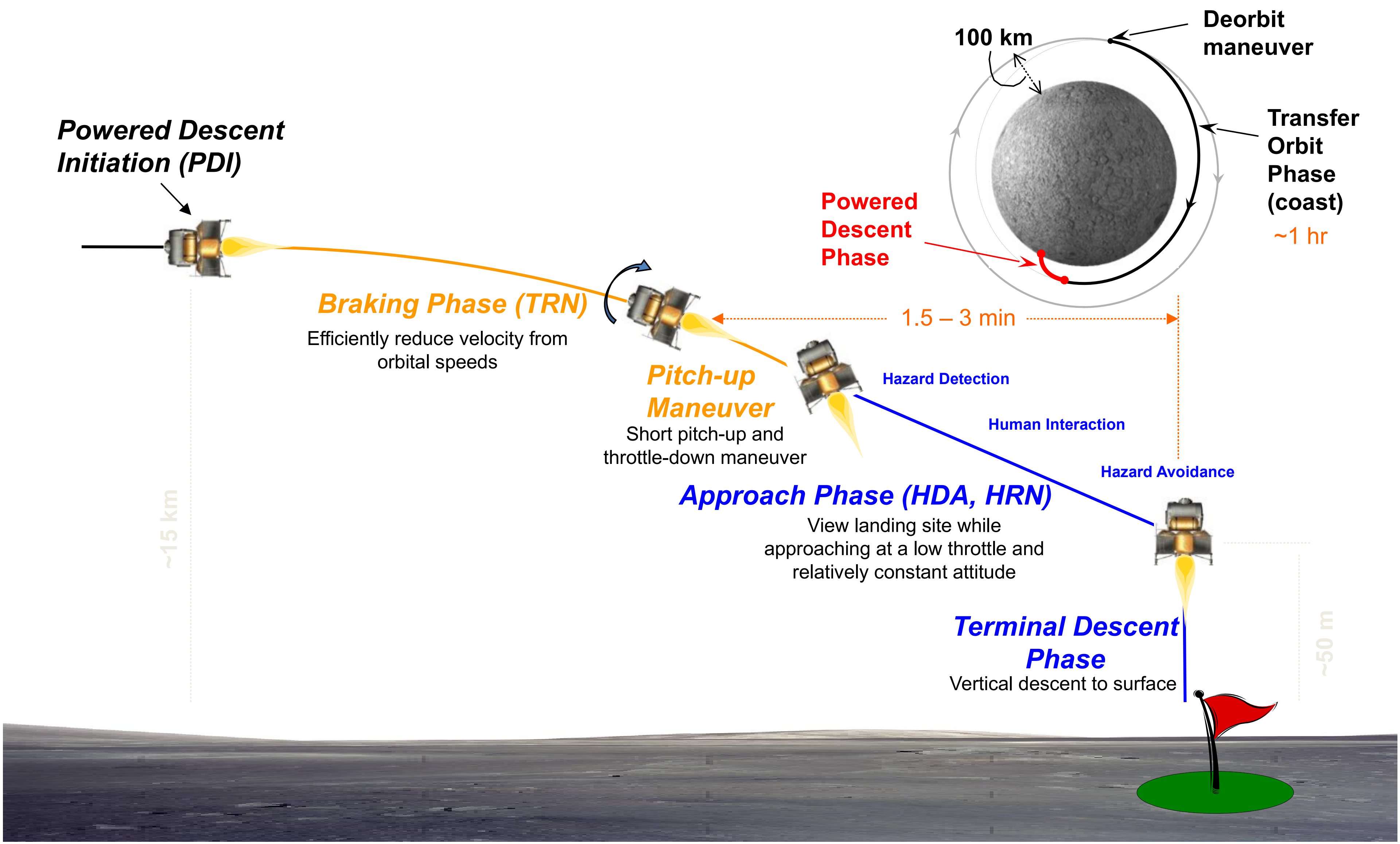
- ***Terrain Relative Navigation (TRN) – Global Navigation***
  - TRN function compares onboard reconnaissance data with real-time terrain imaging data to update the onboard navigation state.
  - Enables early and efficient elimination of major trajectory errors and delivers the lander into close proximity to the pre-defined landing area

- ***Hazard Detection and Avoidance (HDA)***
  - ALHAT Hazard Detection System (HDS) generates a high-resolution, 3-D terrain map in real-time during the descent and landing trajectory. The HDS ranks the safe landing aim points and delivers the safe site list to the lander GN&C system.
  - The landing vehicle must possess sufficient propulsive divert capability to reach the selected safe site.

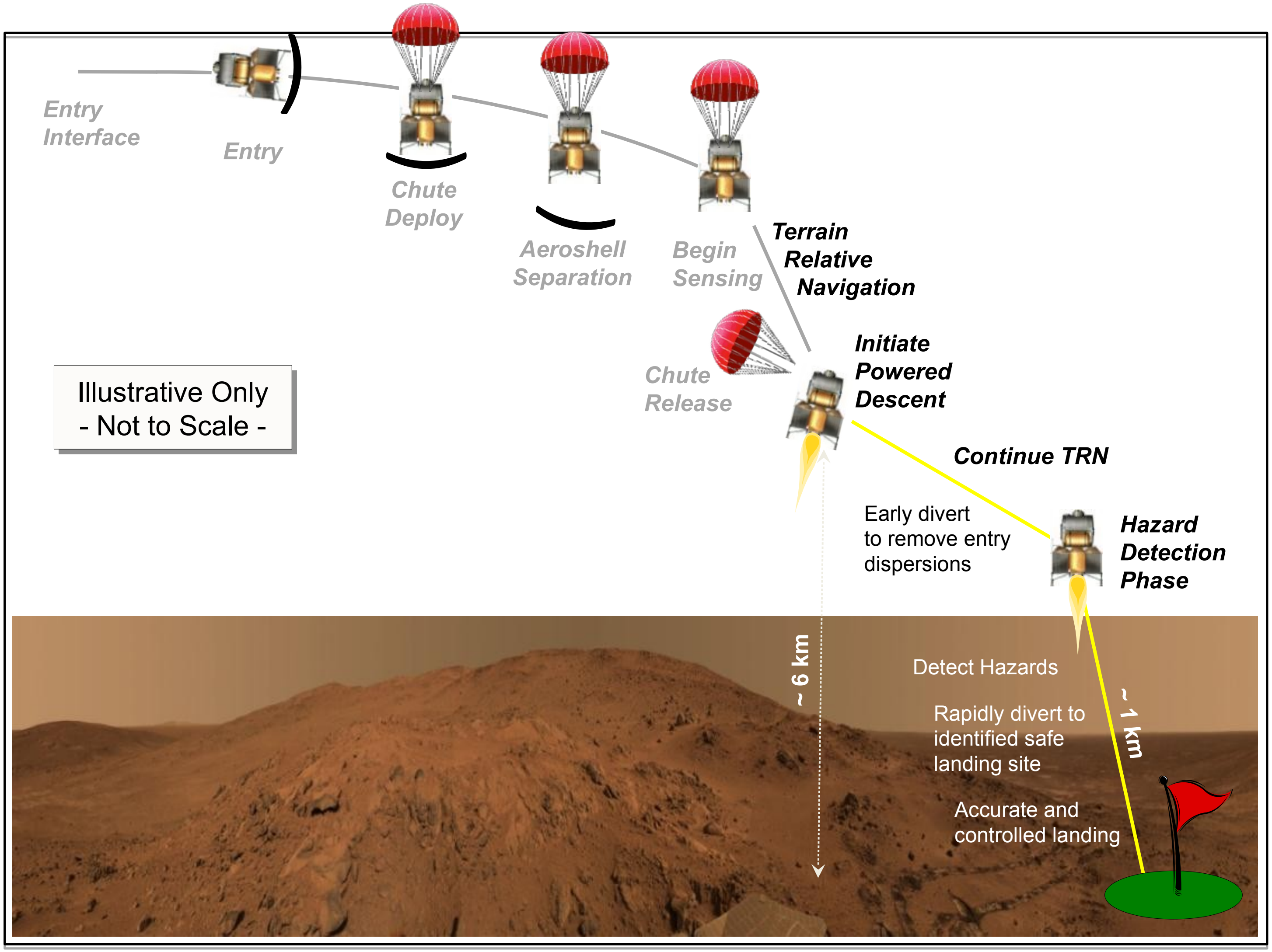
- ***Hazard Relative Navigation (HRN) – Local Navigation***
  - HRN function compares the high-resolution onboard terrain map developed by the HDS during the descent and landing trajectory with subsequent real-time terrain imaging data to update the onboard navigation state as the vehicle approaches the landing site. HRN accurately positions the lander above the safe landing site.

- ***Inertial Navigation to Avoid the Dust Problem During Terminal Descent***
  - Lidar sensors initialize the lander navigation system with precise ground-relative measurements before the lander engine kicks up dust. Inertial navigation can then be used to very accurately dead reckon to the safe landing site.

