Morpheus Free Flight 2
Test Failure Investigation

Steve Munday & Jon Olansen
NASA Johnson Space Center
Engineering Directorate
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Contents

- FF2 test failure summary and video
- What did and didn’t fail and why
- IMU nav data path components
- Vibration environment
- Corrective action
- FY13 Plan

Thanks to...
- Morpheus team for data, analysis, plots, charts, expertise, judgment, time, overtime, sweat, etc.
- Failure Investigation Team (FIT): Jenny Devolites, Richard Comin and Mike Baine
- Susan Gomez for SIGI expertise and data
- S&MA Fault Tree Consultant: Karon Woods
- Independent Assessment Team: Mark Hammerschmidt and Greg Blackburn
- Greg Gaddis, KSC Site Manager & Morpheus TAM
- AES, JSC & KSC for strong support of Morpheus
On August 9th, 2012, the Morpheus 1.5 Vertical Testbed (VTB) crashed during Free Flight 2 (FF2) at KSC SLF, resulting in the loss of 1.5 VTB hardware.

JSC/KSC Morpheus team immediately executed the pre-rehearsed Emergency Action Plan to protect personnel and property, so damage was limited to 1.5 VTB hardware.

JSC/KSC Morpheus team secured data and mapped & recovered debris.

Project had pre-declared loss of VTB to be a test failure, not a mishap.

Video
Debris Field

• Polar grid set up around impact point
• ~100 items catalogued: mass, radius & bearing
• Remaining items weighed by sectors for mass distribution
• NESC & KSC Safety will use debris catalog to anchor blast models

- Crash site observations
  - Nearly all debris < 50m, << 1000ft clear distance for Pad Crew (Max estimates: JSC = 325ft, KSC = 653ft, WSTF = 1000ft)
  - Methane tanks burned
  - LOX tanks exploded (BLEVE), +Z tank separated at lower boss & rolled 37m
  - Engine plume dug a small crater; chamber burned, but injector is recoverable
  - Top deck melted into crater, including GN&C plate & SIGI
  - Onboard camera SD card experienced too much heat damage for data recovery
  - APU Solid State Disk Drive data and DFI box recovered

<table>
<thead>
<tr>
<th>Ring</th>
<th>Radius (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>75</td>
</tr>
<tr>
<td>5</td>
<td>150</td>
</tr>
<tr>
<td>6</td>
<td>300</td>
</tr>
</tbody>
</table>
## FF2 Main Event Timeline

<table>
<thead>
<tr>
<th>EDT</th>
<th>MET</th>
<th>Event</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>06:15</td>
<td></td>
<td>Pre-test safety briefing &amp; Emergency Action Plan review at SLF hangar</td>
<td></td>
</tr>
<tr>
<td>06:30</td>
<td></td>
<td>VTB rollout and launch preparation</td>
<td></td>
</tr>
<tr>
<td>12:43</td>
<td>0:00.0</td>
<td>MMCC Operator commands Execute Ignition Sequence (10 sec auto chill-in + 3.8 sec engine ignition seq)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0:10.0</td>
<td>Engine ignition sequence begins with igniter spark; 1st plume visible on video at 11.4 sec</td>
<td></td>
</tr>
</tbody>
</table>
|      | 0:13.8| Prop-to-GNC handover, start of Ascent mode, GNC commands throttle-up to 100%  
  • Vehicle lifts off before throttle reaches 100%  
  • GNC responds appropriately to initial IMU nav state updates with modest pitch rate & 1.17g accel (typically ~1.2g) |          |
|      | 0:14.3| Throttle reaches 100% (actual thrust lags throttle slightly)                                                                                                                                              | Nominal  |
| 0:14.4|      | **IMU nav data flow to CPU stops**  
  • Lacking new IMU data, FSW flags “bad” SIGI data and feeds stale nav data into GNC nav state propagation  
  • GNC responds appropriately to static/stale body rates & acceleration with positive pitch correction, steadily pitching over VTB, eventually throttling down from 100% to 50% between MET = 15-17 sec | Failure  |
| 0:17.8|      | Loss of vehicle telemetry, presumably due to inverted orientation blocking antennas                                                                                                                                 |          |
| 0:18.4|      | Inverted VTB impacts ground next to launch pad and rolls upright  
  • Top deck avionics and GNC components damaged  
  • Engine continues to burn, digging a crater beneath the vehicle  
  • Fire fed by LNG leaking through open throttle valve and severed fuel lines |          |
| 0:19  |      | MMCC Operator sends manual Soft Abort command (no violation of on-board auto Soft Abort limits)                                                                                                         |          |
| 0:20+ |      | MMCC RSO sends Thrust Termination command via independent Flight Termination System (FTS)  
  • FTS presumed unable to close throttle valve or open tank vent valves                                                                                                                             |          |
| 12:45| 2:03 | **1st LOX tank Boiling Liquid Expanding Vapor Explosion (BLEVE), rolls toward Hazard Field**                                                                                                           |          |
Vibration, Throttle & Altitude

