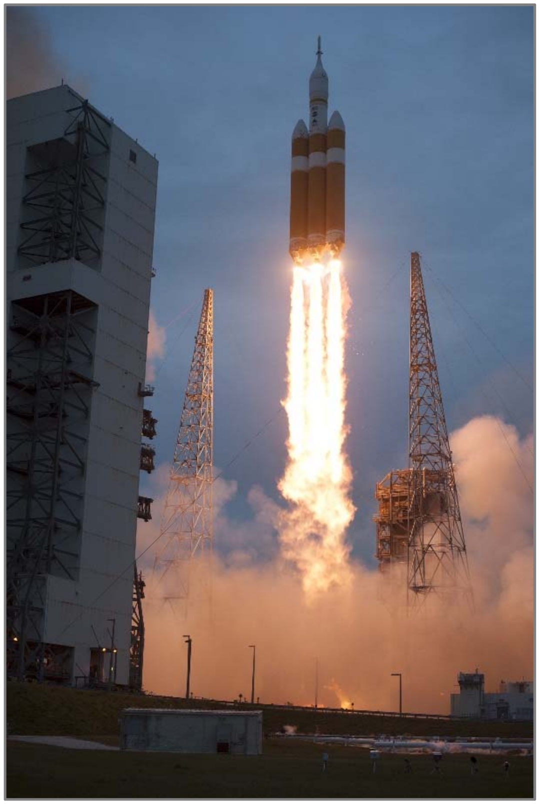
George C. Marshall Space Flight Center
ER42 Fluid Dynamics

Liftoff and Time Equivalent Duration Data Evaluation of Exploration Flight Test 1 Orion Multi-Purpose Crew Vehicle