ALHAT for Lunar Landing



ALHAT for Mars Landing

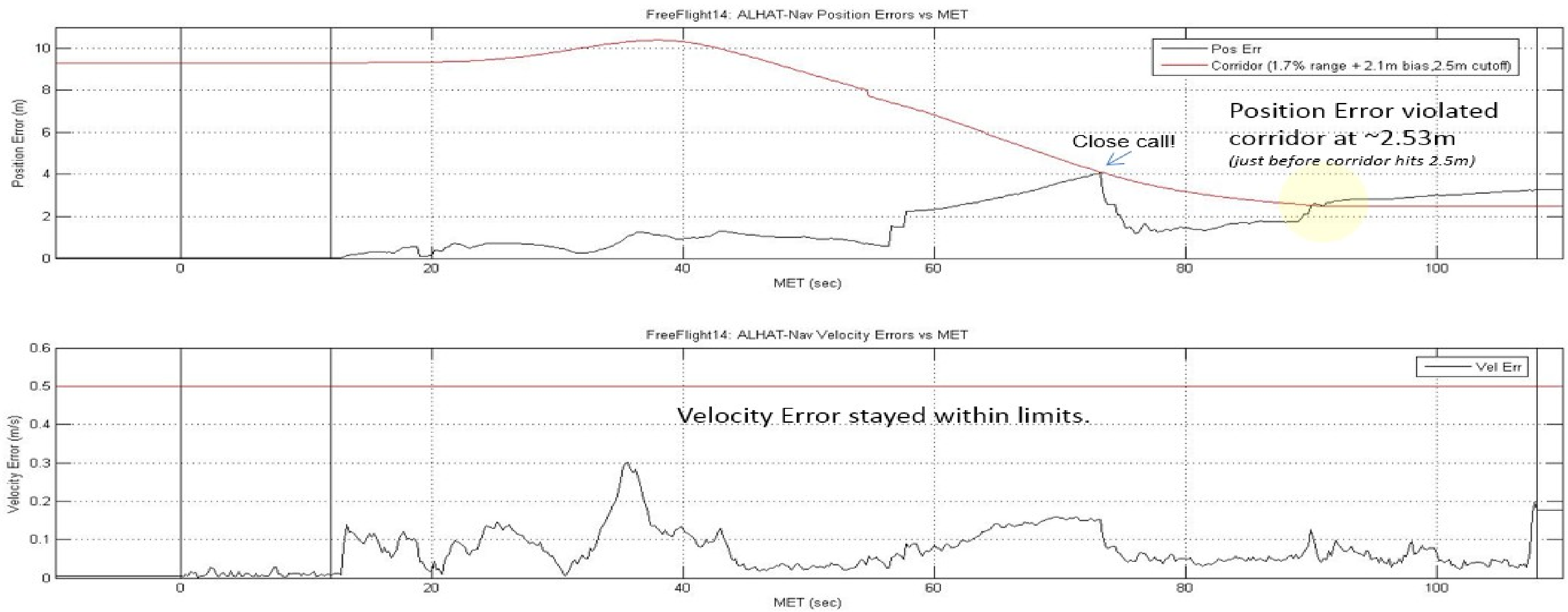


ALHAT Free Flight Performance

- The objective of the Morpheus-ALHAT free flights was to demonstrate real-time hazard detection with safe site selection and accurate surface-relative navigation to land within 3 m of the selected safe site
- FF10 was the first terrestrial flight demonstration of the ALHAT real-time hazard detection and avoidance system fully integrated with the Morpheus VTB
- The first three flights were flown open loop with the vehicle navigated by the Morpheus navigation filter which used GPS, the SIGI IMU, and a COTS Acuity altimeter
- The last two free flights were flown closed loop using the ALHAT Nav filter with the SIGI IMU, flash lidar for hazard detection and safe site selection, and the NDL and the LAlt to maintain a good surface-relative state

ALHAT Free Flight Performance

- A navigation corridor was established that defined the acceptable limits on the position and velocity differences between the ALHAT state and the Morpheus state to ensure a safe and controlled landing of the vehicle
- On FF13, the corridor position limit was exceeded during the HRN phase and AFM moded to VTB Nav and for FF14, the corridor limit was exceeded late in the trajectory, approximately 25 m before touchdown.



ALHAT Performance Summary

- In general, the ALHAT System worked very well with just a few exceptions. In particular induced environmental effects were not adequately anticipated
  - Liftoff dust cloud that drifted between the vehicle and the hazard field affected flash lidar data, particularly during HRN
  - Hot, turbulent air from the engine plume caused major drop outs of Doppler lidar data, and three beam data was very limited
  - This was the first time that the ALHAT navigation filter was fully integrated with ALHAT sensors in a dynamic flight environment and there was insufficient time to fully understand and resolve software integration and formulation issues during the free flight campaigns

VERIFICATION OF ALHAT LEVEL 0 REQUIREMENTS

ALHAT Level 0 Requirements	Verification Status	Verification Method
R0.001 Landing Location The ALHAT System shall enable landing of the vehicle at any surface location certified as feasible for landing.	✓	Analysis & Closed Loop Free Flight Demonstrations (FF13 & FF14)
R0.002 Lighting Condition The ALHAT System shall enable landing of the vehicle in any lighting condition.	✓	Analysis & Closed Loop Free Flight Demonstrations (FF13 & FF14)
R0.003a Global Landing Precision The ALHAT System shall enable touchdown of the vehicle at a pre-defined, map-based landing target with a 3-sigma error of less than 90 meters in the absence of a hazard avoidance maneuver.	✓	Analysis & Field Test 3 Open Loop Navigation Results
R0.003b Local Landing Precision The ALHAT System shall enable landing of the vehicle at a selected safe landing point with a 3-sigma error of less than 3 meters.	?	Status subject to review of closed loop free flight data (FF13 & FF14)
R0.004 Hazard Detection and Avoidance The ALHAT System shall detect hazards with an elevation change of 30 cm or larger and detect slopes of 5 deg and steeper, and provide landing point designation based on detected hazards.	✓	Closed Loop Free Flight Demonstrations (FF13 & FF14)
R0.005 Vehicle Commonality The ALHAT System shall enable landing of crewed, cargo, and robotic vehicles.	✓	Design/Inspection
R0.006 Operate Autonomously The ALHAT System shall have the capability to operate autonomously.	✓	Closed Loop Free Flight Demonstrations (FF13 & FF14)
R0.007 Crew Supervisory Control The ALHAT System shall accept supervisory control from the onboard crew.	✓	Inspection and Simulation

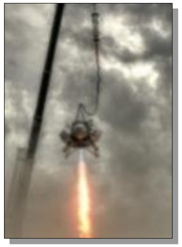
Verification of R0.003b via closed loop flight demonstration was prevented by:

- ALHAT lidar sensor interactions with the induced flight environment
- Lack of flight experience with the ALHAT navigation filter
- Violations of imposed free flight corridor safety constraints relative to VTB nav

FY15 Options

Purpose of Additional Morpheus/ALHAT Flights

- The Morpheus/ALHAT project declared success after five fully integrated free flights at KSC, with three precision open-loop and two closed-loop flight tests
- However, there are some objectives yet to be demonstrated fully:
  - Engine plume prevented Doppler Lidar from collecting 3-beam data through much of flight
  - ALHAT nav did not correctly process Hazard Relative Navigation (HRN)
  - Vehicle transitioned from ALHAT nav back to VTB nav just before final descent
- Additional flight testing will provide the opportunity to:
  - Demonstrate completion of objective to fly full trajectory on ALHAT Nav with HRN and safe site selection by HDS
  - Better demonstrate capability of Doppler Lidar in new mounting location without plume interference



Tether 34
Mar 27, ALHAT

FF10
Apri2, 96 s

FF11
Apr 24,98 s

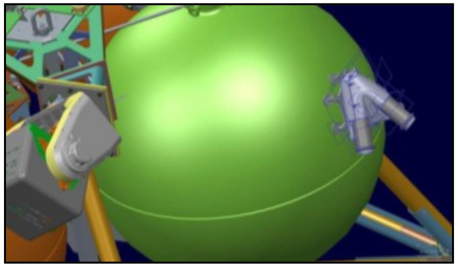
FF12
Apr 30, 94 s

FF13
May 22, 95 s

FF14
May 28, 98 s

Factors to Consider for Flying Again

- Team has worked nav analysis to increase likelihood of meeting objectives for next flight
  - Replay and sim show marked performance improvement
  - Also planning to relocate Doppler Lidar to reduce plume interference
- Required personnel need to be available for KSC test campaigns
  - This may get tougher the longer we delay
- As long as the vehicle is at KSC we have to continue paying maintenance costs
- Engine life is a concern
  - The propulsion team has continued to monitor crack growth on the injector face oxygen orifices after each flight
  - The current engine (HD4A) has over 3000 seconds of run time; but it is expected to be good for at least one more free flight, and quite possibly more
    - Failure not expected to be a risk to flight; if cracks grow further, engine needs to be swapped for spare
  - The HD4B engine has already been tested at Stennis, but needs a couple more tests to finalize the performance data needed for flight
    - Swapping engines requires a tether test prior to resuming free flights
    - Testing could be performed using the nearly finished C vehicle instead of at Stennis