Lost IMU data shortly after max vibration and 100% throttle

Plume first visible in video

Lost comm

Impact

Spark flag

Prop-to-GNC handover

% Throttle

Vibration

Altitude

AFM MET (sec)
What Didn’t Fail?

- **Power:** bus voltage & current data (right) show no power loss
- **Propulsion**
  - Engine performance, tank temp and pressure data were nominal
  - EMA position feedback data showed nominal tracking of GNC commands
- **Structure:** video and forensics show no evidence of structural failure before impact
- **Software**
  - Downlinked FSW parameters were nominal, responding appropriately
  - MMCC GSW nominal
- **Weather and winds** benign, within LCC
- **Survivors**
  - HD4 engine injector plate
  - RCS thruster bodies
  - Javad GPS antenna
  - ALHAT HDS mass simulator
  - FTS boxes ejected, one still operational
  - Footpad insulation made by KSC
  - *Morpheus Team expertise!*
What Failed?

HW failure in IMU data path => loss of nav data to GNC

- Hardware failure along IMU data path => loss of navigation data
  - Autonomous VTB GNC requires IMU nav data to correctly propagate nav state & maintain stable flight
  - VTB became “blind” during initial ascent, unable to sustain stable flight
  - Available data does not isolate a root cause; no single “smoking gun”

- Prime suspects:
  - **SIGI**, source of IMU nav data, hard-mounted (not vibe-isolated by design)
  - **1553 bus**, carries SIGI data to APU, mostly hard-mounted, partially vibe-isolated
  - **Avionics & Power Unit (APU)**, contains CPU with GNC FSW, vibe-isolated
Top Deck Layout

- 1553 Bus Coupler & Terminator
- SIGI
- Top Deck Triaxial Accelerometer
- DFI
- APU
- 1553 Bus Coupler
- LOX (+Z)
- LNG (-Y)
- X up
- Y stbd
- Z fwd
### SIGI Data Timeline

<table>
<thead>
<tr>
<th>SIGI_cfs_time_tag (corresponds to Nav time)</th>
<th>Calc. AFM MET (sec)</th>
<th>Sigi_modeWord (health)</th>
<th>gpsTimeOfWeekLSW</th>
<th>eo24BusTime</th>
<th>pvtOKMasterAntID_ID (GPS ant)</th>
<th>Event/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1028565820.477</td>
<td>0.000</td>
<td>0</td>
<td>22236</td>
<td>65238</td>
<td>1</td>
<td>GNC/AFM Receives Command &quot;Execute Ignition Sequence&quot;, AFM MET = 0</td>
</tr>
<tr>
<td>1028565821.190</td>
<td>0.713</td>
<td>0</td>
<td>23236</td>
<td>15327</td>
<td>1</td>
<td>Auto chill-in (10 sec) continues toward Engine Ignition Sequence</td>
</tr>
<tr>
<td>1028565822.190</td>
<td>1.713</td>
<td>1.000</td>
<td>24236</td>
<td>30952</td>
<td>1</td>
<td>Nominal operations, no failure flags, data changing...</td>
</tr>
<tr>
<td>1028565823.190</td>
<td>2.713</td>
<td>1.000</td>
<td>34235</td>
<td>56130</td>
<td>1</td>
<td>Start Engine Ignition Sequence (3.8 sec)</td>
</tr>
<tr>
<td>1028565833.190</td>
<td>12.713</td>
<td>1.000</td>
<td>35235</td>
<td>6219</td>
<td>1</td>
<td>Start Ascent, throttle up cmd from GNC (est from 10Hz data &amp; TT19)</td>
</tr>
<tr>
<td>1028565834.190</td>
<td>13.713</td>
<td>1.000</td>
<td>35935</td>
<td>16844</td>
<td>1</td>
<td>Estimated last fresh SIGI data received from 1553 Bus (700 ms later than last full second)</td>
</tr>
<tr>
<td>1028565834.297</td>
<td>14.713</td>
<td>0.700</td>
<td>35935</td>
<td>16844</td>
<td>1</td>
<td>Estimated First Stale SIGI Data, and subsequent (cfs time) +/-40 ms</td>
</tr>
<tr>
<td>1028565835.190</td>
<td>15.713</td>
<td>0</td>
<td>35935</td>
<td>16844</td>
<td>1</td>
<td>70% of this 1 Hz frame is fresh data (confirmed with SIGI time &amp; eo24Bus Time)</td>
</tr>
<tr>
<td>1028565836.190</td>
<td>16.713</td>
<td>0</td>
<td>35935</td>
<td>16844</td>
<td>1</td>
<td>Stale data</td>
</tr>
<tr>
<td>1028565837.190</td>
<td>17.713</td>
<td>0</td>
<td>35935</td>
<td>16844</td>
<td>1</td>
<td>Stale data</td>
</tr>
<tr>
<td>1028565838.190</td>
<td>17.820</td>
<td>0</td>
<td>35935</td>
<td>16844</td>
<td>1</td>
<td>Last Data Transmission from Vehicle</td>
</tr>
<tr>
<td>1028565838.297</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>