5th Joint Meeting Acoustic Society of American and Acoustical Society of Japan

Janice Houston

November 29, 2016

Photo credit - http://mediaarchive.ksc.nasa.gov

EFT-1 Mission

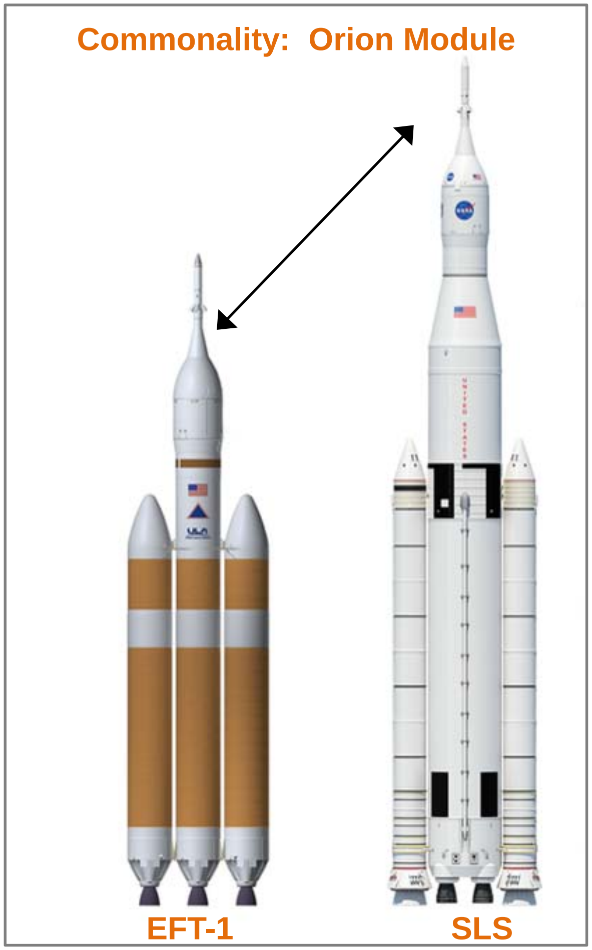
Background

- EFT-1 launch on December 5, 2015 at 7:05 AM EST

Video credit - https://www.nasa.gov/exploration/systems/orion/videos

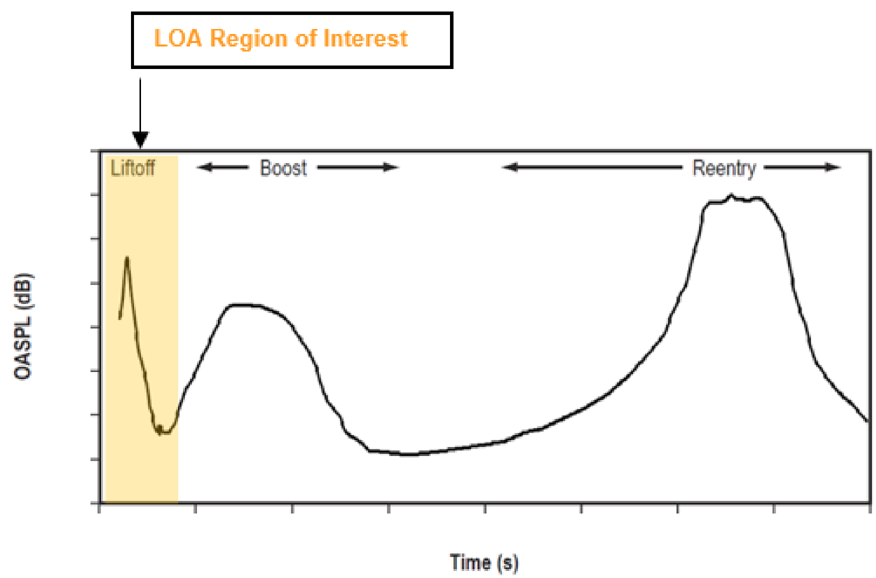
Objective

- Objective of this work is to define the EFT-1 liftoff acoustics (LOA) fatigue-weighted duration
  - Vibroacoustic engineers require the fatigue-weighted duration for qualification testing
  - Useful for the development of the Space Launch System (SLS)



Objective

- Definition of Fatigue-weighted time duration, T_{eq}, is taken from:
    - NASA TM-2009-215902: '*Using the Saturn V and Titan III Vibroacoustic Databanks for Random Vibration Criteria Development*'
    - Available at NASA Technical Reports Server https://ntrs.nasa.gov/
- From TM-2009-215902:
    - 'Equivalent damage time (T_{eq}) is the time required to induce an amount of damage at a high test level equivalent to that induced by exposure to a varying stress level.
    - Acoustically induced random vibration on launch vehicles is a non-stationary environment, i.e., its root-mean-square (RMS) amplitude changes fairly rapidly over its duration.'



EFT-1 Instrumentation Overview

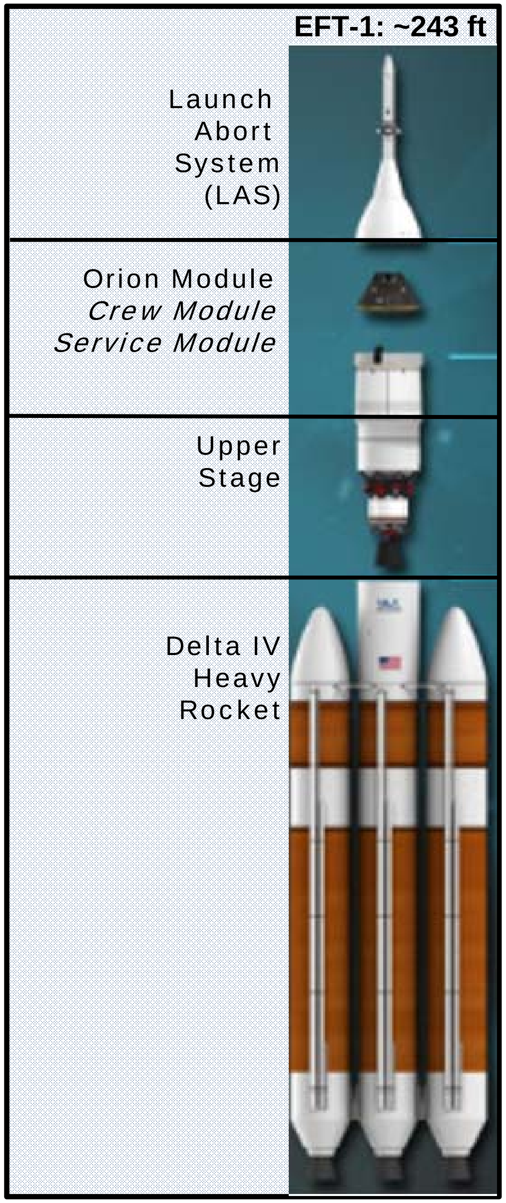
EFT-1
Vehicle & Instrumentation

Sensors: *Piezoresistive Pressure Transducers*

- External Locations
  - 5 sensors on LAS
  - 17 sensors on Crew Module (CM)/Service Module (SM)
- Internal Location
  - 1 sensor on CM/SM