Alternate DL location on +Z tank

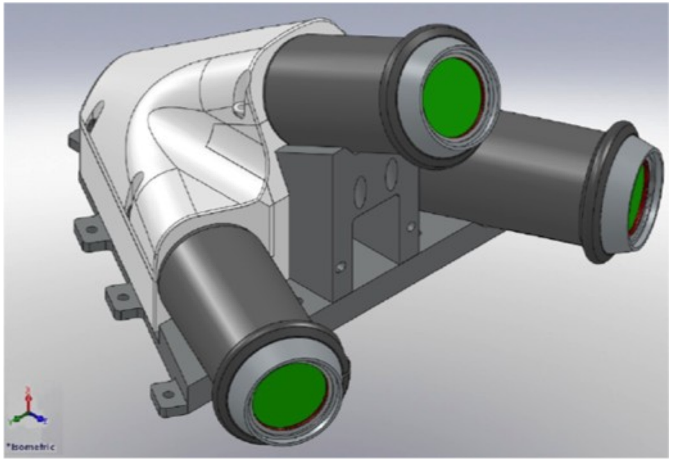
Bravo in storage at KSC

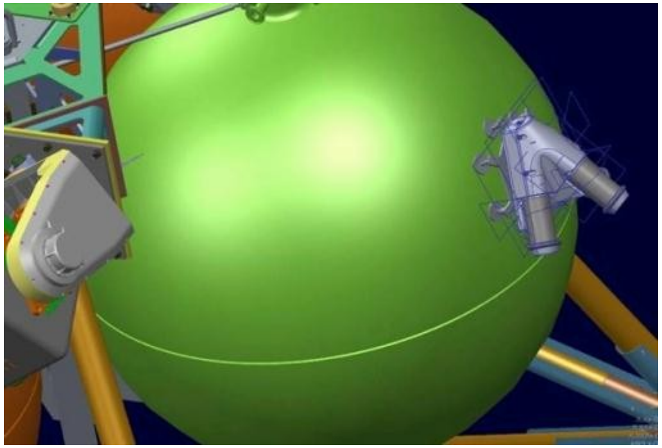
Morpheus main engine test at SSC-E3

ALHAT/Morpheus FF15 Forward Work

The Morpheus/ALHAT Projects are ready to perform two more free flights at KSC with the updates listed below:

- Flight placard to mitigate dust cloud impact
- HDS: reintegration of HDS LN200, FL pixel checks, ground functional checkouts
- LAlt: laser repair and replacement, calibration, reintegration onto vehicle, ground functional checks
- NDL: fabrication of new optic head and mounting bracket, beam alignment, reintegration onto vehicle, on-vehicle metrology, ground functional checks
- Checkout updated navigation filter I-loads and update the Morpheus flight software with the updated navigation filter software.





Morpheus/ALHAT Advances

SE&I - Project Scale of Rigor

- May or may not use guidelines
- Learn as you go
- May only implement processes after failure

<u>Process Rigor</u>
CM, Requirements, Data Management, Formal Documentation, etc.

<u>Technical Rigor</u>
Factors of safety
Quality control
Amount of testing, etc.

Research & Development

Human Space Flight

NASA guidelines: NPR 7120.5d, 7123.1, 7120.2, etc.

- **Low cost project**
- **Low consequence of failure**
- **Easily replaceable hardware**
- **Little schedule pressure**
- **Under the radar**

More documentation, rigor, discipline, record-keeping, planning, etc

- **High dollar project**
- **High reliability required**
- **Crew safety**
- **Mission critical**
- **Expensive payloads**
- **High visibility**
- **Schedule constraints**
- **Costly replacement**
- **Paying customer**

1.5A **1.5B**

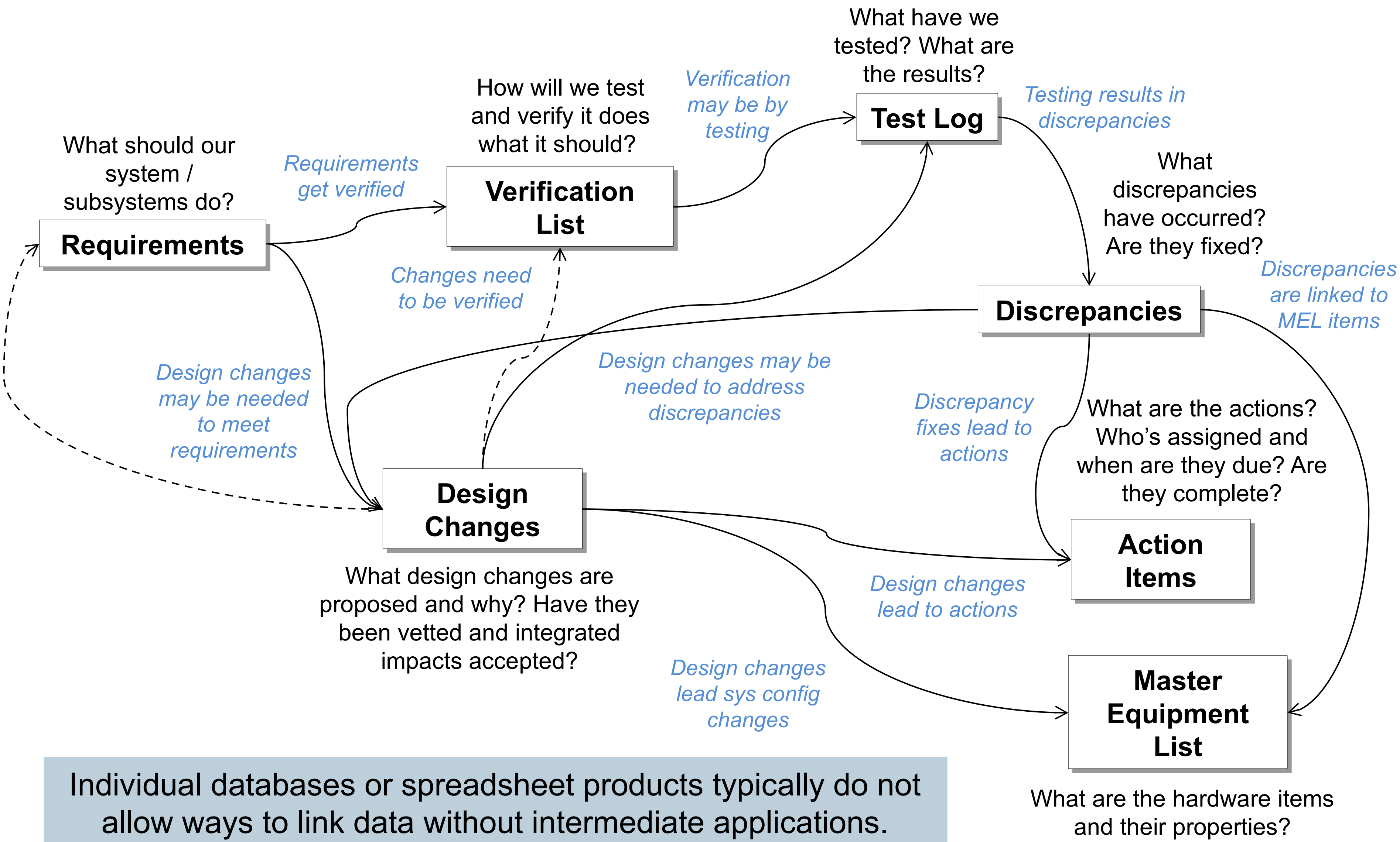
Technology Development / R&D

Morpheus ALHAT

Shuttle, ISS, Orion

The scale of project rigor should always be adapted to the needs and scope of the project. Some attributes will drive rigor but not equally for all processes.

SE&I - Maintaining Data Relationships



Individual databases or spreadsheet products typically do not allow ways to link data without intermediate applications.

Technology Advancement – ALHAT Sensors

- ALHAT project developed, refined, and demonstrated closed loop operation of three advanced lidar sensors in a relevant flight environment
- Laser Altimeter combines extended operational range, high repetition rate, and very high accuracy and precision
- Three beam Doppler Lidar provides extraordinary surface-relative velocity accuracy and precision and can also provide simultaneous line-of-sight range measurements
- Flash lidar uses TigerEye Sensor Engine, a custom-built laser, and real-time gain control and calibration algorithms to achieve long distance operation with improved 3-D image quality compared to prior art
  - ALHAT invested considerable resources on NIR detector and Read-Out Integrated Circuit (ROIC) technologies to further increase sensitivity, improve range measurement accuracy and precision, and reduce noise
  - These investments are being leveraged in the ARM BAA sensor suite development efforts
- The recent closed loop Morpheus/ALHAT free flights has advanced the ALHAT sensor hardware and software to TRL 6

