Morpheus Free Flight 2
Test Failure Investigation

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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
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- Independent Assessment Team: **Mark Hammerschmidt** and **Greg Blackburn**
- **Greg Gaddis**, KSC Site Manager & Morpheus TAM
- **AES, JSC & KSC** for strong support of Morpheus

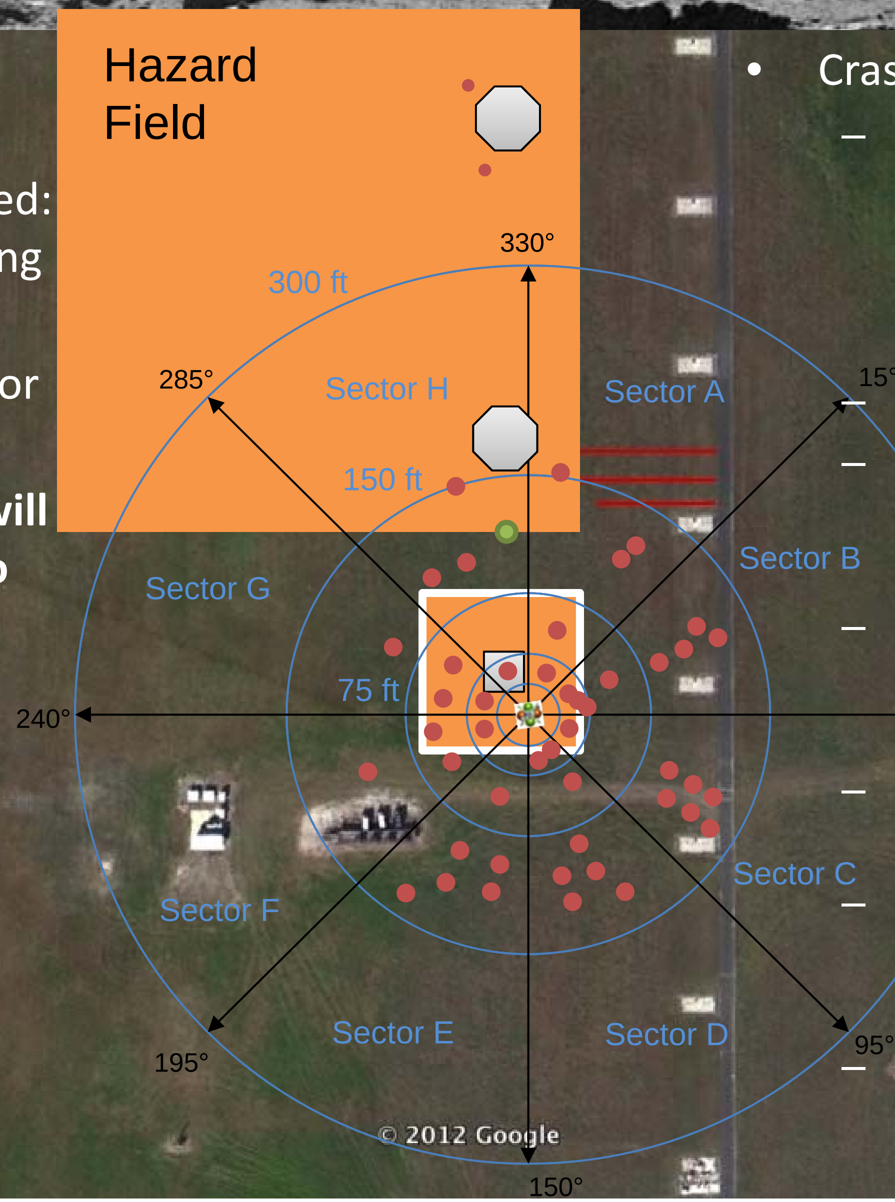
FF2 Summary

- 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**

Ring	Radius (ft)
1	10
2	25
3	50
4	75
5	150
6	300

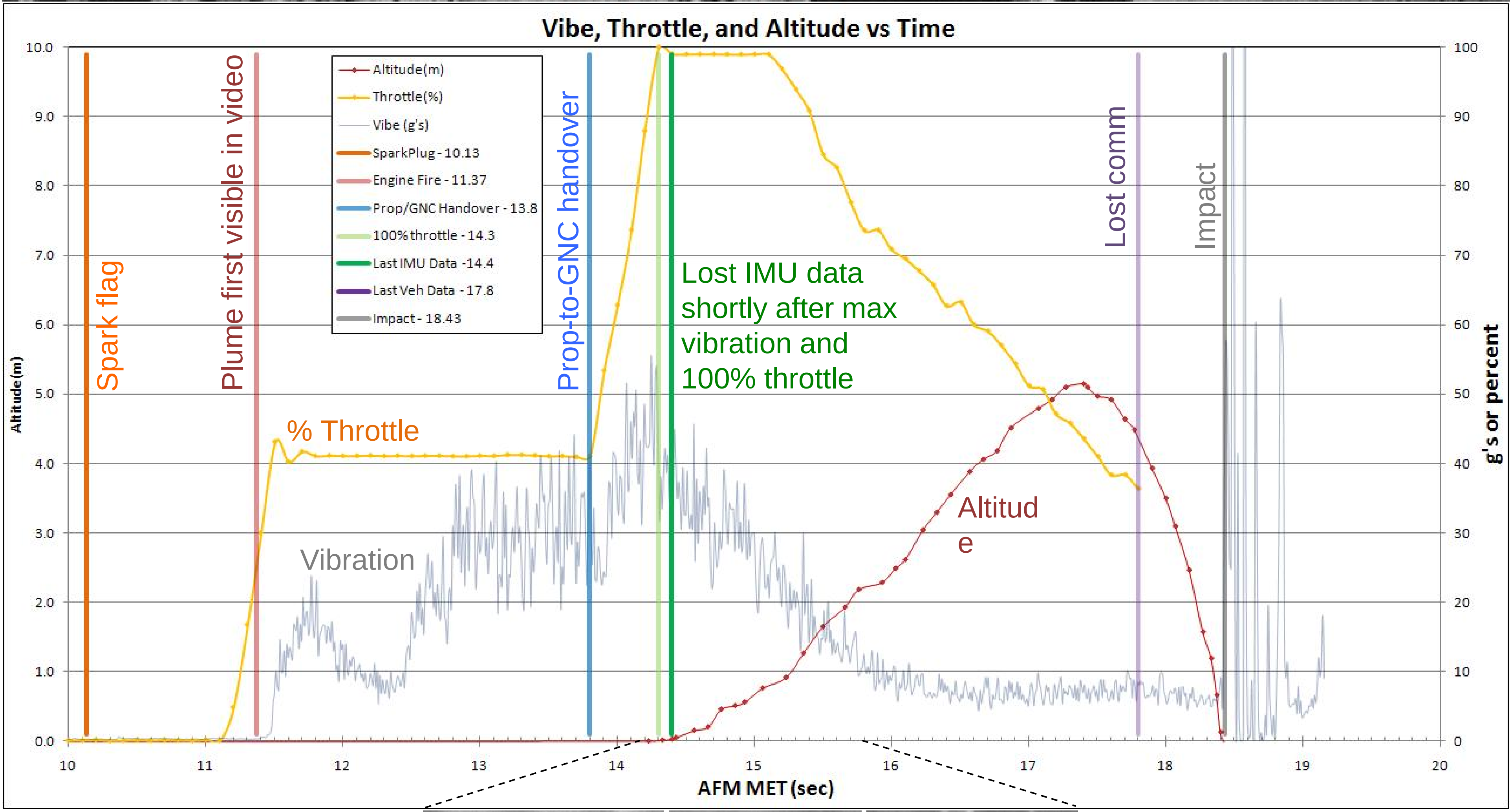


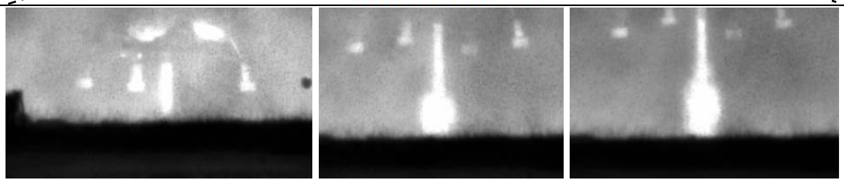
- Crash site observations
  - Nearly all debris < 50m, << **1000ft clear distance** for Pad Crew (Max estimates: JSC = 325ft, KSC = 653ft, WSTF = 1000ft)
  - Methane tanks burned
  - LOX tanks exploded (BLEVE), +Z tank separated at lower boss & rolled 37m
  - Engine plume dug a small crater; chamber 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**

FF2 Main Event Timeline

EDT	MET	Event	Status
06:15		Pre-test safety briefing & Emergency Action Plan review at SLF hangar	
06:30		VTB rollout and launch preparation	
12:43	0:00.0	MMCC Operator commands Execute Ignition Sequence (10 sec auto chill-in + 3.8 sec engine ignition seq)	
	0:10.0	Engine ignition sequence begins with igniter spark; 1st plume visible on video at 11.4 sec	
	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	