Data Acquisition Units

- DAU1: all 5 LAS sensors
- DAU2: 10 CM/SM sensors
- DAU 3: 8 CM/SM sensors



Sensors

LAS

LASM01
LASM02
LASM03
LASM04
LASM05

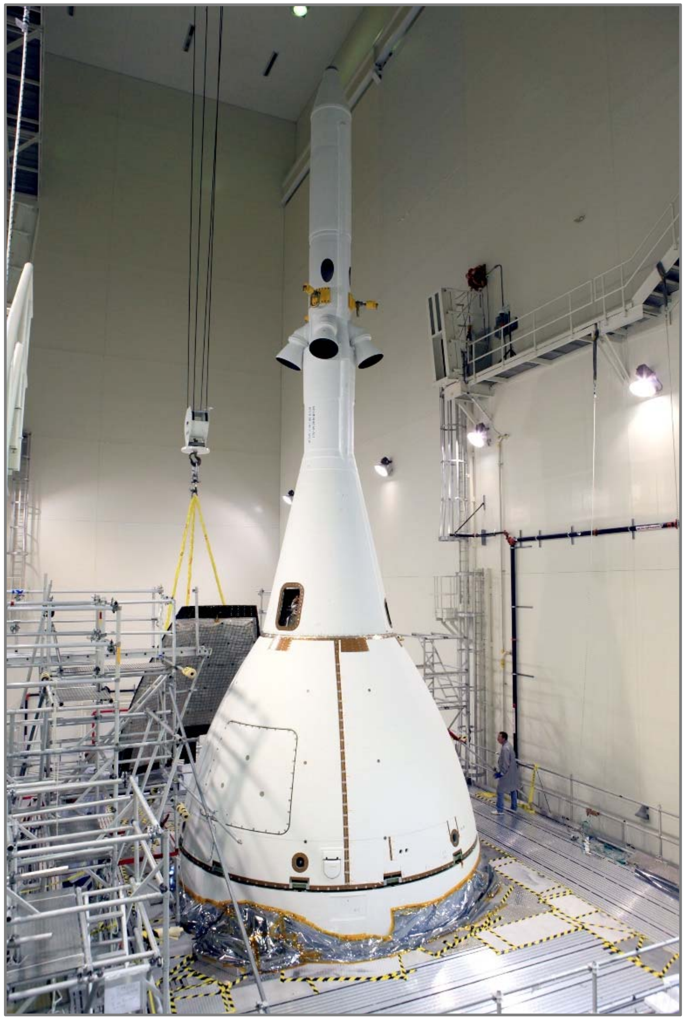
ORION MODULE

OM01int
OM01
OM02
OM03
OM04
OM05
OM06
OM07
OM08
OM09
OM10
OM11
OM12
OM13
OM14
OM15
OM16
OM17

Data Acquisition Units

DAU1
DAU2
DAU3

EFT-1
Orion LAS/Ogive and Service Module



Orion LAS/Ogive Cover

Orion Service Module

Photo credit - http://www.nasa.gov/content/orion-prepares-to-move-to-launch-pad
Photo credit - http://www.nasa.gov/content/at-your-service-orion-service-module-complete

Data Analysis

Data Analysis Challenge & Process

- Challenge: Data "thrown over the fence"
- Analysis Software: PCSignal Version 2.5