Technology Advancement – ALHAT TSAR Software

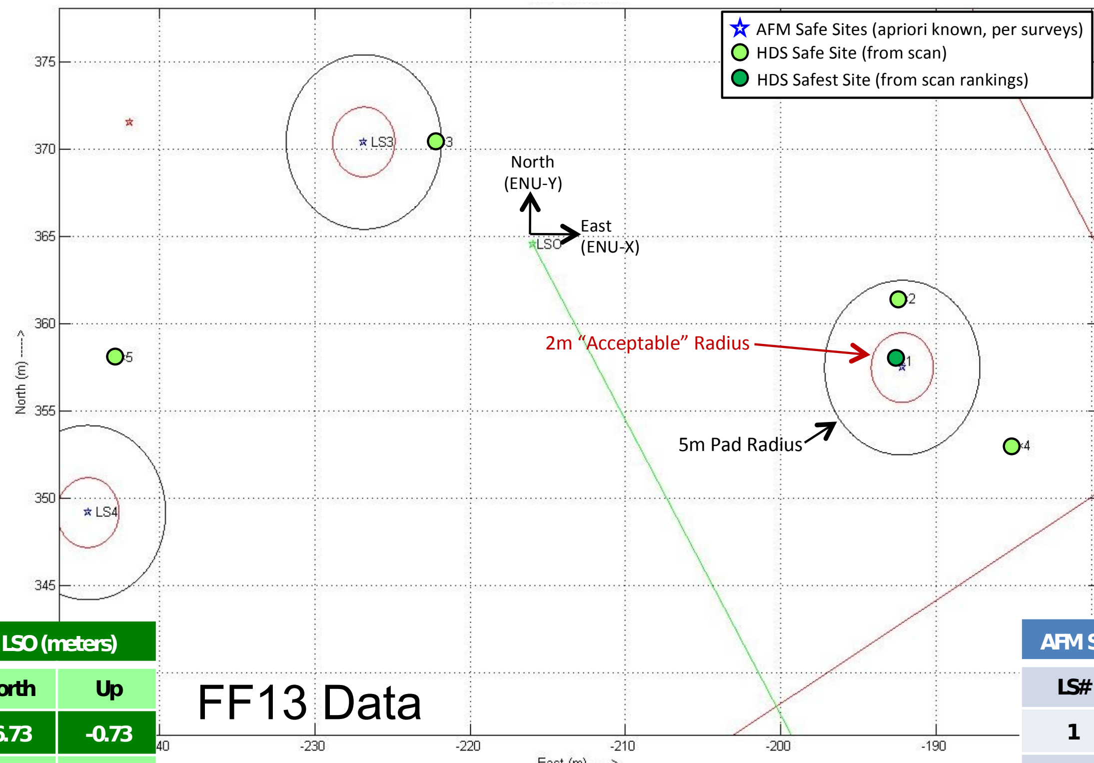
- ALHAT project developed, refined, and demonstrated closed loop operation of two advanced terrain sensing and recognition software functions in a relevant flight environment
- Hazard Detection & Avoidance (HDA) generates a terrain DEM, parses it for slope and roughness hazards, and generates a ranked list of safe landing sites (TRL 6)
- Hazard Relative Navigation (HRN) compares the high-resolution terrain DEM generated during the descent and landing trajectory with subsequent real-time terrain imaging data to update the onboard navigation state as the vehicle approaches the landing site
  - Processing of HRN measurements by the onboard ALHAT navigation filter was not fully successful during the recent Morpheus/ALHAT free flights
  - HRN is deemed to be TRL 5 pending a fully successful end-to-end demonstration
- ALHAT project developed, refined, and thoroughly tested multiple Terrain Relative Navigation (TRN) software algorithms for lidar and passive optical sensors in open loop flight on a fixed-wing aircraft over a variety of terrains, operational altitudes, and lighting conditions (TRL 5+)

Technology Advancement – ALHAT Navigation Filter

- ALHAT project developed an extended Kalman navigation filter for safe, precision landing and matured it in cooperation with the Morpheus project
- ALHAT Nav filter uses a dual-state inertial/surface relative approach to rendezvous the spacecraft with the selected landing target
- ALHAT Nav filter performance was reasonably successful during the closed loop Morpheus/ALHAT free flights
  - Completed most of FF13 and nearly all of FF14 using ALHAT Nav despite the tight navigation corridor constraint relavtive to VTB Nav
  - Processing issues with respect to ALHAT HRN and NDL measurements resulted in sufficient divergence from VTB Nav to violate the trajectory corridor boundary
  - Playback and simulation results from recent revisions to the ALHAT Nav filter appear promising for future free flights, but the ALHAT Nav filter is deemed to be TRL 5+ pending a fully successful end-to-end demonstration

ALHAT Landing Site Evaluation

- **Landing Site Designation**
  - Designates landing site location based on HDS scan data (cross-checked with apriori-known safe site locations it maintains) and commands offset "divert" coordinates to Guidance, accordingly.
  - Maintains a safe site for flying a Designated Abort safely into the Hazard Zone, in case of ALHAT-Fail.



HDS Safe Site Coords wrt LSO (meters)			
HDS	**East**	**North**	**Up**
→ **1**	**23.83**	**-6.73**	**-0.73**
2	24.00	-3.13	-0.67
3	-5.82	5.84	-0.96
4	31.36	-11.55	-0.69
5	-26.42	-6.47	-1.18

Landing Site Evaluation Overview Page:
(several links from this page)
https://oasis.jsc.nasa.gov/projects/ProjectM/GNC/Morpheus%20Flight%20Dynamics%20Wiki/1.2.13.6%20Landing%20Site%20Designation%20and%20Abort%20Zones.aspx

AFM Safe Site Coords wrt LSO (meters)			
LS#	**East**	**North**	**Up**
1	**23.79**	**-7.08**	**0**
2	-10.46	44.14	0
3	-10.88	5.85	0
4	-28.64	-15.38	0
5	-46.92	23.71	0

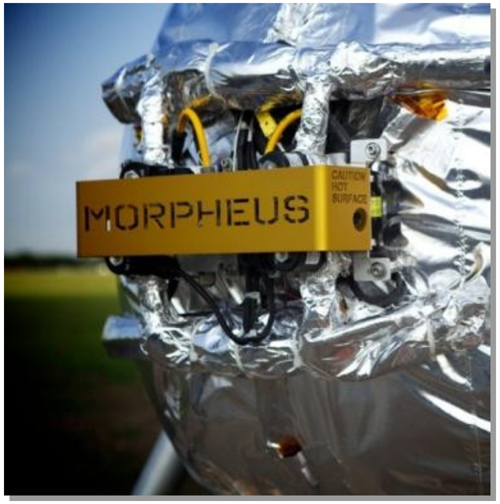
Technological Advances - Propulsion

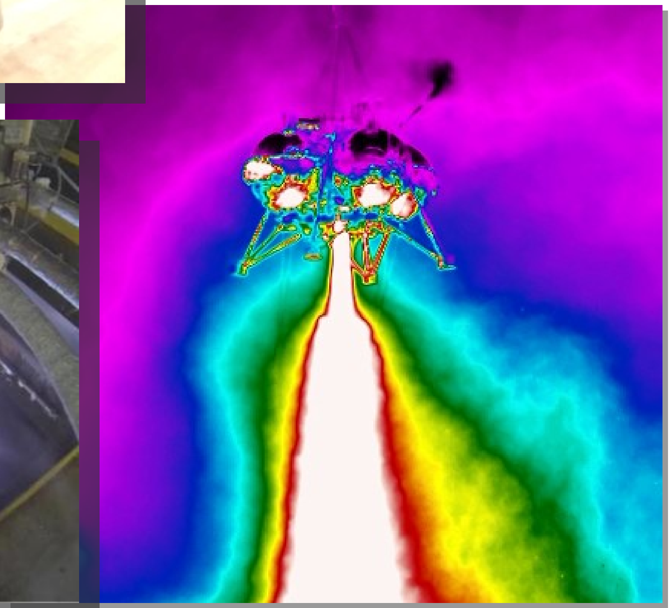
Engines

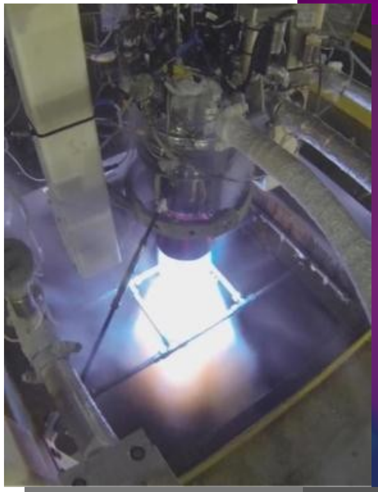
- In-house designed and built ~5300 lb thrust LOX/Methane main engine
  - Demonstrated reliable performance in relevant flight environment
  - >3000 sec of run time
  - Identified design considerations that influence engine stability
- Integrated LOX/Methane RCS engines for roll control

Feed System and Tanks

- Propulsion subsystem maturation including feed system and startup conditions for engine stability
- Propellant management with multiple tanks in quad tank lander design
- Tested and demonstrated aluminum tanks with cryogenic propellants







Technological Advances - Propulsion

System Level Operations

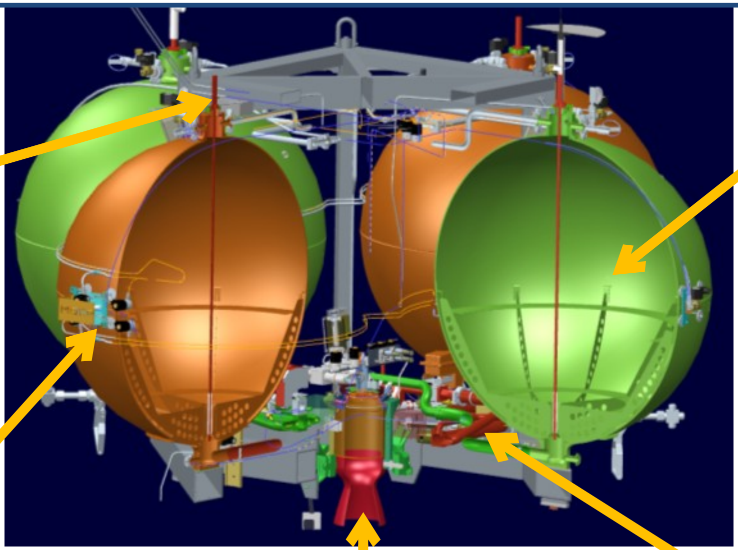
- Conducted 12 Hot-Fire Tests, 34 Tether Flights, 12 Free-Flights
- System Level Flight Operational Experience Gained
  - Prop System Turnaround measured in hours
  - No major issues working with LNG and Lox
    - ie. No hardstarts/No purge run for RCS in-flight, no corrosion, little to no soot, safed quickly with GN2 post flight
- Low Cost of development, fabrication, and operations
  - Developed and Built 3 vehicles for ~500K per year procurement $90K in FY2014, + 6-7 FTE

High Vapor Pressure & clean propellants is good for engines and operations

All Hardware common between O2 and CH4

Parallel Tank Differential Draining – Prop Manag.