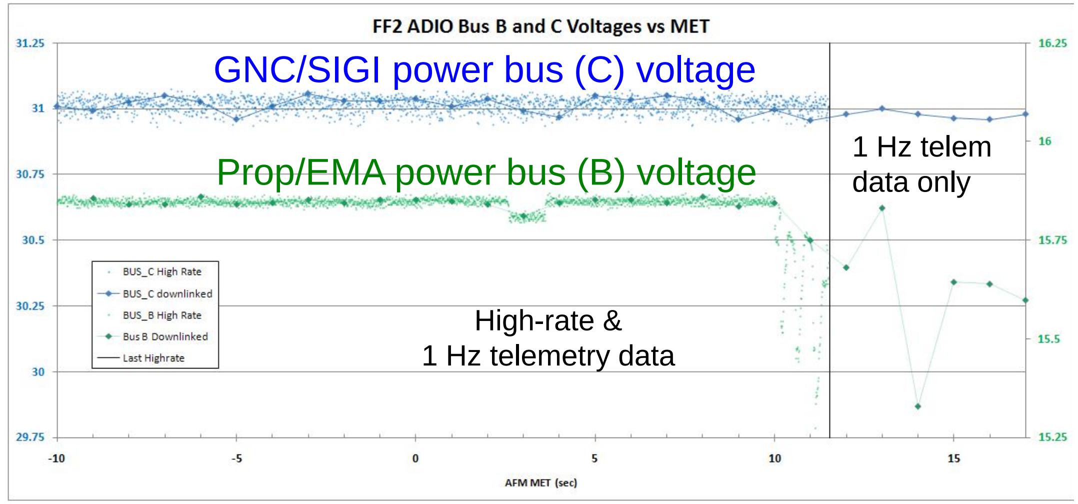
Vibration, Throttle & Altitude

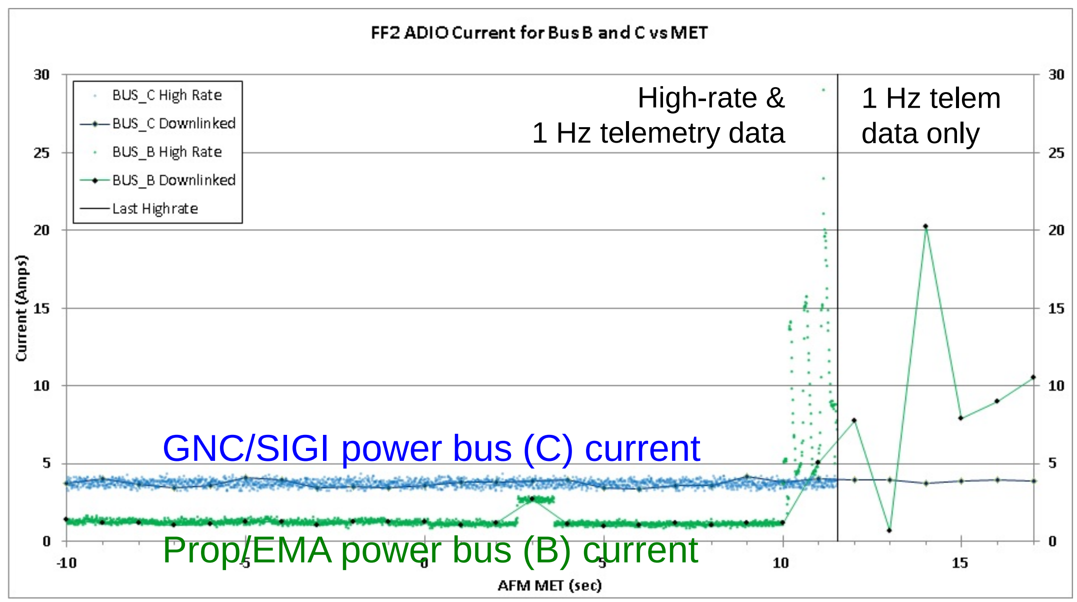




What Didn't Fail?

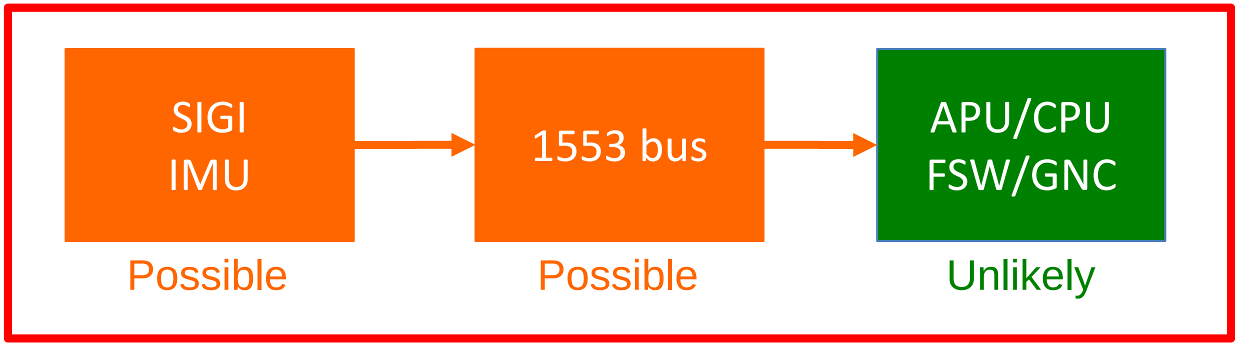
- Power: bus voltage & current data (right) show no power loss
- Propulsion
  - Engine performance, tank temp and pressure data were nominal
  - EMA position feedback data showed nominal tracking of GNC commands
- Structure: video and forensics show no evidence of structural failure before impact
- Software
  - 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!*





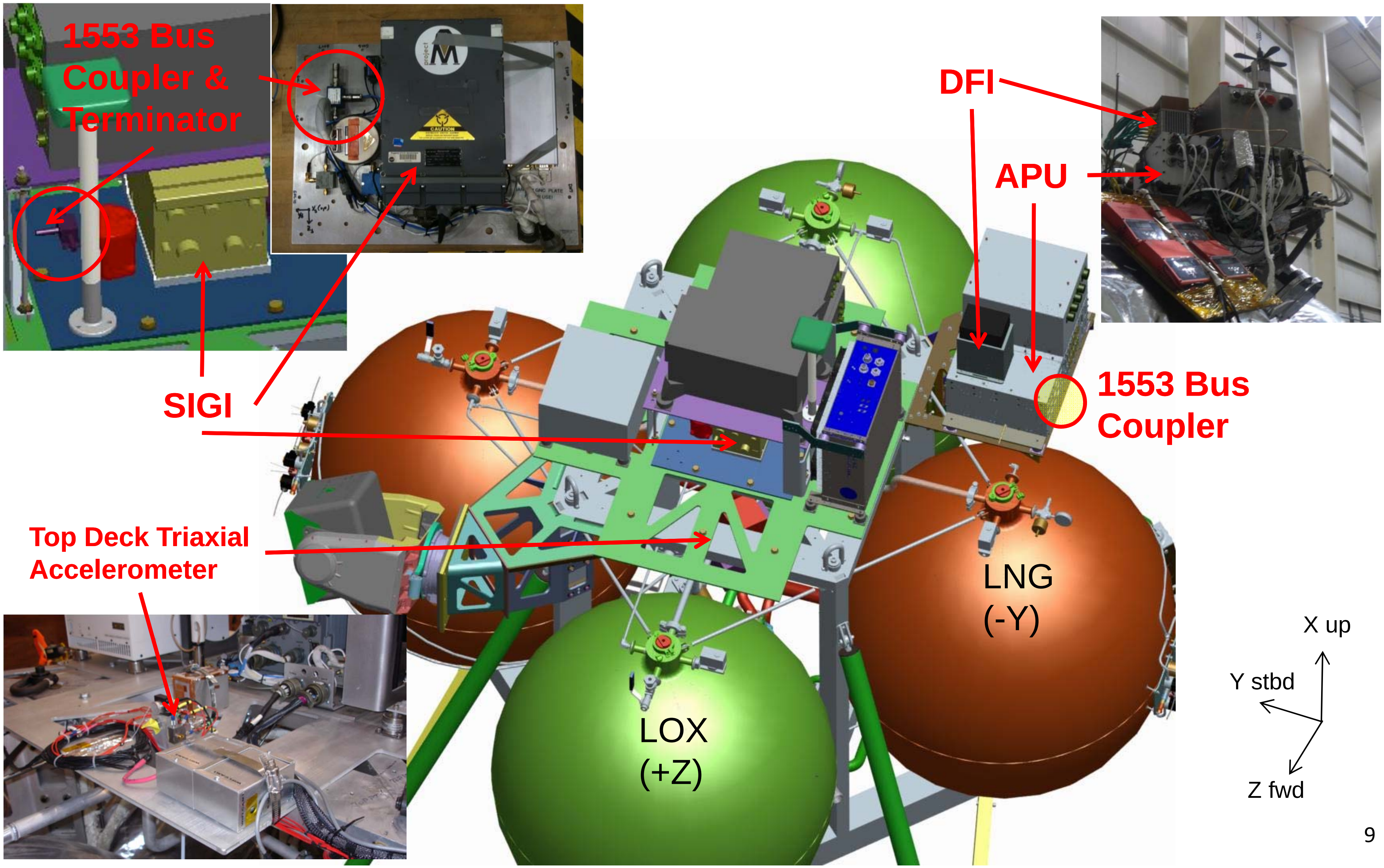
What Failed?

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



SIGI Data Timeline

SIGI_cfs_time_tag (corresponds to Nav time)	Calc. AFM MET (sec)	SIGI_provided_timetag (eo-24)	Δ timetag from last 1 sec sample	**sigiMode Word (health)**	gpsTimeOfWeekLSW	eo24Bus Time	pvtOKMasterAntID_ID (GPS ant)	Event/Comments
1028565820.477	0.000							GNC/AFM Receives Command "Execute Ignition Sequence", AFM MET = 0
1028565821.190	0.713	1028565821.15		**0**	22236	65238	1	Auto chill-in (10 sec) continues toward Engine Ignition Sequence
1028565822.190	1.713	1028565822.15	1.000	**0**	23236	15327	1	Nominal operations, no failure flags, data changing…
1028565823.190	2.713	1028565823.15	1.000	**0**	24236	30952	1	
	10.000							Start Engine Ignition Sequence (3.8 sec)
1028565833.190	12.713	1028565833.15	1.000	**0**	34235	56130	1	
1028565834.190	13.713	1028565834.15	1.000	**0**	35235	6219	1	
1028565834.275	13.798							Start Ascent, throttle up cmd from GNC (est from 10Hz data & TT19)
1028565834.800	14.323							Throttle at 100% (50.06mm), 10Hz telem downlink +/- 100 ms
1028565834.890	14.413							Estimated last fresh SIGI data received from 1553 Bus (700 ms later than last full second)
1028565834.910	14.433							Estimated First Stale SIGI Data, and subsequent (cfs time) +/-40 ms
1028565835.190	14.713	**1028565834.85**	0.700	**0**	35935	16844	1	70% of this 1 Hz frame is fresh data (confirmed with SIGI time & eo24Bus Time)
1028565836.190	15.713	**1028565834.85**	0.000	0	35935	16844	1	Stale data
1028565837.190	16.713	**1028565834.85**	0.000	0	35935	16844	1	Stale data
1028565838.190	17.713	**1028565834.85**	0.000	0	35935	16844	1	Stale data, Last 1 Hz SIGI Data point received from vehicle
1028565838.297	17.820							Last Data Transmission from Vehicle