**Notes:**

1. Last SIGI data indicated no internal failures (sigiModeWord = 0) and good GPS antenna lock (pvtOKMasterAntID_ID = 1)
2. SIGI I/O SW on CPU flags & sends stale SIGI data to GNC if no new data is received from 1553 Bus
3. Although STALE flag from SIGI was not downlinked, it can be deduced from stale eo24busTime. SIGI did not send stale data, but in fact no more SIGI data was received on the 1553 Bus.
4. GNC/AFM time is 10ms greater than the IMU_Pre timestamp, from data analysis
Why Did Hardware Fail?

• Probable or possible causes:

  1. **Vibro-acoustic environment near ground** repeatedly exceeding component qual limits and eventually causing fatigue failure during FF2

  2. Non-flight components not sufficiently robust to environment (1)
     • Lab grade 1553 bus components
     • Development unit CRV SIGI (s/n 1580) believed to be “flight-like” due to same internal part numbers as ISS flight units built 2 months later, one of which was used for HTV3

  3. Workmanship Quality Assurance provided insufficient robustness for environment (1)

  4. Production imperfections in primary components reduced robustness to environment (1)

• Programmatic contributors:

  5. Accepted single-string IMU risk
     • Simulated but did not test FSW down-mode to backup IMU in response to primary IMU failure
     • Discovered backup IMU malfunction and no-opted it shortly before FF2
     • One of a few single-string critical systems (e.g., engine gimbal and throttle valve EMAs)

  6. Accepted risk of brief (first few seconds after ignition on ground) exceedance of ISS SIGI qual limits (based on 3 minute vibe tests) due to HF6 (ground environment enveloping case) and FF1 test experience

  7. Accepted risk of lower grade components (e.g., 1553 bus) due to availability and zero cost

  8. High operational tempo (partially due to self-imposed FY12 ALHAT HDP milestone schedule pressure), risk acceptance & budget limited QA activity and verification testing
Fault Tree, Top

1 = Likely
2 = Possible
3 = Unlikely

FF2 EVENT: Failure to update inertial navigation state data input to flight computer leads to unstable flight during ascent (G036)

INS data path (SIGI/1553/APU) failure during ascent (G026, 1.1.1-1.1.1-1.1.1)

SIGI failure (G037)
1553 bus failure between SIGI & APU (G042)
APU failure to process data from SIGI (G029)

(Fault tree item closure rationales in Backup section)
Nav Data Path Components

- Inertial Sensor Assembly (Gyros, Accels)
- Power Converter
- GPS (used for time, not nav)
- Inertial Electronics
- Power Supply
- System Processing Card
- SIGI 1553 chip
- Internal cabling
- SIGI 1553 bus connector
- 1553 bus cable

APU (vibe-isolated)

1553 bus

Key:
- Good Continuity
- No Continuity
- Not Tested

Loss of SIGI data resulted in SIGI I/O App reporting “stale” SIGI data to IMU Pre.

Loss of SIGI data would be caused by failure of any box upstream/left of this red dashed line.

Verified pin/sockets were in place with good crimps. Lack of continuity may be due to melted connector.