- Capacitance probe in each tank
- Demonstrated propellant balance during free flight
- Demonstrated self-correcting behavior (passive, no liquid control valves)



Propellant Slosh Control

- Demonstrated damping of Lo2/ Methane propellants

Four RCS jets x 20 lbf(max)

- Demonstrated GNC control using Lox/LNG RCS engines
- 40msec to 30+sec pulses
- Operated in blowdown from 350 psig to 160 psig
- Operated over range of Inlet Conditions in flight
  - Gas-gas , gas-liq ., liq.-liq.
- Reliable engine and ignition obtained after a few modifications
  - Spark extend, Pc tube locations, plug mods

Gimbaled, Throttled Main Engine

- ~5400 lbf engine
- >4:1 throttle capability with simple ball valve mechanism
- >2500 sec operations, > 120 starts
- Excellent stability during main stage
- Start is stable with cold Lox and warm methane gas. Possibly unstable if liquid methane

Integrated Main Engine and RCS, Tank & Feedsystem

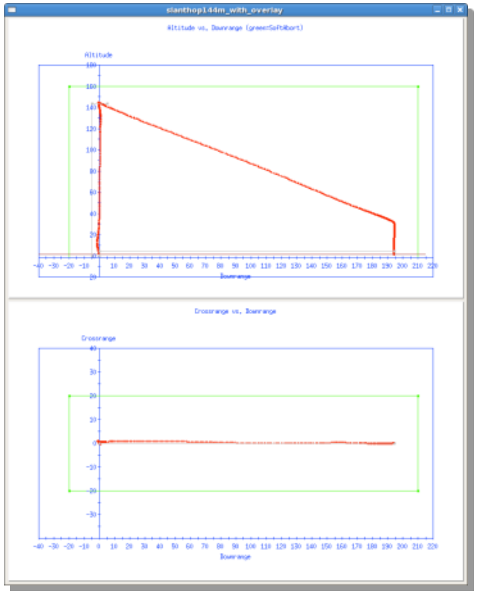
- Blowdown Pressurization
- RCS feedsystem mounted to tanks and TVS operated in flight
- Cryo RCS worked even in Texas and Flordia summer environment
  - Venting seen in videos is the initial chill-in from gas to liquid temps
- Tanks used purged aerogel blankets (non-flammable)

Technological Advances – Precision Landing

GN&C

- Core G&C design for thrust vector control with gimbaled, throttling engine and roll control jets
- Multi-sensor precision navigation, including vibration isolation of IMUs
- Autonomous flight manager architecture
- Demonstrates capability for autonomous GN&C during final approach of lunar descent and landing

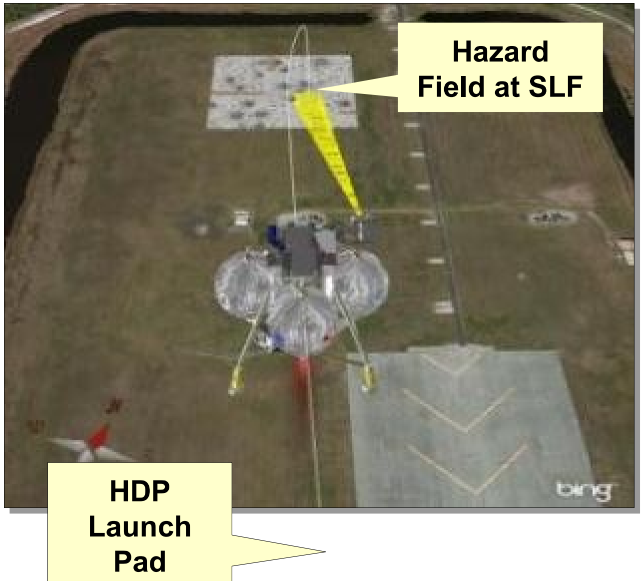
PA1 SIGI in Vibe Isolation Cage



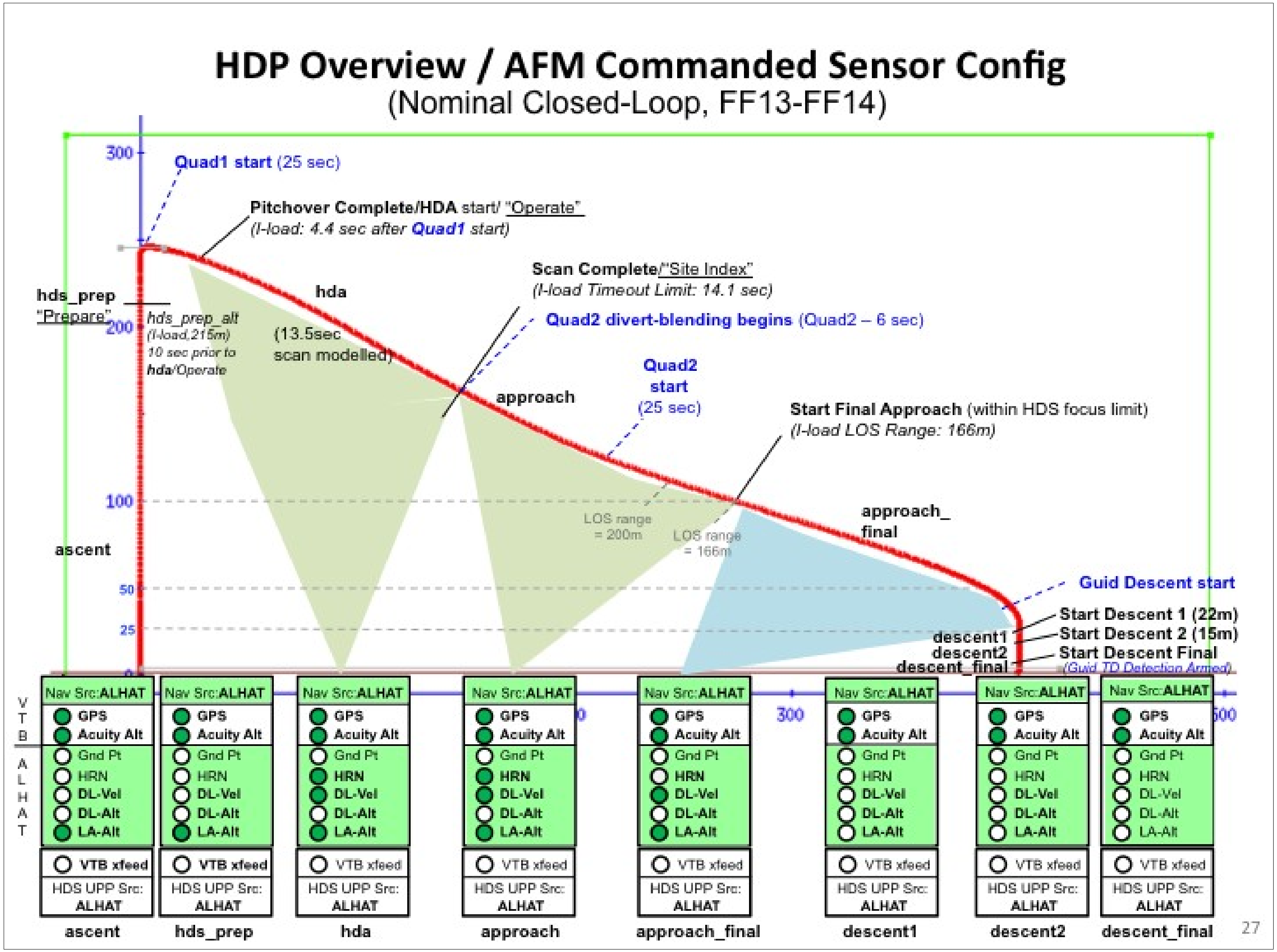
ALHAT Flash Lidar mounted on Morpheus

ALHAT

- Integrated ALHAT hardware with vehicle and operations
- Autonomous hazard detection and trajectory re-planning
- Precision landing using only inertial and surface relative navigation