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

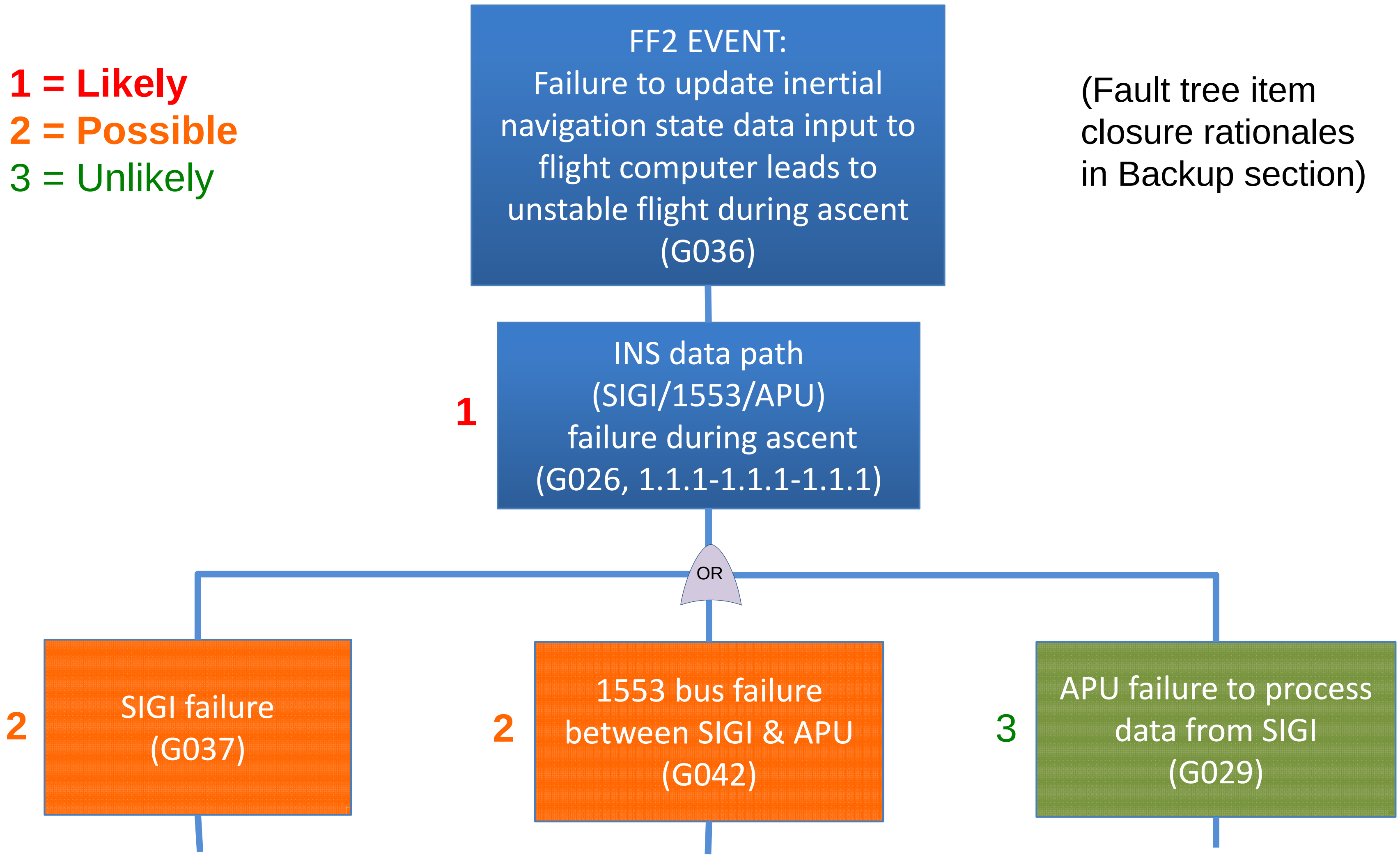
Why Did Hardware Fail?

- 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

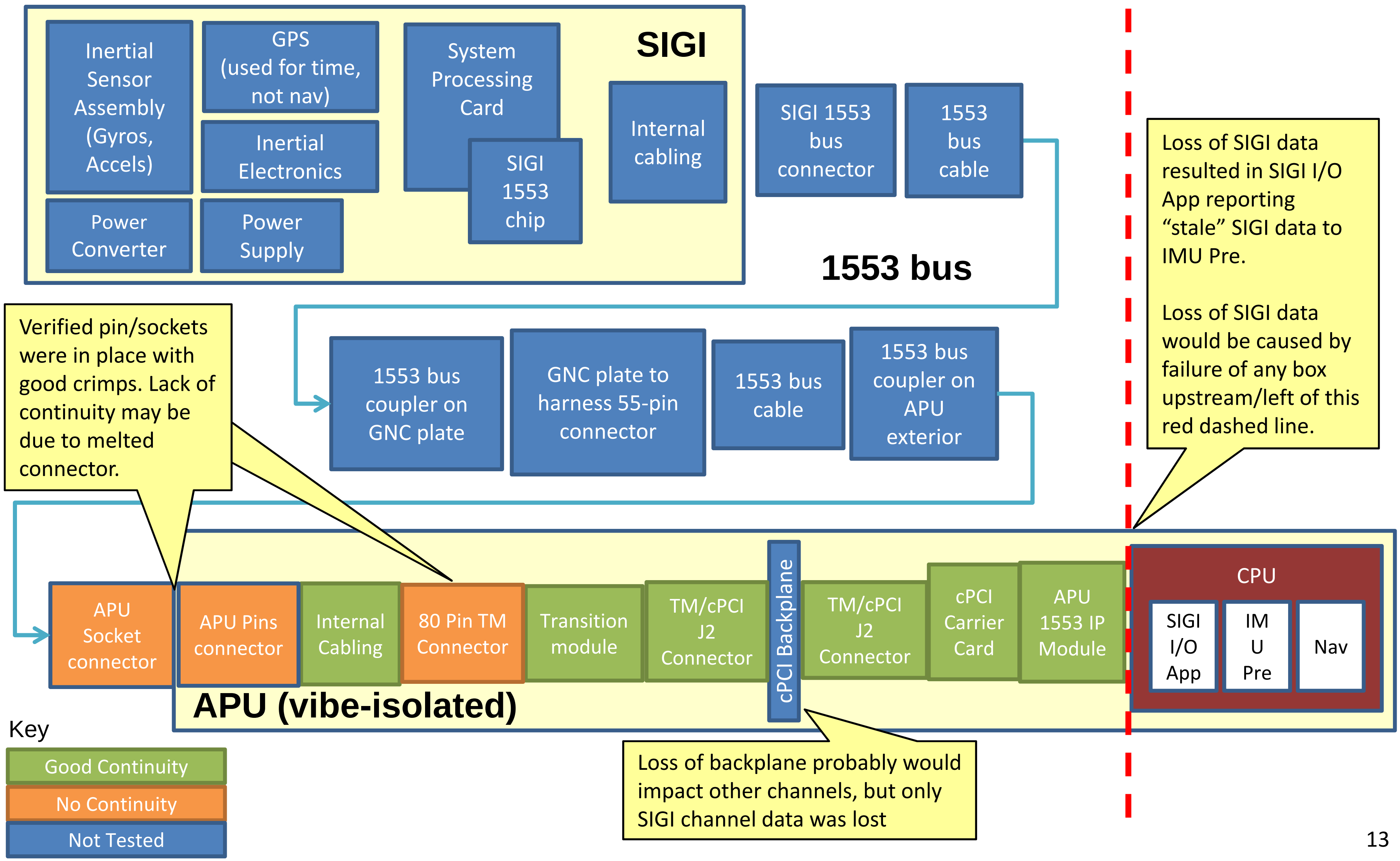
Fault Tree, Top

1 = Likely
2 = Possible
3 = Unlikely

(Fault tree item closure rationales in Backup section)