Loss of backplane probably would impact other channels, but only SIGI channel data was lost.
APU Inspection and Continuity Testing

- Card to cPCI connection has good continuity.
- Backplane looks good.
- Wires are firmly in connectors but no continuity through melted connectors.
- Crimps and wires have good continuity and pass pull test.
- DIO/1553 Card
- DIO/1553 TM Connector
- 1553 Front Panel Connector (55 pin)
- 1553 Front Panel Pins (55 pin connector)
Fault Tree, APU

1 = Likely
2 = Possible
3 = Unlikely
4 = Highly unlikely

APU failure to process data from SIGI (G029)

- APU transition module failure (G048, G)
- APU cPCI back-plane failure (G054, I)
- APU 1553 card failure (G052, H)
- APU cabling, harness or connector failure (G055, E & F)

- APU CPU failure or SIGI I/O SW App falsely reported stale data (G053)
- APU power failure (G111)
- APU data drop due to EMI (G112)
1553 Bus Functional Schematic

- 1553 Bus Terminator
- 1553 Bus Coupler
- 1553 Bus Connector
- 1553 Bus Cable
- SIGI 1553 Connector
- SIGI
- APU 1553 Connector
- APU2

- On GNC Plate:
  - Primary Structure: Hard-Mounted, Not Vibration Isolated
  - On APU plate: Vibration Isolated
1553 Bus Failure Possibilities

- **1553 bus couplers**
  - GNC plate coupler hard-mounted to plate, deck & primary structure, not isolated from vibration; coupler on APU vibe-isolated.
  - In 2009, L-M Mission Success Bulletin #09-17 cited a few lots of couplers (from a different manufacturer) for having cracked solder joints on terminal lugs due to vibration & thermal environments, affecting Atlas and Orion PA1

- **1553 bus connectors**
  - Spring-pressure over-center BNC connectors
  - Can be connected without locking if there is sufficient friction in connection; unlikely given no connector issues in previous tests, not demated since Feb
  - High vibration environment could cause connectors to back off, even if locked

- **1553 bus terminators**
  - Same unlikely connection issue as connectors, not demated since Feb
  - Long, cantilevered terminators are susceptible to high vibration environment

Lab grade 1553 bus harnesses may have been susceptible to high vibration. VTB 1.5B will have higher quality 1553 bus harnesses and more vibe isolation.
Fault Tree, 1553 Bus

1 = Likely
2 = Possible
3 = Unlikely
4 = Highly unlikely

1553 bus failure between SIGI & APU (G042)

- 1553 cable or connector failure (G056)
  - 2

- 1553 timing latency (G031)
  - 4

- 1553 bus coupler failure (G113, D)
  - 2

- 1553 bus terminator failure (G114)
  - 2

- Improper 1553 bus termination (G115)
  - 4

- 1553 data drop due to EMI (G047)
  - 3
SIGI Components

- Inertial Electronics
- Inertial Sensor Assembly (Mounted Under Inertial Electronics)
- Trimble GPS Receiver Module
- ISS SIGI Including Adapter Plate
- System Processor
- ACOCS - 120 VDC Power Conversion
- DC Power Supply
Fault Tree, SIGI

1 = Likely
2 = Possible
3 = Unlikely
4 = Highly unlikely
Accumulated Vibration Time

**Morpheus 1.0 (2011): 290 sec HD3 Engine Burn Time**

<table>
<thead>
<tr>
<th>VTB</th>
<th>Engine Burn Time (sec)</th>
<th>Time in High Vibe Ground Effect (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>290</td>
<td>-</td>
</tr>
<tr>
<td>1.5</td>
<td>850</td>
<td>14</td>
</tr>
<tr>
<td>Total</td>
<td>1140</td>
<td>14 (1%)</td>
</tr>
</tbody>
</table>

**Morpheus 1.5 (2012): 850 sec HD4 Engine Burn Time**

<table>
<thead>
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<th>VTB</th>
<th>Engine Burn Time (sec)</th>
<th>Time in High Vibe Ground Effect (sec)</th>
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</thead>
<tbody>
<tr>
<td>1.0</td>
<td>290</td>
<td>-</td>
</tr>
<tr>
<td>1.5</td>
<td>850</td>
<td>14</td>
</tr>
<tr>
<td>Total</td>
<td>1140</td>
<td>14 (1%)</td>
</tr>
</tbody>
</table>
Vibration Flight Experience

Tether Test ignitions “at altitude” produce far less vibration than HF6 & FF ground ignitions.