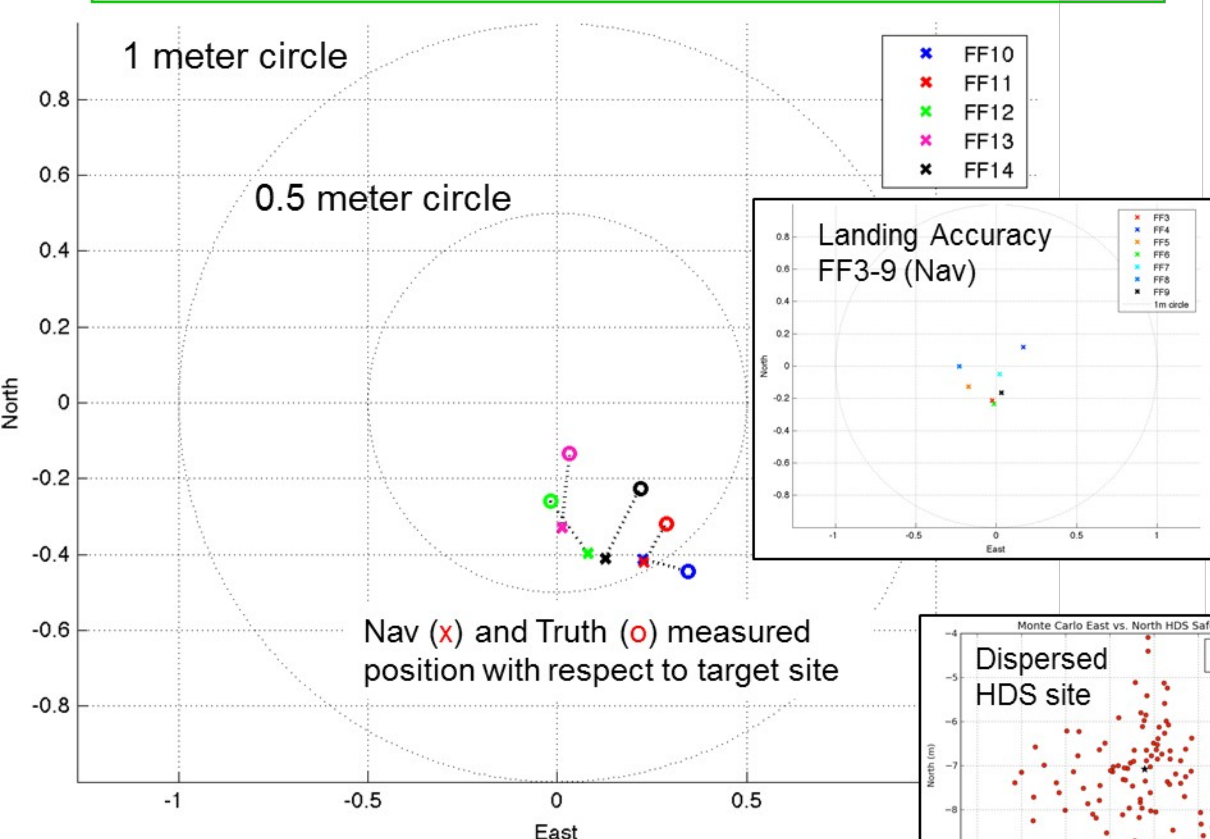
ALHAT HDP Profile

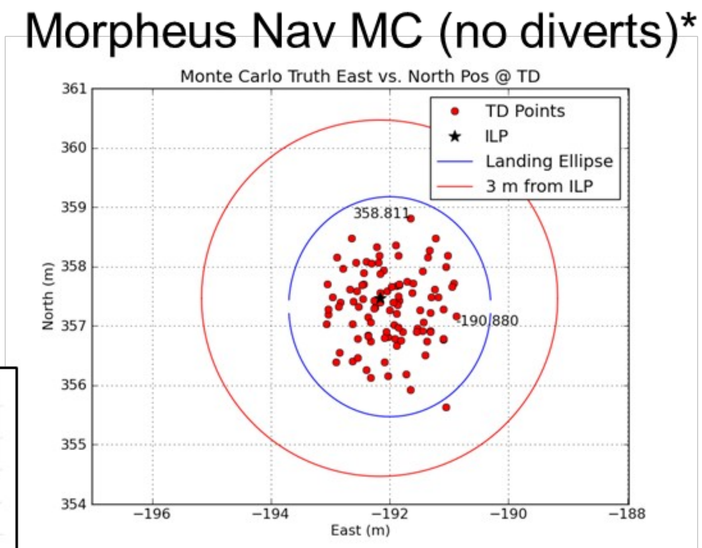


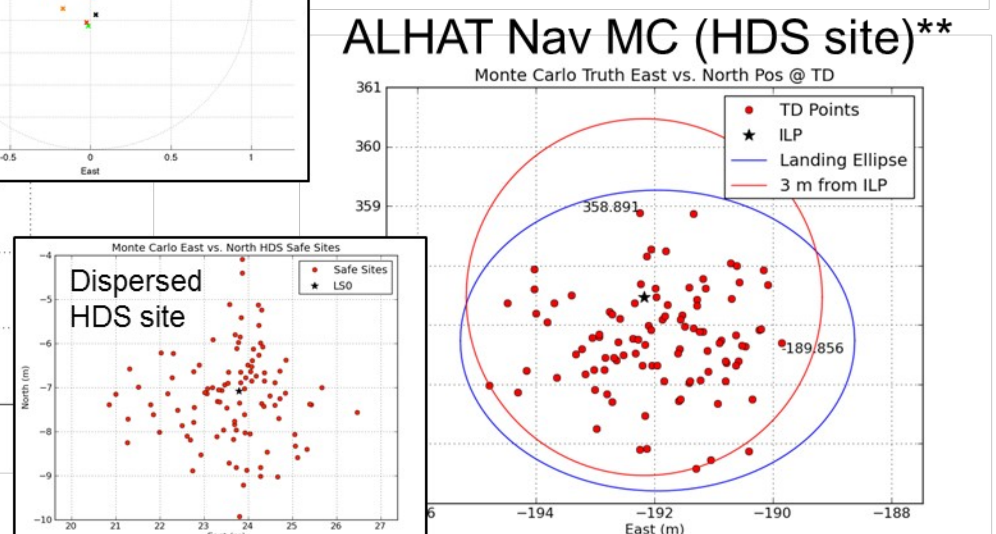
Summary of Flight Test Results: Landing Accuracy

R2.082	Landing Accuracy	< 3	m

Demonstrated landing accuracy in flight within 0.5 m
- **Including non-zero landing site diverts (FF12 and FF13)**
- **And VTB Nav downmodes (FF13 and FF14)**