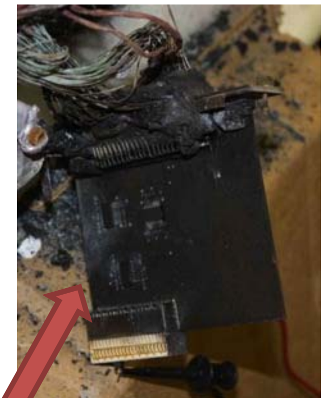


Nav Data Path Components



APU Inspection and Continuity Testing

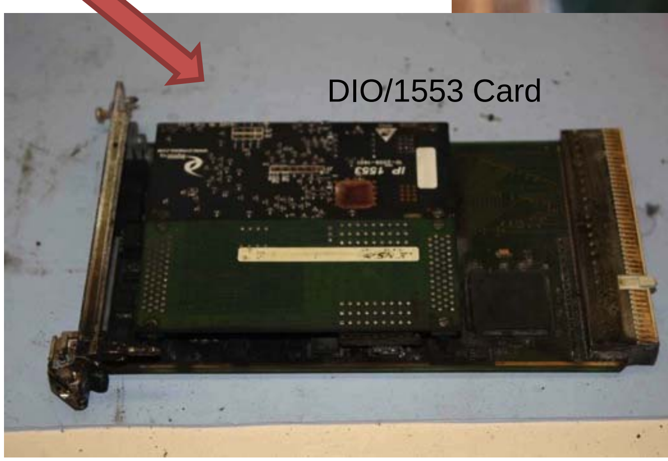
DIO/1553 TM



Card to cPCI connection has good continuity

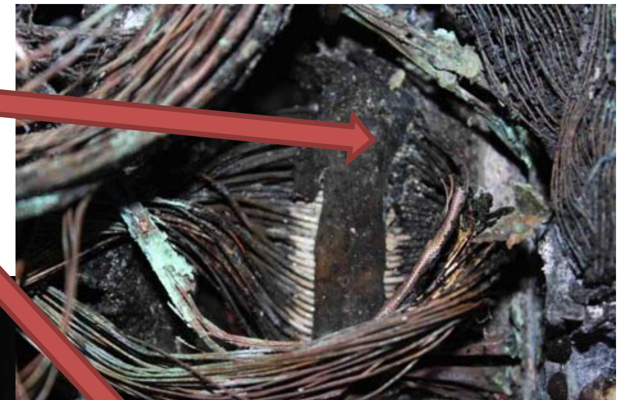
Backplane looks good

DIO/1553 Card

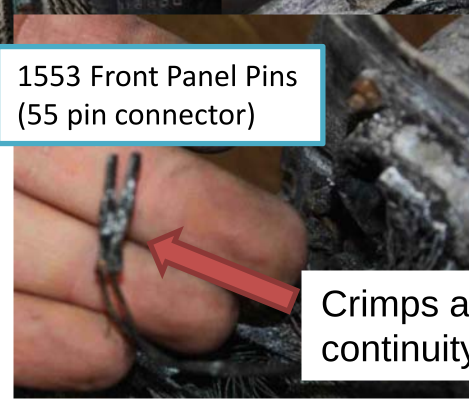


Wires are firmly in connectors but no continuity through melted connectors

DIO/1553 TM Connector



1553 Front Panel Connector (55 pin)

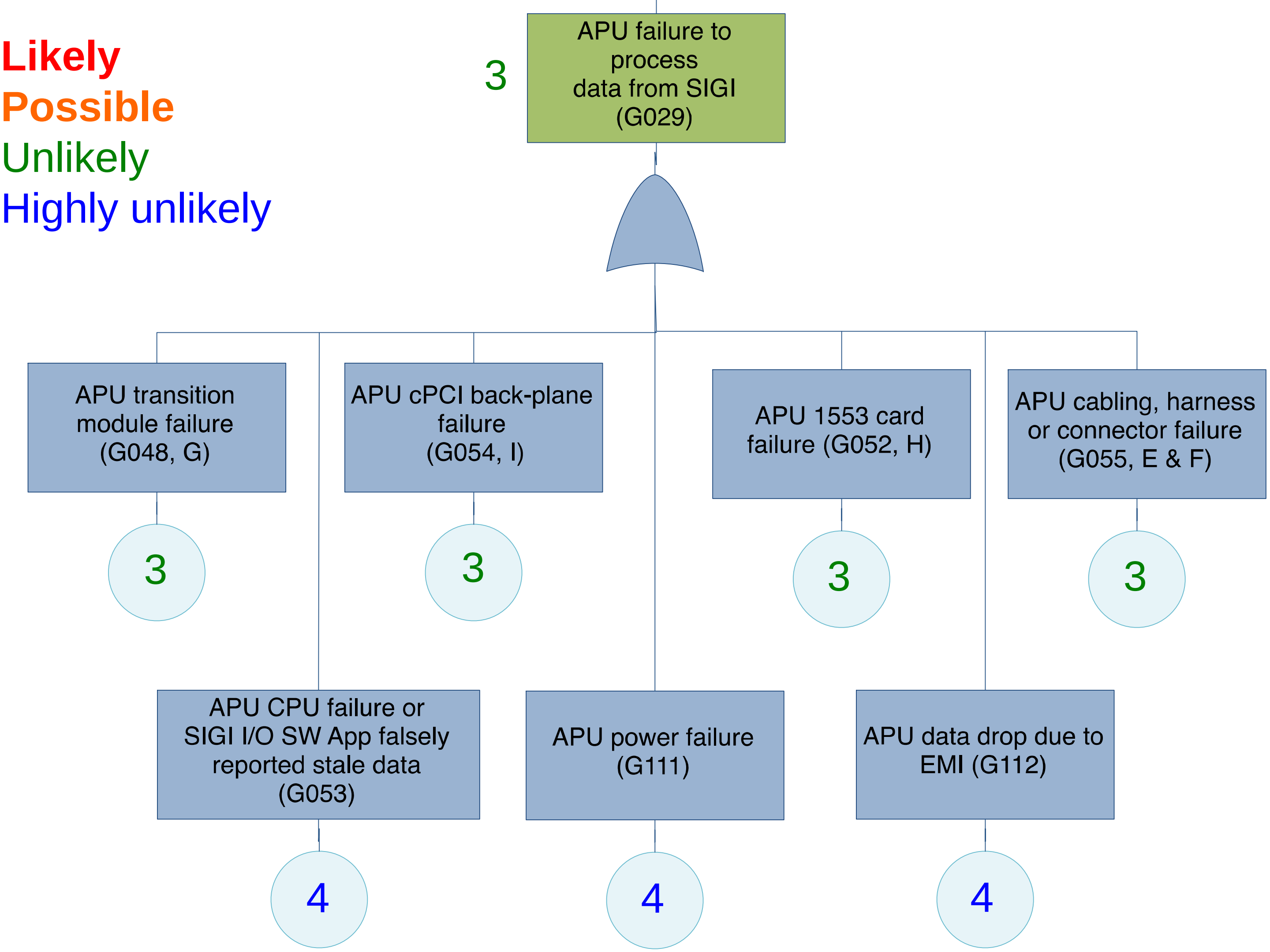


1553 Front Panel Pins (55 pin connector)

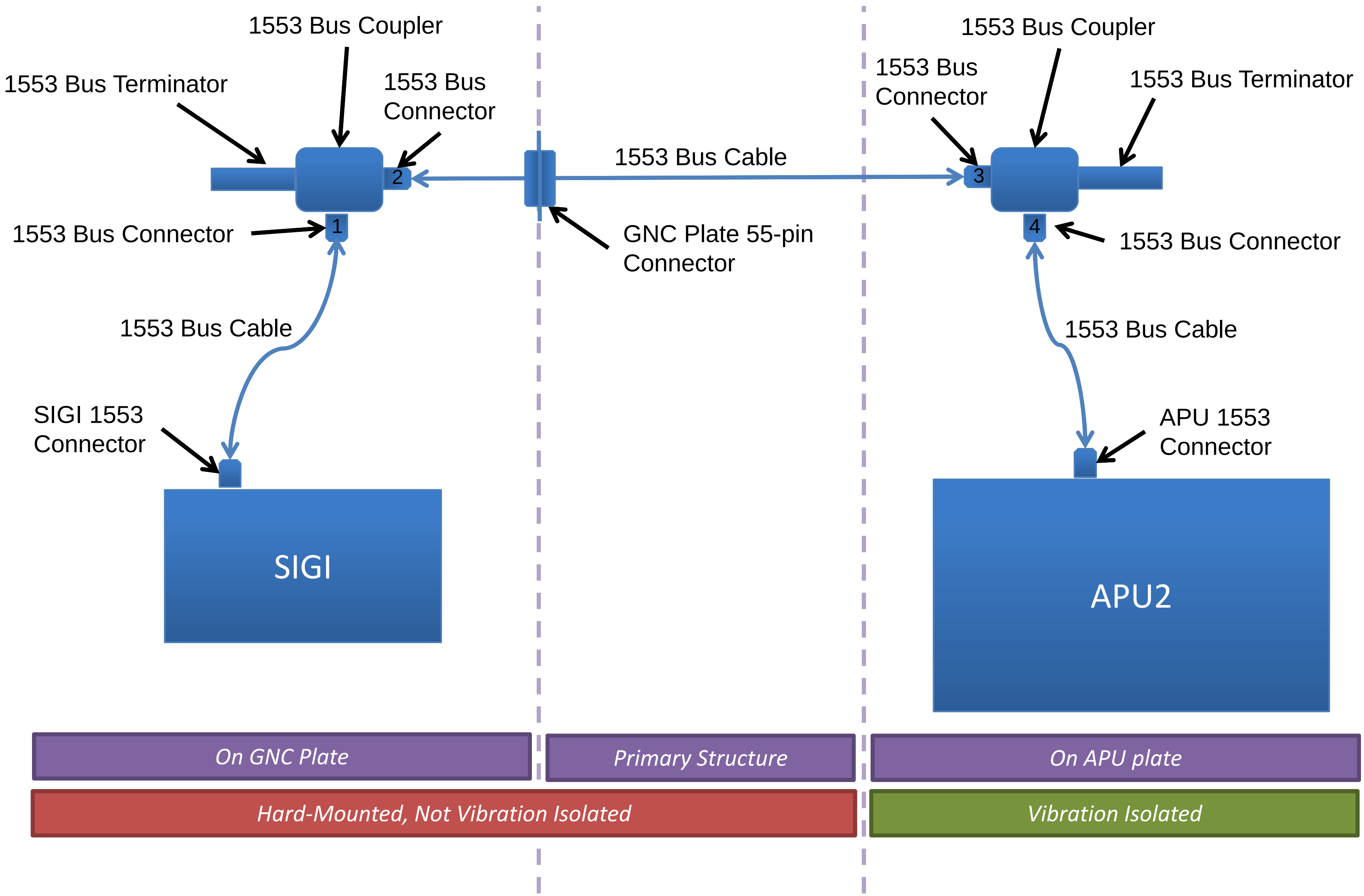
Crimps and wires have good continuity and pass pull test

Fault Tree, APU

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



1553 Bus Functional Schematic



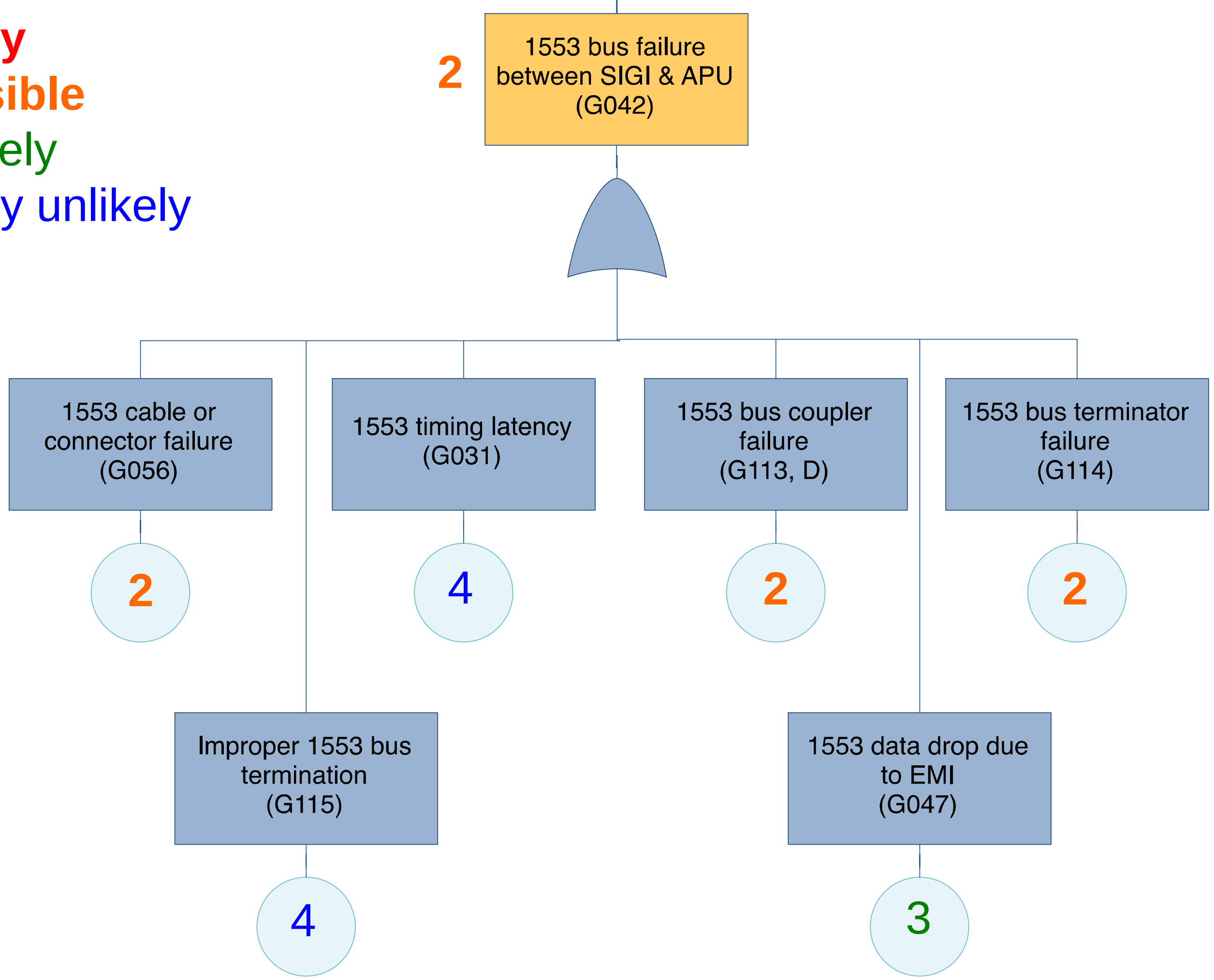
1553 Bus Failure Possibilities

- 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.