FF2: VTB escaped vibro-acoustic ground effect ~4 sec after ignition, ~1 sec after liftoff.

Flight Test Color Key
- HF6 at JSC, chained to ground
- FF1 at KSC, soft abort at 0.3m altitude
- FF2 at KSC, reached 5m altitude
- TT20 at KSC, “launch” at 6m altitude
- TT19 at JSC, “launch” at 6m altitude
HF6, FF1 & FF2 vibration briefly exceeded ISS SIGI qual limits at high frequencies. Vibe-isolated PA1 SIGI has much higher qual limits, above Morpheus test experience.
Vibe Isolation Effectiveness in HF6

Top Deck accel was hard-mounted. APU accel was vibe-isolated.

Vibe isolation reduced peak g’s by an order of magnitude.
Vibe Isolation Effectiveness in HF6

**Diagam Title:** Morpheus HF6

**Graph Title:** High Frequency Accelerometer PSD

**Graph Details:**
- +X (up) PSD in g²/Hz
- 10 Hz to 10,000 Hz frequency range
- LN-200 limit, SIG-ISS Qual limit, SIGI-CRV Op limit
- APU vibe-isolated
- Top Deck accelerometer hard-mounted

**Table:**
- LN-200 limit: 15 gms
- SIG-ISS Qual limit: 8.6 gms
- SIGI-CRV Op limit: 1.0 gms

**Legend:**
- 4x M1.5 HFB Top Deck 14.3 gms
- 4x M1.5 HFB APU 2.72 gms
- APU vibe-isolated
- Top Deck accelerometer hard-mounted
# Probable or Possible Cause or Contributor | Corrective Action
---|---
1 Vibro-acoustic environment near ground repeatedly exceeding component limits and eventually causing fatigue failure during FF2 | **Reduce vibro-acoustic environment**
   a. **Vibe isolation** for key components (e.g., SIGI, backup IMU(s) & 1553 bus)
      • IMU risk: misalignment due to plastic deformation of vibe isolator
      • IMU challenge: attenuate high frequency vibe but not lower FCS frequencies
   b. **Relocate IMUs** away from center of top deck toward primary structure
   c. **Flame trench** for ground ignitions at JSC and KSC (assuming feasibility)
      • May increase effective launch altitude by roughly a body length, reducing launch vibration by up to an order of magnitude
      • Landing vibration becomes stress case, but is roughly half magnitude of current launch vibration due to half throttle, and occurs while descending near touchdown
   d. **Leverage NASA vibro-acoustic expertise** to supplement team experience
## Corrective Actions 2-5

<table>
<thead>
<tr>
<th>#</th>
<th>Probable or Possible Cause or Contributor</th>
<th>Corrective Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td><strong>Non-flight components</strong> not sufficiently robust to environment (1)</td>
<td><strong>Increase component robustness</strong></td>
</tr>
<tr>
<td></td>
<td>a. Use PA1 SIGI flight unit</td>
<td>- Designed for high vibration PA1 environment</td>
</tr>
<tr>
<td></td>
<td>b. <strong>Procure higher quality 1553 bus</strong> components with greater robustness to high vibe environments</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c. <strong>Use both channels of 1553 bus</strong></td>
<td>- Only channel A was used for VTB 1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 1553 bus will automatically switch between channels A &amp; B as necessary, and can report channel usage to CPU</td>
</tr>
<tr>
<td>3</td>
<td><strong>Workmanship</strong> QA provided insufficient robustness for environment (1)</td>
<td><strong>Improve workmanship quality assurance/control</strong></td>
</tr>
<tr>
<td></td>
<td>a. <strong>Crew Chief</strong> provides tighter control over vehicle access and components</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b. <strong>Wiring/Cabling Subsystem Lead</strong> implements best practices (e.g., strain relief) and focuses upon quality improvements &amp; assurance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c. <strong>Certified wiring technicians</strong> for build, installation and inspections</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td><strong>Production imperfections</strong> in primary components reduced robustness to environment (1)</td>
<td><strong>Improve system quality and verification</strong></td>
</tr>
<tr>
<td></td>
<td>a. <strong>Higher quality components</strong> (e.g., connectors, cables)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b. More verification testing (e.g., SIGI vibe testing, tethered liftoff test)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td><strong>Accepted single-string IMU risk</strong></td>
<td>Dissimilar, non-colocated backup IMU(s)</td>
</tr>
<tr>
<td></td>
<td>a. Test backup IMU down-mode and soft abort logic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b. <strong>LCC requirement</strong> for operational backup IMU(s)</td>
<td></td>
</tr>
</tbody>
</table>
Corrective Actions 6-8