* FF11 day-of-flight nominal MC runs

** FF14 day-of-flight nominal MC runs (82 divert cases of 100)

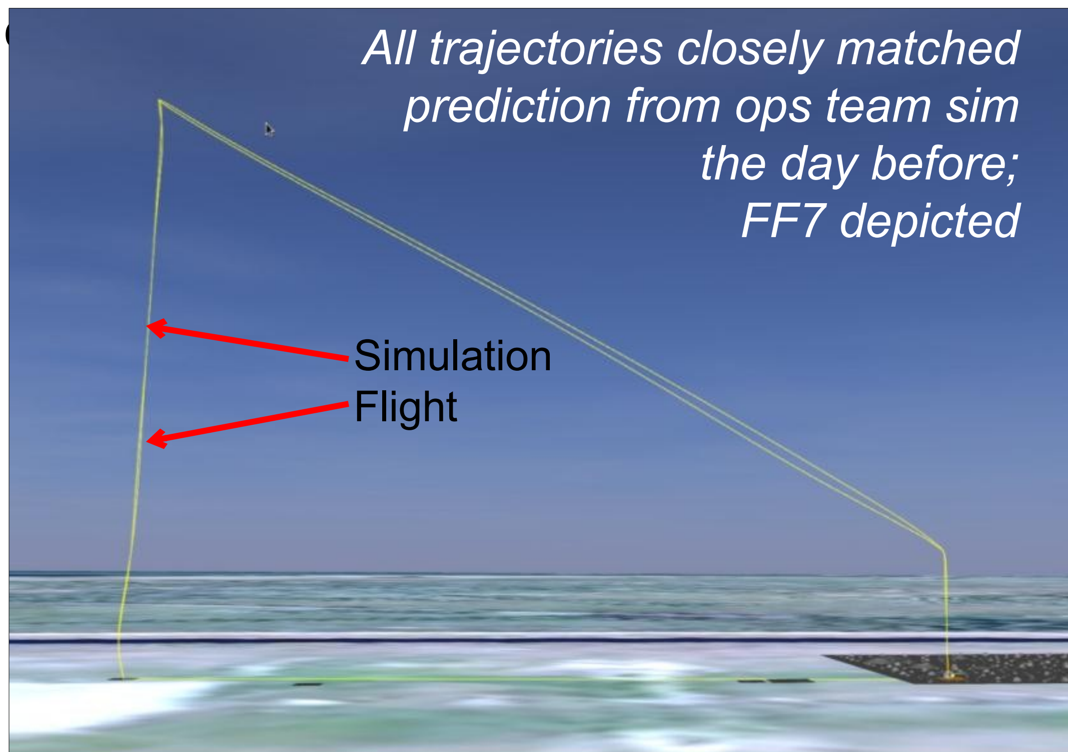
Advances – Flight Software

Software

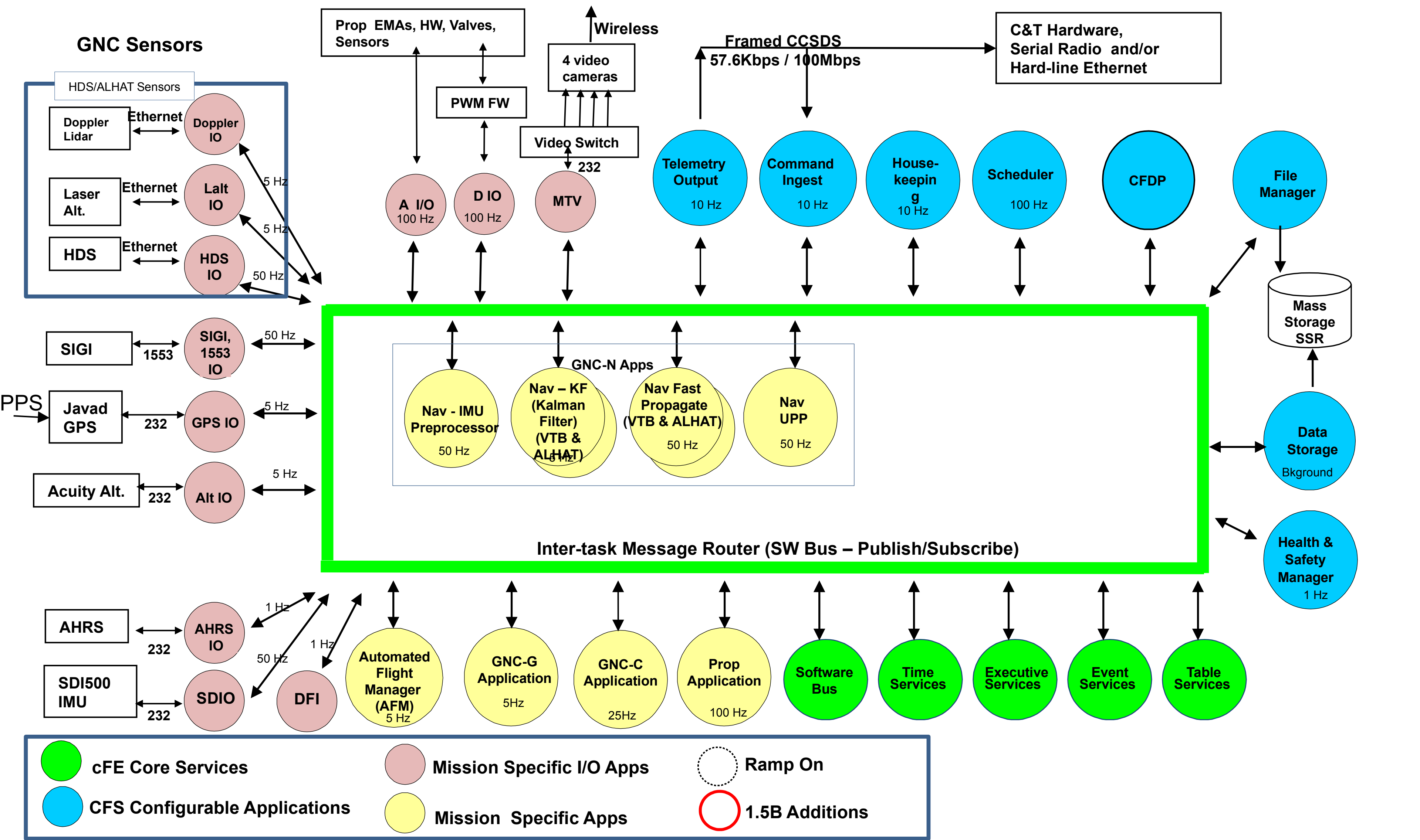
- GSFC's Core Flight Software on-board; incorporated reusable AFM and GNC algorithms
- GSFC's ITOS for ground software and displays; updates fro near real-time usage
- Flight and ground software architecture matured; core services and executive complete; timing and avionics (

Simulation

- Uses JSC's Trick environment (C++)
- EDGE graphics for situational awareness during flight and for ops team training
- Matches flight data well…

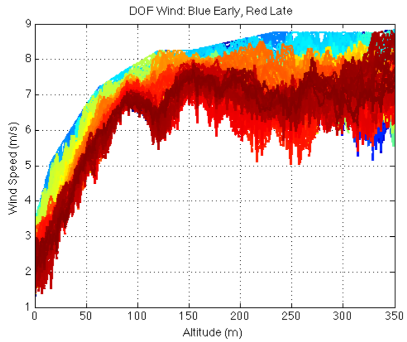


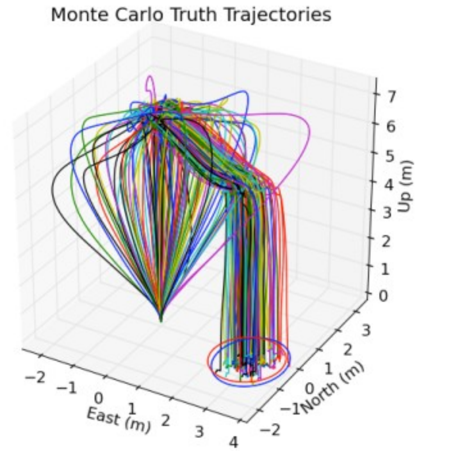
Morpheus 1.5B Flight Software Architecture



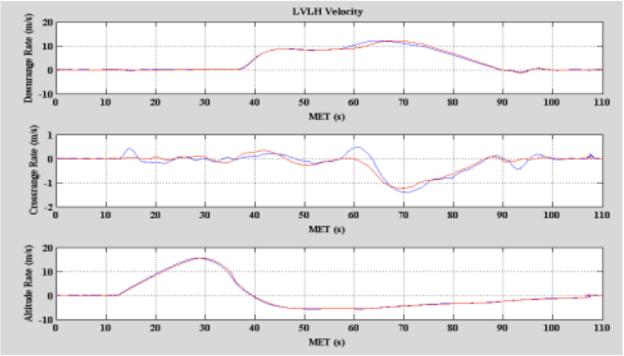
Advances - GNC Simulation and Analysis

- FSW Development
- Trajectory Design
- Operations Training
- Pre-Flight Vehicle Checkouts
- Pre-Flight Certification Runs (“Monte Carlo”)
  - Nominal Runs
  - Soft-Abort Cases

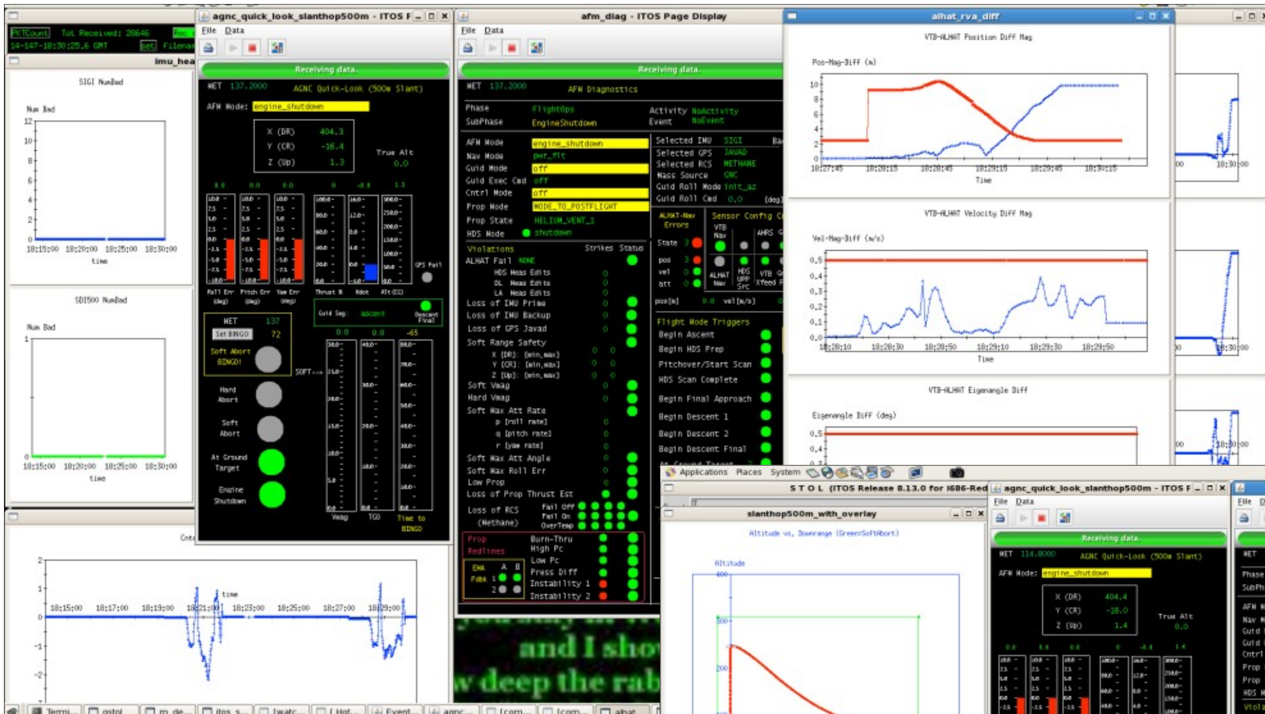




- Day-of-Flight
  - Propellant Loading
  - Wind Placards
- Post-Flight Reconstruction



Morpheus ITOS Displays
GNC Examples for ALHAT Flight



System/Sensor Health
Nav Differences

Trajectory
Flight Segment Transitions

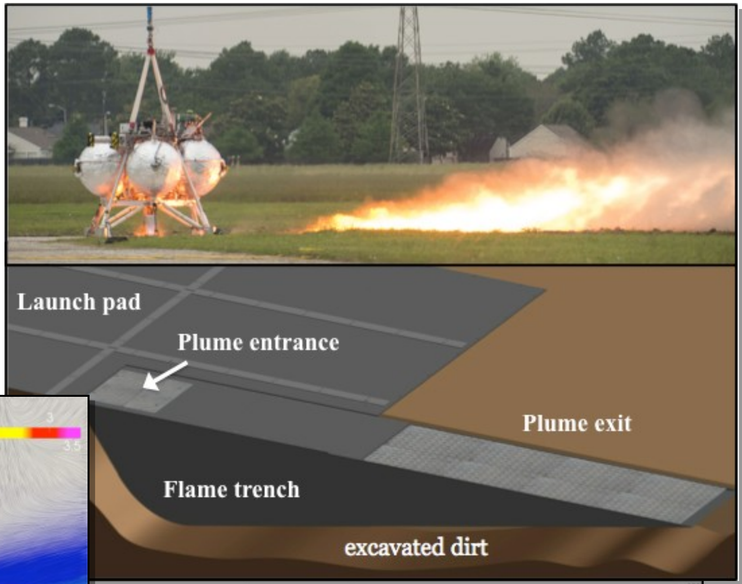
Accomplishments – Integrated Vehicle

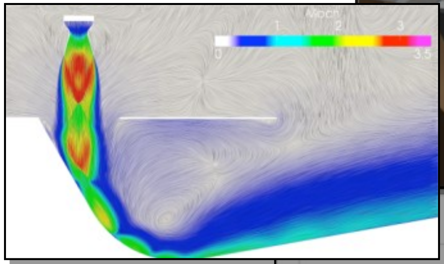
Core vehicle components:

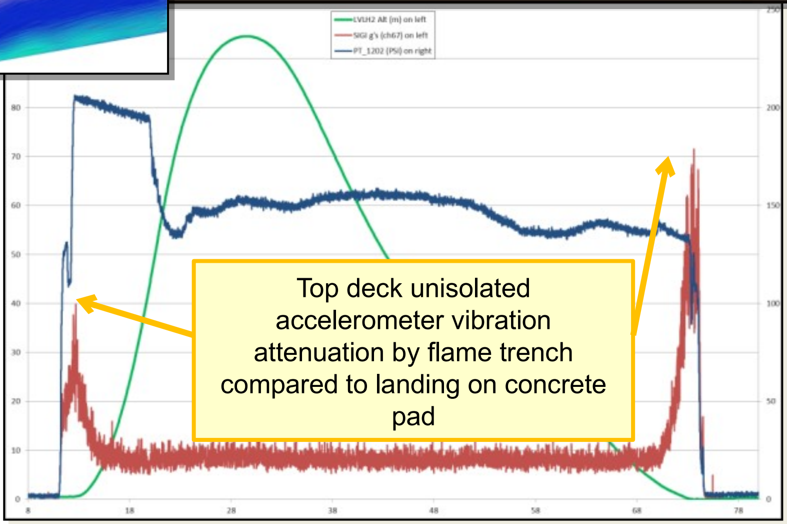
- 60 Flight tests completed
- Welded aluminum structure
- Flight avionics with path to space flight hardware (including valve controller boards, CPU, I/O, command/telemetry)
- Power management and power distribution

Integrated system challenges:

- Mass management
- Environments
- Thermal
- EMI
- Vibro-acoustics
- Vehicle instrumentation
- FDIR
- Flame trench design and ablative







Ground Systems and Operations

- Developed operator workstations, ground software and displays, plus communications capability from vehicle to control center (and to remote NASA centers)
- Conducted safe and efficient propellant loading and launch operations
- Managed flight-to-flight turnaround of vehicle – maintenance and R&R
- Moved JSC operations team across country to Florida to support operations on ~2-week intervals
- Engineers serving as operators improves design, operability and sustainability

Morpheus Vehicles

1.5A	1.5B	1.5C



"Alpha" Vehicle
June 2010-Aug 2012
5 Hot fires
20 Tether tests
2 Free flight attempts at KSC
HD4A Engine
LOV August 8, 2012

"Bravo" Vehicle
June 2012-Aug 2014+
7 Hot fires
14 Tether tests
1 GTAL
12 Free flights at KSC
~70 upgrades from Alpha
HD4A-LT Engine (refurbished)

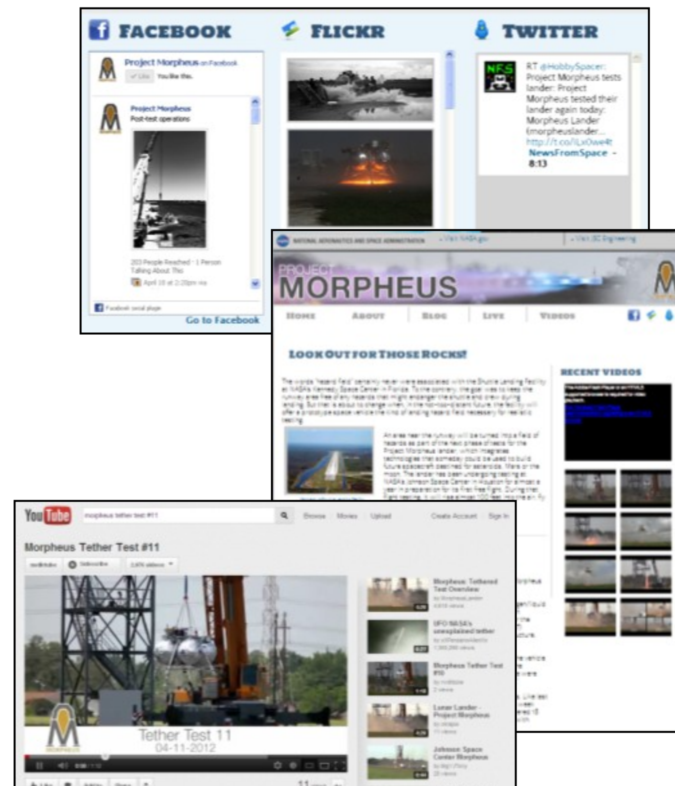
"Charlie" Vehicle
Sept 2012-Aug 2014+
- Structure 90% complete
- Prop system 90% complete and low-pressure leak checked
- Needs wiring and avionics installed (already have parts)
- HD4B engine tested at SSC

Achievements: Schedule

- Over four years, the project has spanned a total project life cycle from concept of operations through flight operations and sustaining engineering, with multiple prototypes and iterative design and development. In this time, the Morpheus project has built 2.75 nearly identical prototype vehicles, and conducted 60 flight tests over 37 months: 12 static hot fires, 34 tether tests, and 14 free flights. The final five free flights at KSC successfully reached an altitude of 245 m and traveled 800 m downrange to a land safely in the hazard field with the ALHAT components integrated on board.
- Project moved seamlessly from design cycles to component test to flight testing phases (and repeated the transitions after the crash of 1.5A) by modifying processes as needed for effectiveness
- Rapid pace of project life cycle enabled by the SE approach:
  - Rapid decision-making enabled by daily interaction of PM and SE&I management with the technical team
  - High level of forward momentum by daily management of team tasks during critical periods of the project
  - Pace set with intermediate milestones to force progress
  - Use of collaborative environment provided the whole team with immediate access to the “authoritative source” of project information
  - Flat organizational structure with less boards and panels meant less time vetting presentation material before bringing forward to management
  - After the crash of the 1.5A vehicle in August 2012, the Bravo vehicle was ready to fly just 8 months later. This demonstrated the quality of relevant design documentation, which allowed Bravo to be nearly identical other than the ~70 design upgrades that were incorporated.
  - Flight-to-flight maintenance was scrupulously managed using a maintenance list in the collaborative environment which allowed a quick turnaround between flights

Morpheus Outreach and Education

- Representative academic grants and partnerships :
  - University of Washington (wind tunnel testing)
  - Marquette University (GNC algorithm development)
  - Purdue University (Pintle engine design, build and test)
  - UTEP (RCS engine development/test)
- Morpheus team has hosted >60 co-op and intern tours



- Effective social media presence: NASA Morpheus website, Facebook page, Twitter, YouTube channel
- Live streaming video during most flight tests
- Real-time broadcast available on-site at JSC, KSC & HQ
- Team members conduct tours and visit schools
- Frequent student workshops at Space Center Houston

LESSONS

Lessons Learned

- **Vibro-acoustics matter**
  - Lean teams, by definition, cannot be deep in every area.
  - Rapid prototyping development won't generate prototypes with longevity.
- **Interfaces matter**: Personnel and/or hardware
- **Risk trades matter**
  - Assess risk of LOV (or system losses) vs. rapid development
    - Depending upon risk/reward, schedule pressure may be OK
    - Test articles must not be too precious to test!
  - Carefully balance project-level risk acceptance and appropriate team risk culture
    - "The vehicle is largely single string, so what's one more single point failure?!"
- **Communications matter**
  - Pre-declared test failure as a non-mishap
  - Repeatedly inform agency management
  - Manage expectations of team, management and public

Lean Development Lessons

- Small focused team with in-house development enables rapid spiral development with dedicated personnel and little overhead
  - Streamlined, electronic documentation
  - Specific content can be scaled and applied across the agency

- We talk a lot about lean processes, but it is also about the people
  - Creating an environment that:
    - empowers
    - has a sense of urgency
    - respectfully questions the past methods and techniques
    - they know you will forgive them
    - is inclusive of all orgs

  - Invaluable hands-on technology development and testing experience for Morpheus team members will benefit NASA for decades with know-how and motivation

Lean Development Lessons

- Prototyping leading requirements development
  - Rapid, iterative prototype development and testing at a much lower cost than traditional NASA projects
    - Lean/agile development with "Home Depot" engineering
  - Testing enables rapid advancement, albeit with higher project risk, especially with aggressive Morpheus testing schedule
    - Example: inexpensive electrical connectors and components can have higher failure rates leading to operational delays => learning where to selectively target more expensive procurements to balance cost with operational risk
  - HF and TT tests have uncovered several issues not seen in simulations that would have prevented successful FF tests => frequent, iterative testing reduces risk of rapid development