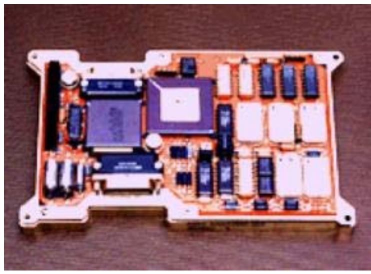
Fault Tree, 1553 Bus

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

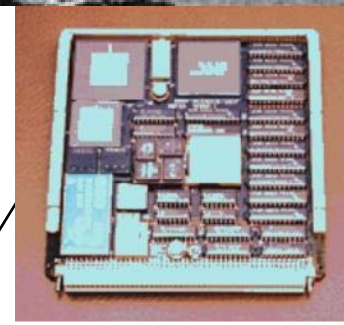


SIGI Components

Inertial Electronics



Trimble GPS Receiver Module

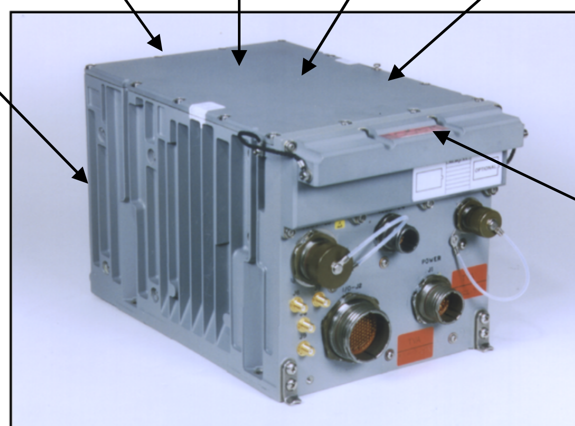


System Processor

Inertial Sensor Assembly

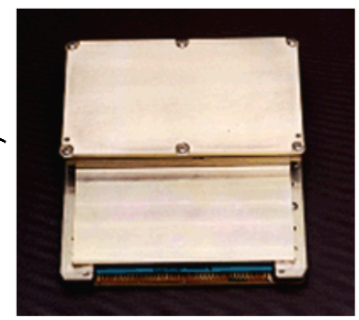
(Mounted Under Inertial Electronics)

ACOCS - 120 VDC Power Conversion



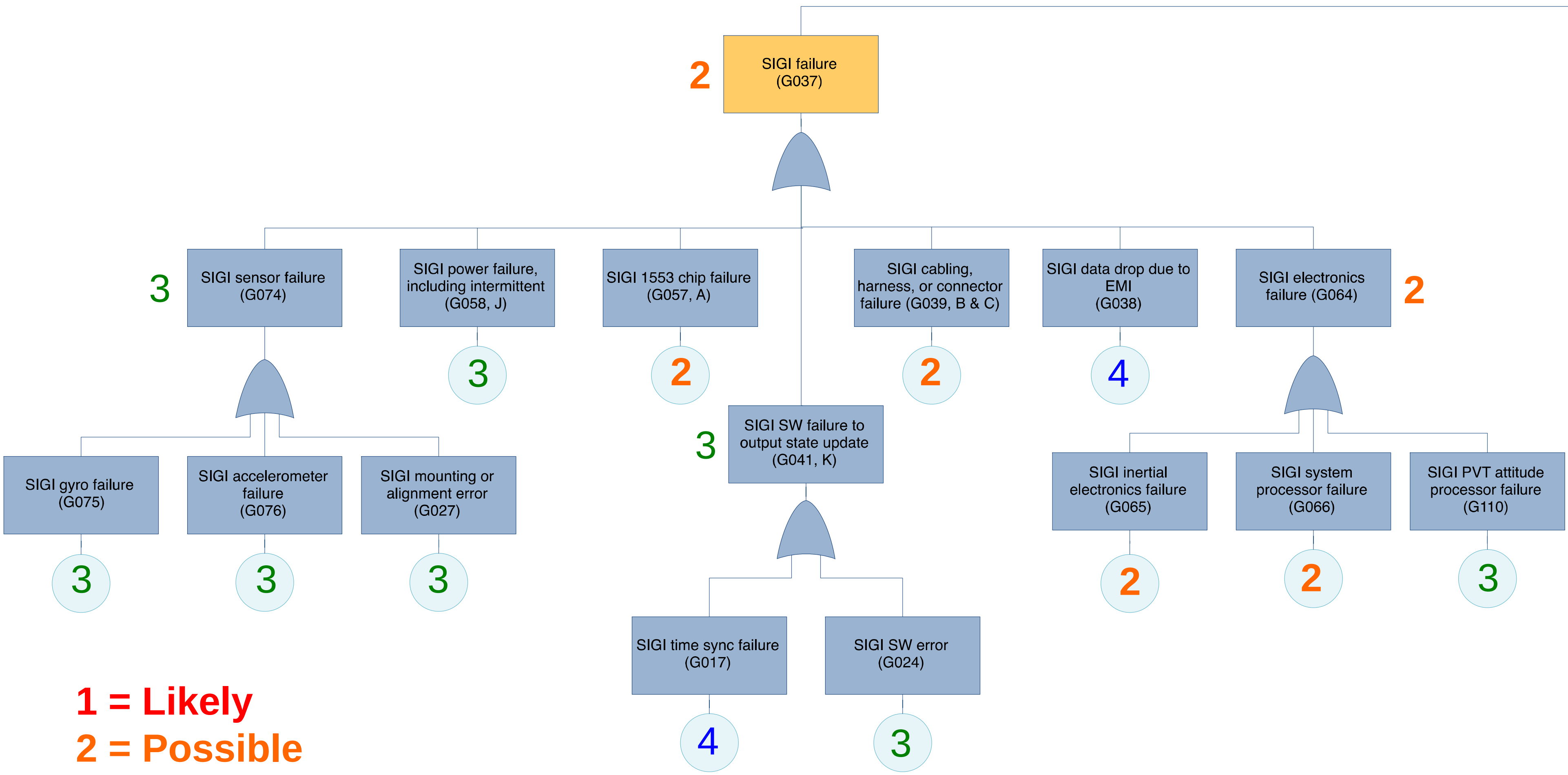
SIGI

DC Power Supply



ISS SIGI Including Adapter Plate

Fault Tree, SIGI

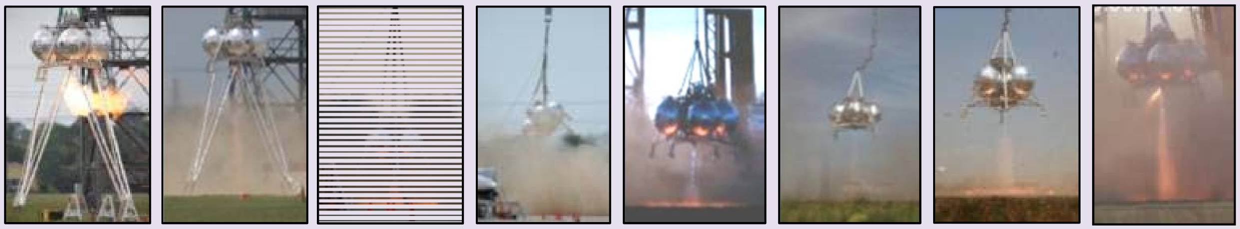


1 = Likely
2 = Possible
3 = Unlikely
4 = Highly unlikely

Accumulated Vibration Time

VTB	Engine Burn Time (sec)	Time in High Vibe Ground Effect (sec)
1.0	290	-
1.5	850	14
Total	**1140**	**14 (1%)**

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



Hot Fire 1	Hot Fire 2	Tether 1	Tether 2	Tether 3	Tether 4	Tether 5	Tether 6
April 14	*April 19*	*April 25*	*April 27*	*May 3*	*May 4*	*June 1*	*August 31*
103 sec	54 sec	20 sec	13 sec	20 sec	29 sec	40 sec	11 sec

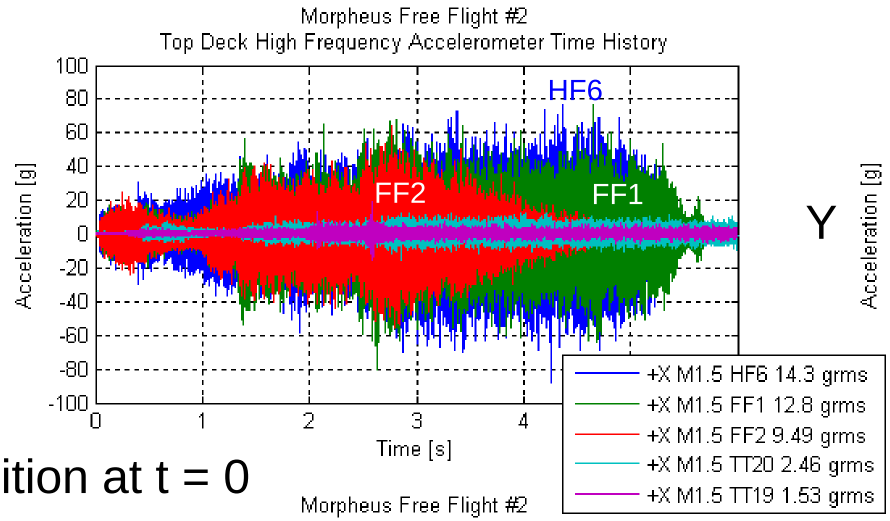
Morpheus 1.5 (2012): 850 sec HD4 Engine Burn Time

Hot Fire 5	Tether 7	Tether 8	Tether 9	Hot Fire 6	Tether 10	Tether 11	Tether 12	Tether 13	Tether 14
February 27	*March 5*	*March 13*	*March 16*	*April 2*	*April 5*	*April 11*	*April 18*	*May 2*	*May 8*
40 sec	30 sec	55 sec	47 sec	5 sec	62 sec	56 sec	67 sec	62 sec	66 sec

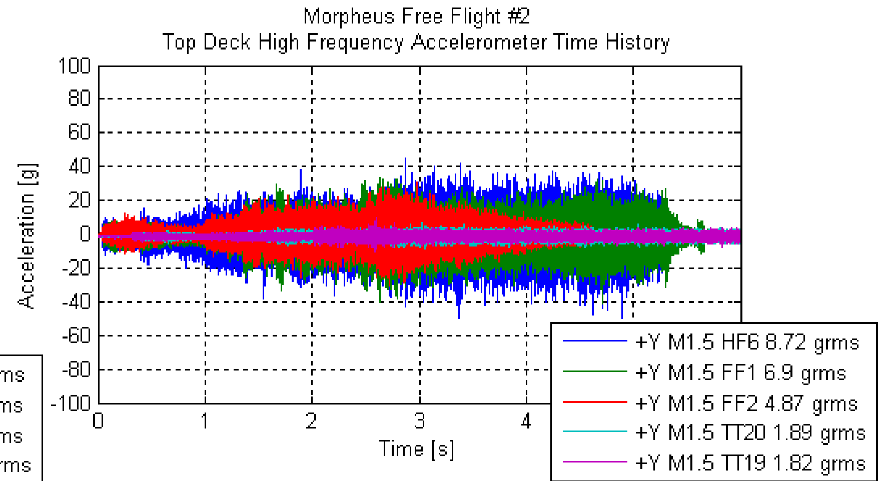
Tether 15	Tether 16	Tether 17	RCS HF1	Tether 18	Tether 19	Tether 20	Free Flight 1	Free Flight 2
May 10	*June 11*	*June 18*	*July 3*	*July 6*	*July 17*	*August 3*	*August 7*	*August 9*
60 sec	41 sec	63 sec	Methane RCS	49 sec	72 sec	63 sec	Soft abort	LOV