<table>
<thead>
<tr>
<th>#</th>
<th>Probable or Possible Cause or Contributor</th>
<th>Corrective Action</th>
</tr>
</thead>
</table>
| 6  | Accepted risk of brief exceedance of ISS SIGI qual limits due to HF6 and FF1 test experience            | (1) Reduce vibro-acoustic environment for IMUs with flame trench, vibe isolation and relocation  
(2a) Use PA1 SIGI flight unit                                                   |
| 7  | Accepted risk of lower grade components due to availability and zero cost                                | (2a&b) Use PA1 SIGI & procure higher quality 1553 bus components                  |
|    |                                                                                                          | (3) Improve workmanship QA                                                          |
|    |                                                                                                          | (4) Improve system quality and verification                                         |
| 8  | High operational tempo, risk acceptance & budget limited QA activity and verification testing            | **Incrementally increase project rigor** in QA, verification testing and risk analysis/mitigation/acceptance, accommodated by more schedule margin, while still practicing lean development (not flight program rigor) |

Project Morpheus is applying these CA to two new vehicles in fabrication in 2012 and to flight testing scheduled to resume at JSC and KSC in 2013.

“It is not the critic who counts; not the man who points out how the strong man stumbles, or where the doer of deeds could have done them better. The credit belongs to the man who is actually in the arena, whose face is marred by dust and sweat and blood; who strives valiantly; who errs, who comes short again and again, because there is no effort without error and shortcoming; but who does actually strive to do the deeds; who knows great enthusiasms, the great devotions; who spends himself in a worthy cause; who at the best knows in the end the triumph of high achievement, and who at the worst, if he fails, at least fails while daring greatly, so that his place shall never be with those cold and timid souls who neither know victory nor defeat.”

— *Theodore Roosevelt*
FY13 Plan

**FY 2012**

<table>
<thead>
<tr>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
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</tbody>
</table>

- ALHAT Helicopter Testing: 12/14
- Morpheus 1.5B Build: Integ T&V 1/31
- JSC Flight Tests: SHIP TO KSC
  - KSC Campaign 0
  - KSC Campaign 1
  - KSC Campaign 2
  - KSC C3: 7/30
- Contributions to RESOLVE plan: 6/30
- Morpheus 1.5C Build: Integ T&V
- First hot fire for 1.5C: 6/30

**Flights Include ALHAT**

**HQ Tracked Milestone**
1. Project Scale of Rigor
2. Stale SIGI Data Summary
3. DFI Sensor Locations
4. KSC Flight Risk Matrix
5. Morpheus System & VTB Overview
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.
Stale SIGI Data

Observed Failure: Stale SIGI Data

SIGI Fail
SIGI 1553 Fail
1553 Cable Fail
APU 1553 Fail
APU Back Plane Fail
FSW Fail

Possible, but unable to distinguish: Data reconstruction with telemetry or high-speed vehicle data would not provide insight to distinguish between these failure cases. Each of these cases results in same “stale flag” and data signature.

Unlikely: If true, would likely show signature of other devices failing, which was not seen.

Unlikely: Behavior was as expected when no data received from SIGI over 1553 bus.

SIGI
1553

Software
CPU
APU
1553
cPCI

Stale SIGI Data
DFI Sensor Locations, Top

- Top Deck Triaxial Accel (Dytran 3039C)
- DFI Box (EDAQ-Lite, 20 HF analog channels)
- APU Box Triaxial Accel (Dytran 3039C)
- FT3 (-Y)
- FT4 (+Y)
- FT1 (-Z)
- QT2 (+Z)

Leg# 1 Qty 3 Uniaxial Accels (Endevco 2221F) on triax mounting block
Leg# 4 Qty 3 Uniaxial Accels (Endevco 2221F) on triax mounting block
DFI Sensor Locations, Side

Top Deck Triaxial Accel (Dytran 3039C)

JSC designed/built Charge Amplifier Box

DFI Box (EDAQ-Lite; 20 HF analog channels)

APU Box Triax Accel (Dytran 3039C) Far Side

Engine Combustion Chamber Pressure Transducer (Kulite .CT-1MA437-500A)