Vibration Flight Experience

X

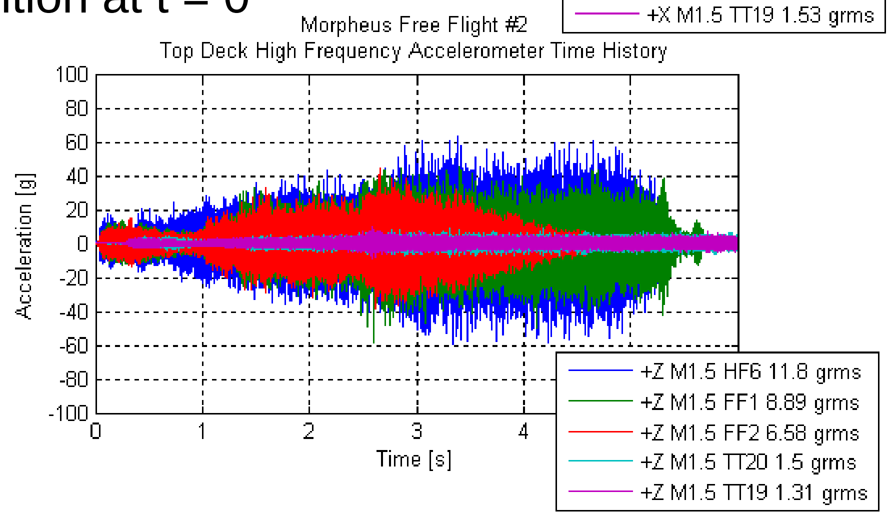


Y



Ignition at t = 0

Z

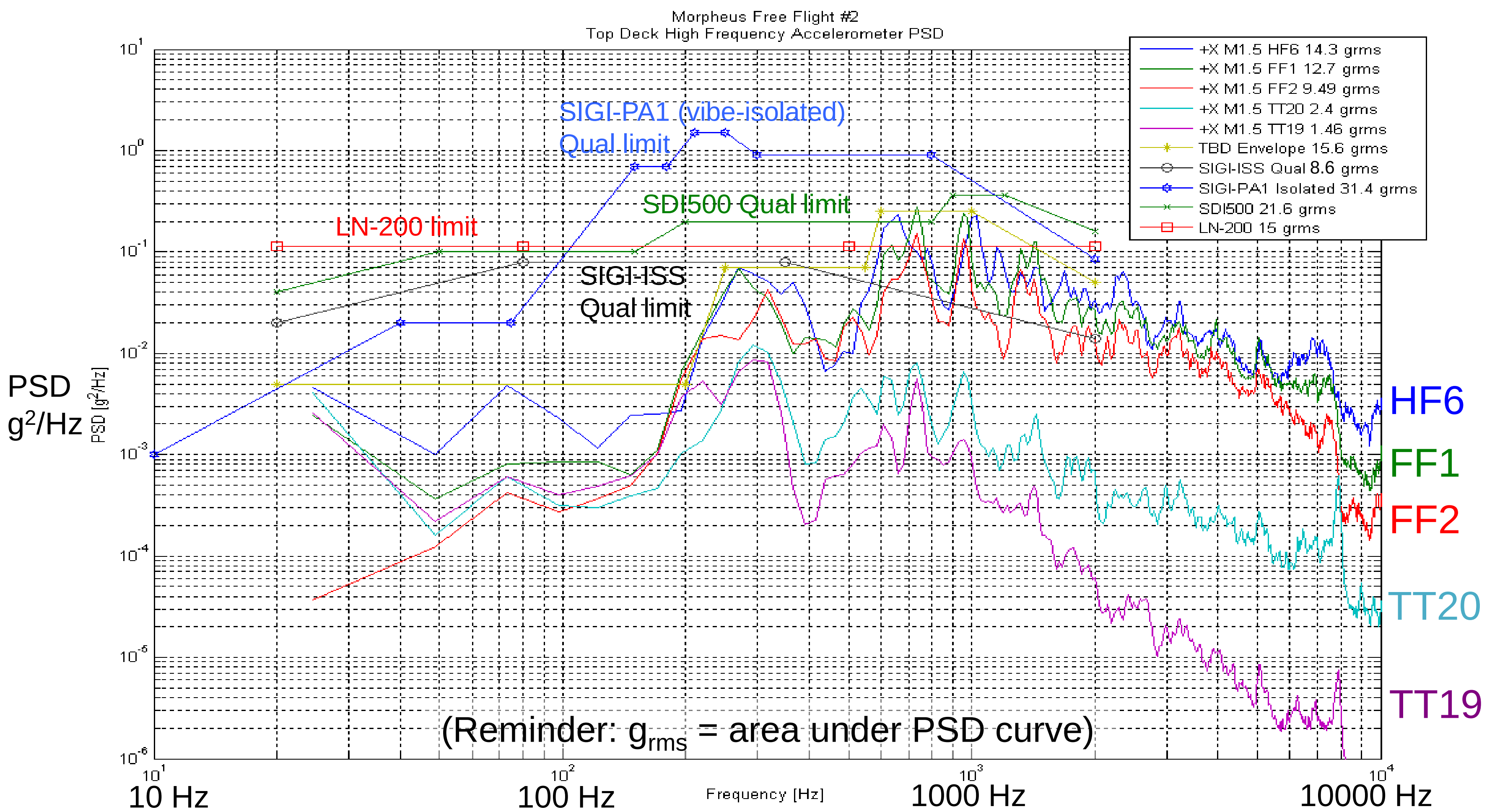


Flight Test Color Key

- 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

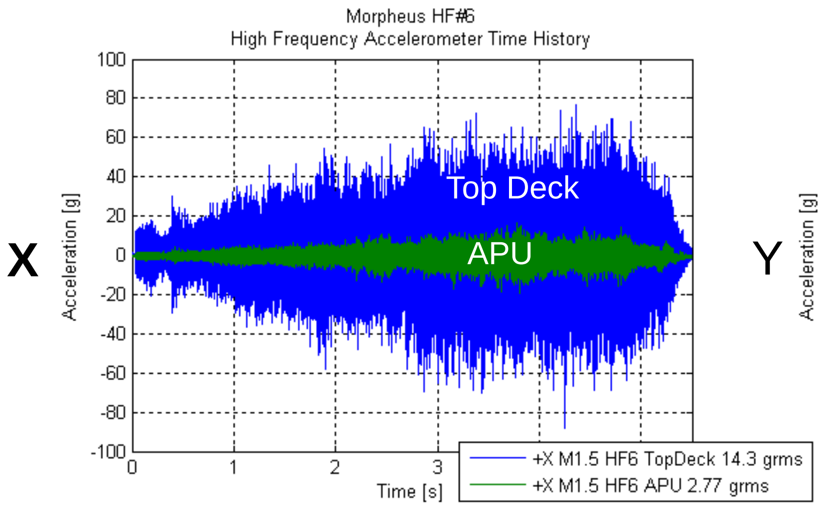
Tether Test ignitions "at altitude" produce far less vibration than HF6 & FF ground ignitions.
FF2: VTB escaped vibro-acoustic ground effect ~4 sec after ignition, ~1 sec after liftoff.

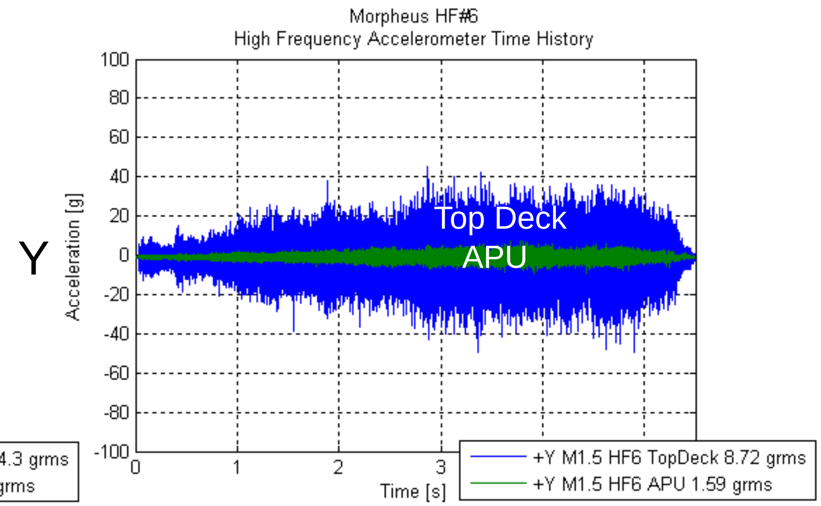
Vibration Flight Levels & IMU Qual Specs, +X

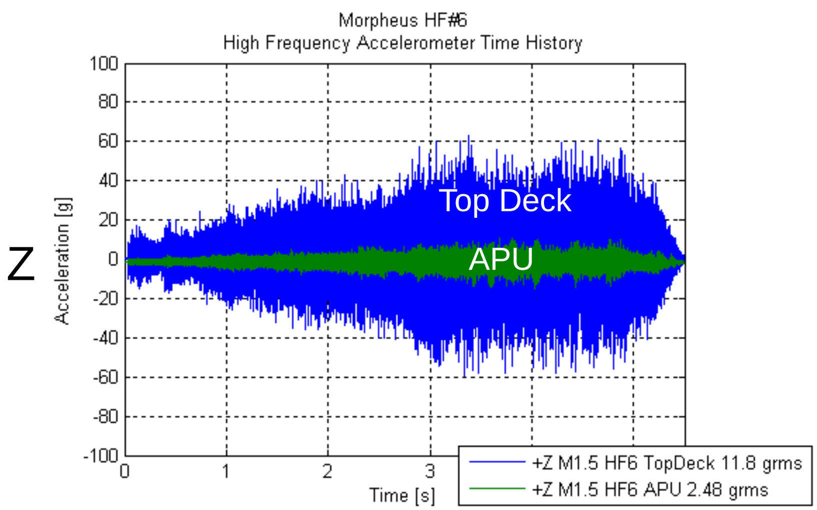


HF6, FF1 & FF2 vibration briefly exceeded ISS SIGI qual limits at high frequencies.
Vibe-isolated PA1 SIGI has much higher qual limits, above Morpheus test experience.

Vibe Isolation Effectiveness in HF6



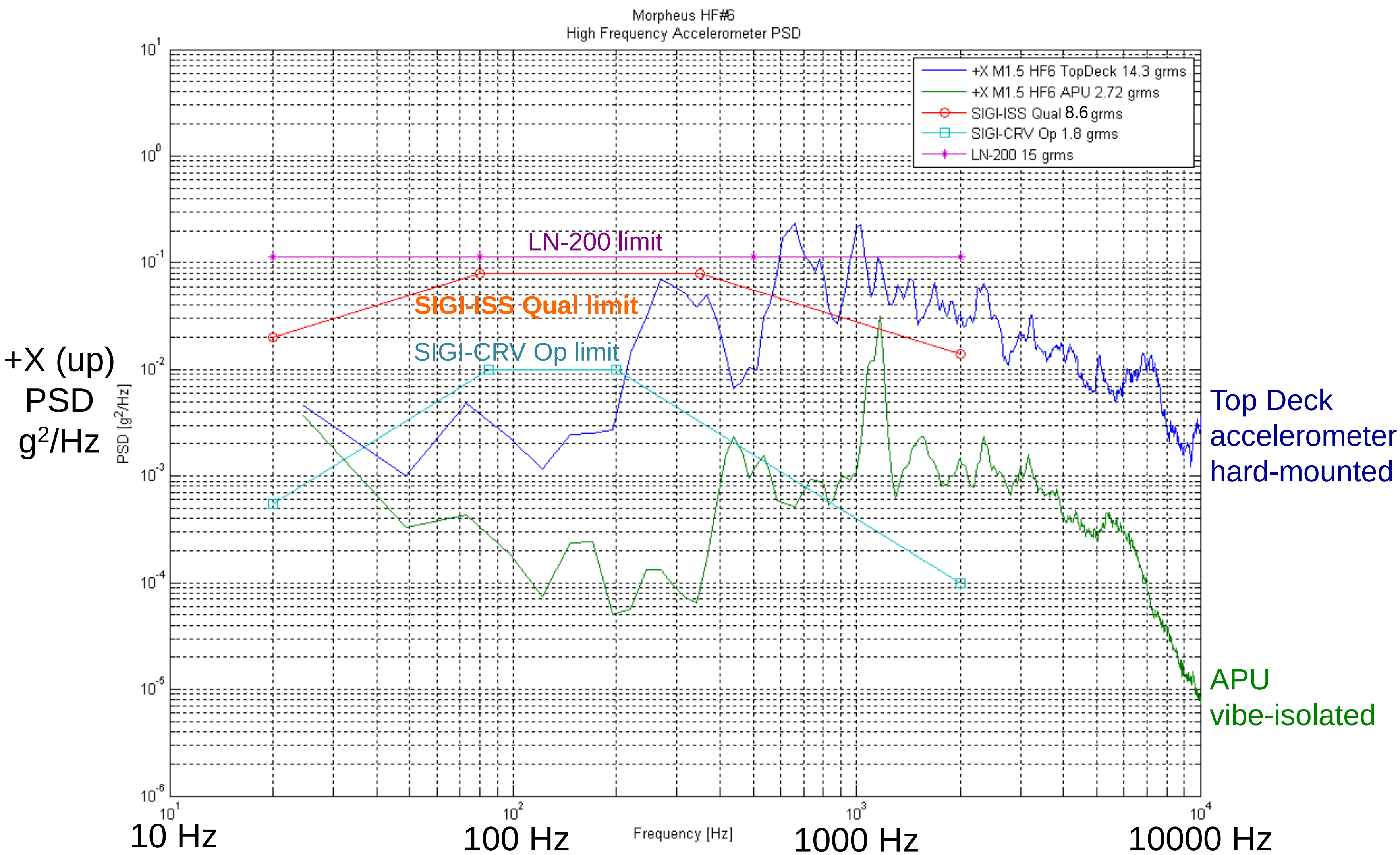




Top Deck accel was hard-mounted.
APU accel was vibe-isolated.

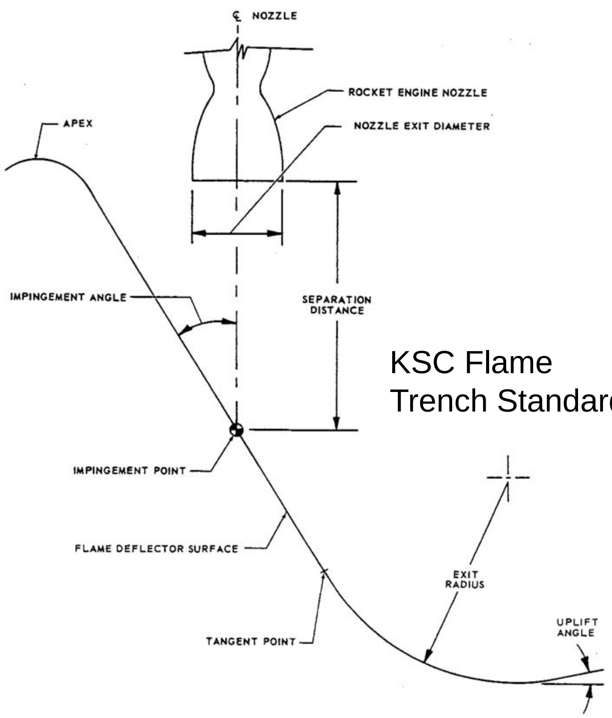
Vibe isolation reduced peak g's by an order of magnitude.

Vibe Isolation Effectiveness in HF6



Corrective Action 1

#	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



KSC Flame Trench Standard


PA1 SIGI in Vibe Isolation Cage

Corrective Actions 2-5

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

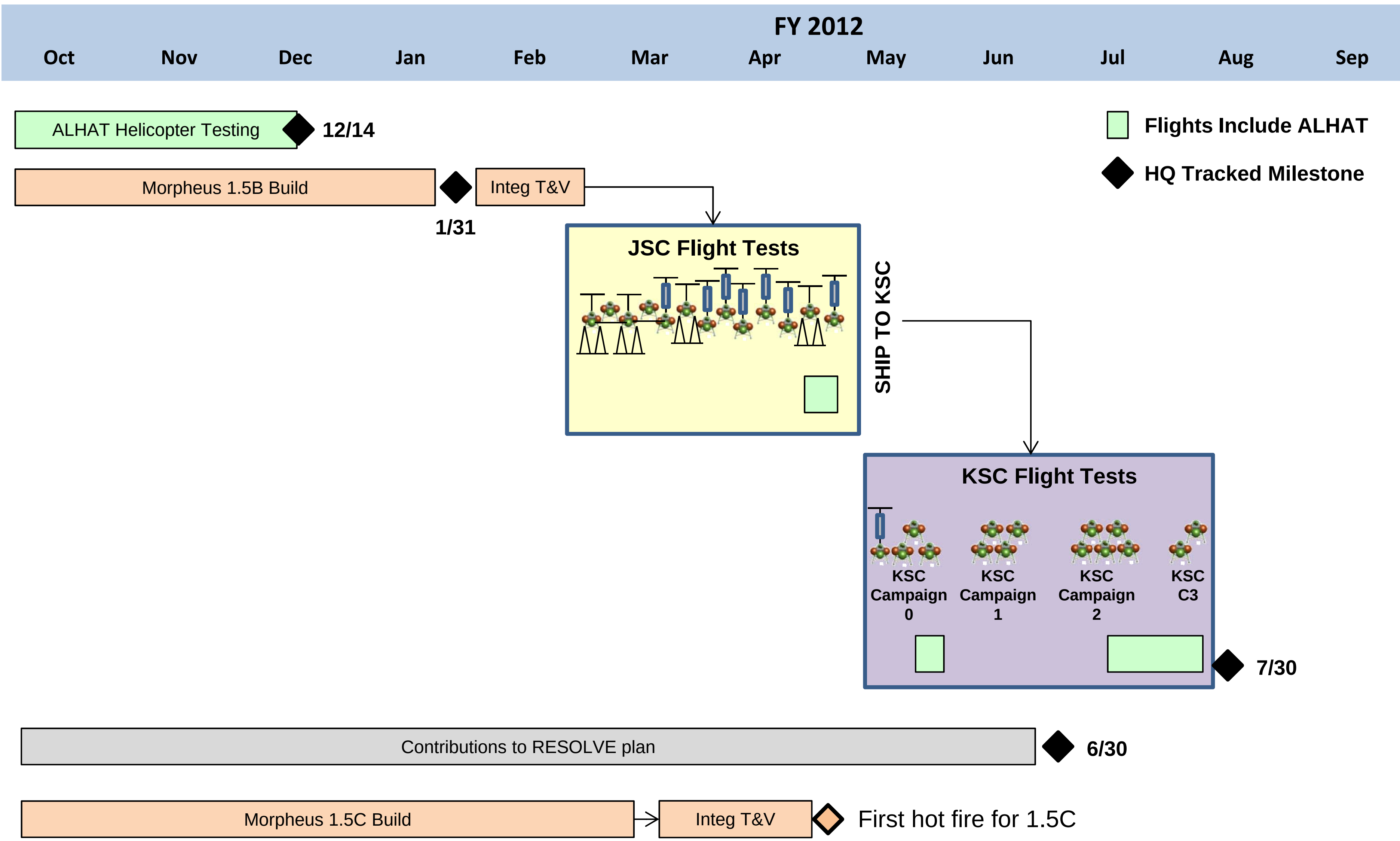
Corrective Actions 6-8

#	Probable or Possible Cause or Contributor	Corrective Action
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
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
ALHAT Helicopter Testing
12/14
Flights Include ALHAT
HQ Tracked Milestone
Morpheus 1.5B Build
Integ T&V
1/31
JSC Flight Tests
SHIP TO KSC
KSC Flight Tests
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

Backup

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

Project Scale of Rigor

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

Rigor
CM, Requirements, Data Management, Formal Documentation, 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