LOX Line Pressure Transducer (Kulite .CT-1MA437-500A)

Leg# 3 Qty 3 Uniaxial Accels (Endevco 2221F) on triax mounting block

Engine Chamber Flange Triax Accel (Dytran 3039C)

Leg# 2 Qty 3 Uniaxial Accels (Endevco 2221F) on triax mounting block

+X

+Y

+Z
## KSC Flight Test Risks

<table>
<thead>
<tr>
<th>#</th>
<th>Risk</th>
<th>L</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>PERFORMANC E</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>PROP-002</td>
<td>Methane RCS engines cannot provide needed performance</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>ALHAT-001</td>
<td>ALHAT does not achieve precision landing performance</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>PROP-001</td>
<td>Uncertain main engine performance margin</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>SEI-002</td>
<td>Aero induced torques exceed vehicle control authority</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>SEI-003</td>
<td>HDP objectives not achievable due to insufficient vehicle performance</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>SEI-004</td>
<td>Morpheus unable to meet HDS nav error budget</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>SEI-001</td>
<td>Lift off ground effect damages vehicle hardware (repeated shock, vibe, heat)</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>PROP-005</td>
<td>Tank imbalance during flight causes c.g. shift leading to control issues</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>PROP-003</td>
<td>High usage of helium RCS degrades engine performance due to depressurization</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>GNC-004</td>
<td>Morpheus does not achieve precision landing performance</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>GNC-001</td>
<td>Free flight lateral instabilities</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>GNC-002</td>
<td>Free flight vertical instabilities</td>
<td>2</td>
<td>2</td>
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<tr>
<td>RELIABILITY</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>PROP-008</td>
<td>Main engine burn-through</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>PROP-007</td>
<td>EMA or throttle valve failure during flight</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>PROP-010</td>
<td>Insufficient propellant remaining to complete flight</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>PROP-009</td>
<td>Methane RCS reliability</td>
<td>3</td>
<td>3</td>
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<tr>
<td>STRCT-001</td>
<td>Landing gear buckling during landing</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>SEI-004</td>
<td>Lack of critical spares delays flight test schedule</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>AV-001</td>
<td>CPU reset during flight</td>
<td>1</td>
<td>5</td>
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<tr>
<td>INSTR-001</td>
<td>Loss of critical instrumentation during flight</td>
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<td>5</td>
</tr>
<tr>
<td>PWR-001</td>
<td>Loss of power during flight</td>
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<td>5</td>
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<tr>
<td>OTHER</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEI-005</td>
<td>Weather</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

### Likelihood

- **Highly Likely**
- **Likely**
- **Possible**
- **Unlikely**
- **Highly Unlikely**

### Consequences

- **Minor impact**
- **Flight test needs to be repeated or delay to flight schedule**
- **Significant delay but recoverable**
- **Unable to complete test campaign (loss of mission) – major damage or unable to meet perf. req.**
- **Loss of vehicle**
Like any planetary launch and landing vehicle, Morpheus includes a vehicle, subsystems, operations, and ground systems.
Morpheus 1.5 Vertical Testbed (VTB)

<table>
<thead>
<tr>
<th>Weight</th>
<th>Dry: 2245 lb 70-sec flight: 1700 lb prop 90-sec flight: 2000 lb prop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>~9’ high, ~10’ wide</td>
</tr>
<tr>
<td>Engine</td>
<td>Film-cooled, LOX/methane 5:1 throttling engine 4400 lbf (HD4) 5000 lbf (HD5)</td>
</tr>
<tr>
<td>Navigation</td>
<td>SIGI, LN-200 IMU, Javad GPS, Acuity laser altimeter</td>
</tr>
<tr>
<td>CPU</td>
<td>AI Tech S900 CompactPCI with a PowerPC 750 Processor</td>
</tr>
<tr>
<td>Software</td>
<td>Flight software uses GSFC’s Core Flight Software; C code: total SLOCs 238K (166K SLOCs are CFS)</td>
</tr>
<tr>
<td>ALHAT</td>
<td>Flash lidar (including gimbal, dedicated IMU, compute electronics, and dedicated power), doppler velocimeter, laser altimeter</td>
</tr>
</tbody>
</table>

GN&C Components
ALHAT Computing and Power Components
Avionics and Power Unit (APU)
Cold Gas RCS Jets (x4)
Methane RCS Engines (x4)
LOX tanks (x2)
LOX/Methane Engine “HD4”
Methane Tanks (x2)