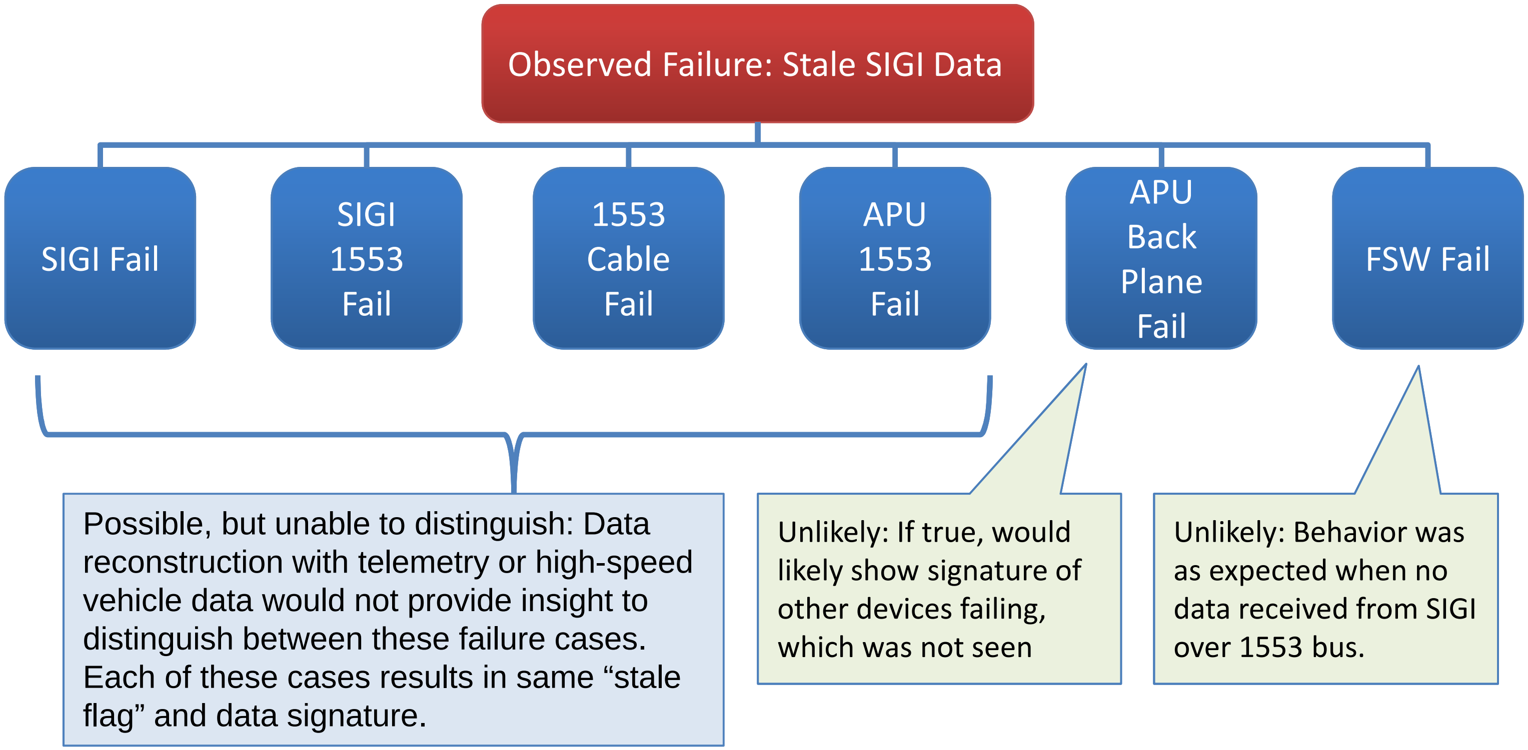
- **High dollar project**
- **High reliability required**
- **Crew safety**
- **Mission critical**
- **Expensive payloads**
- **High visibility**
- **Schedule constraints**
- **Costly replacement**
- **Paying customer**

NUDGE

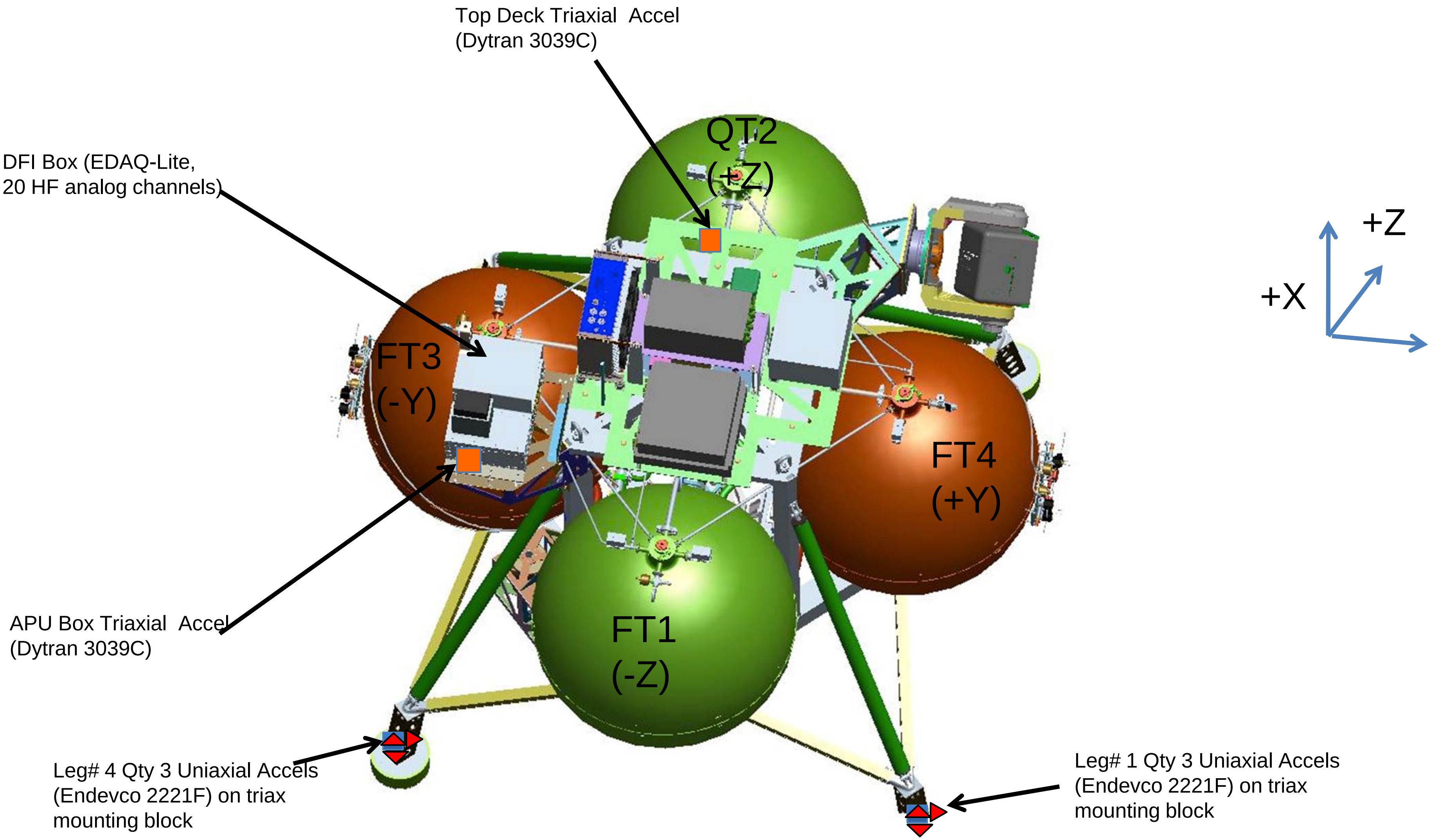
Technology Development / R&D | **Morpheus** | **Shuttle, ISS, Orion**

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.

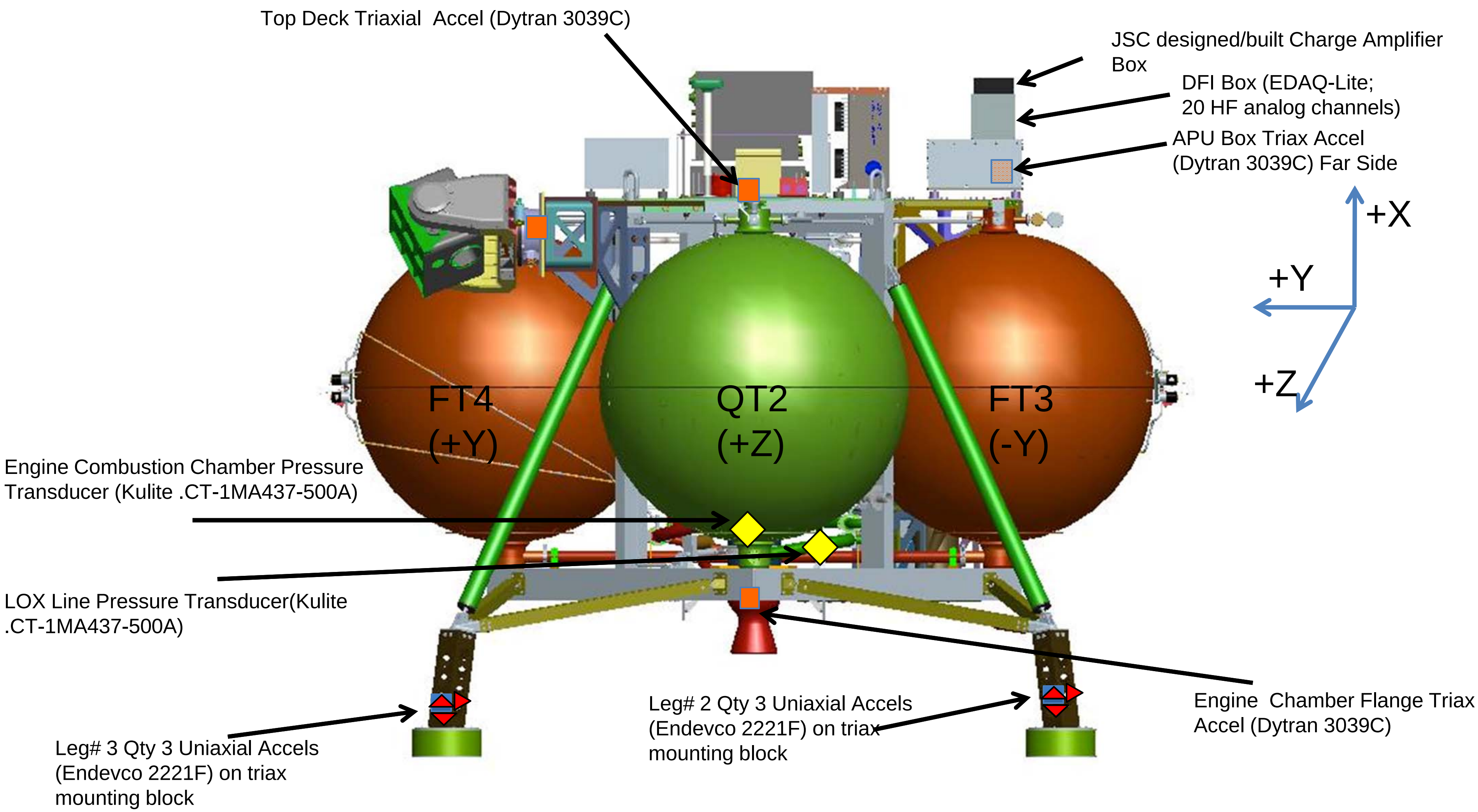
Stale SIGI Data



DFI Sensor Locations, Top



DFI Sensor Locations, Side



KSC Flight Test Risks

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

LIKELIHOOD		CONSEQUENCES 1	2	3	4	5
Highly Likely	5					
Likely	4		- Weather			
Possible	3		- Tank imbalance - Helium RCS usage	- Methane RCS reliability	- Methane RCS perf. - ALHAT precision landing	
Unlikely	2		- Lateral instabilities - Vertical instabilities	- Ground effect damage - Landing gear buckling - Lack of spares	- Insufficient vehicle perf for HDP - Navigation error budget	- Engine burn-thru - Engine performance - EMA / throttle valve failure -Low prop -Aero torques
Highly Unlikely	1				- Morpheus precision land.	- CPU reset - Loss of instr. - Loss of power
		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

Morpheus System Overview

MORPHEUS VEHICLE

GROUND SYSTEMS EQUIPMENT
Mechanical, Fluid, Electrical

FLIGHT OPERATIONS
TC, OPR, RSO, Prop, GN&C, ALHAT, APS, DFI, FM

Like any planetary launch and landing vehicle, Morpheus includes a vehicle, subsystems, operations, and ground systems

Morpheus 1.5 Vertical Testbed (VTB)

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