Time History

- 2 Hz trend removed

Quality Checks

Histogram Statistics

PSD

- Block Size: 8192
- Blocks: 30
- Time selected in launch window

Engineering Judgment

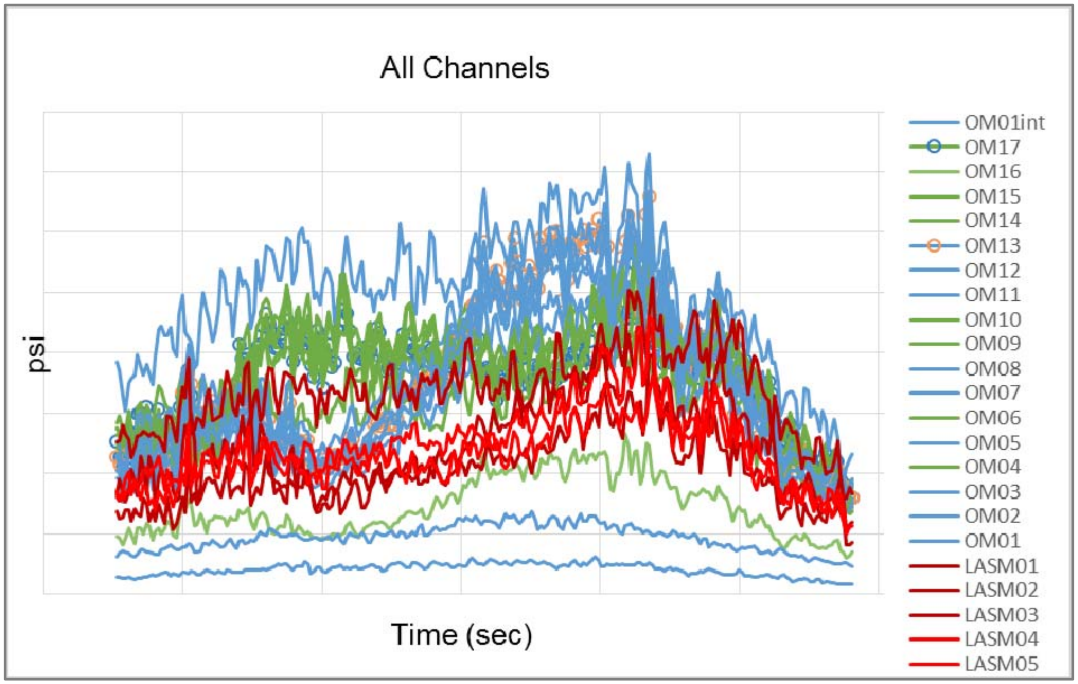
Discard bad data from set

Teq Calculations

- Time step = 0.086 sec

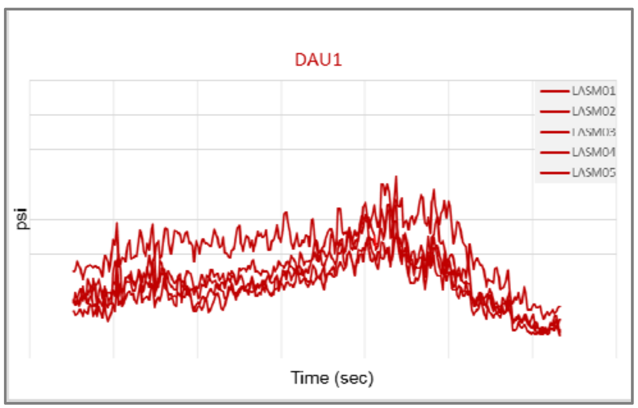
*will discuss blue boxes

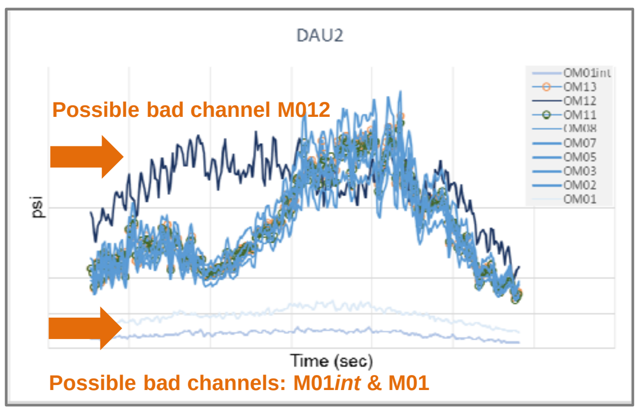
Time History

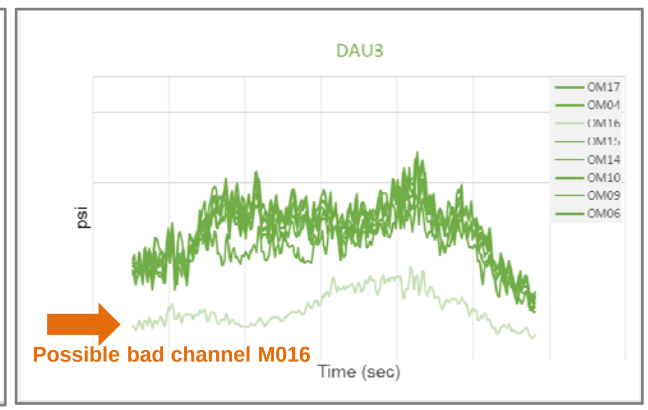


Evaluation led to:

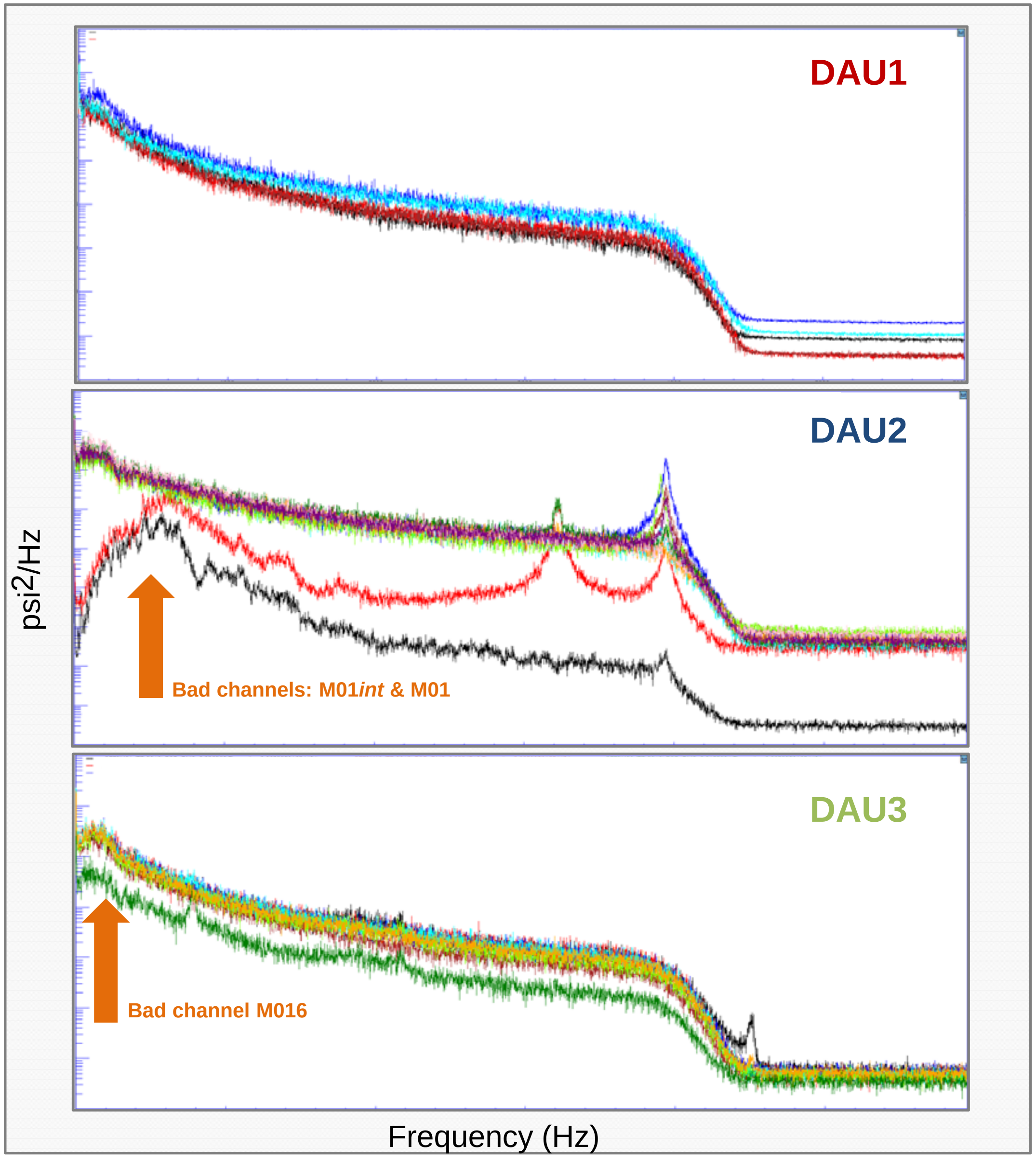
- Possibility that some channels were "bad"
  - DAU2/M01*int*
  - DAU2/M01
  - DAU2/M012
  - DAU3/M016 (gain issue)
- Determination that time history shape unique per DAU
- Further data analysis became DAU specific







PSD
Evaluated per DAU



Evaluation Conclusions:

- **DAU1**
  - Channels look great
  - Filter Rolloff consistent and at expected frequency
- **DAU2**
  - M01int and M01 are not in family
  - Other channels show peak prior to roll-off
- **DAU3**
  - M016 is 10x below other channels in magnitude
- DAUs do not have same characteristics
  - Requires slot evaluation
    - ***Two time windows***
    - Ambient
    - Launch window

Evolved Data Analysis Process

- DAU contains cards which are located and identified by numbered “slots”
- The cards can host multiple channels
    - Cards can host different sensor types simultaneously
- DAU1 – Sensors located on 1 slot
- DAU2 - Sensors located on 4 slots
- DAU3 – Sensors located on 4 slots

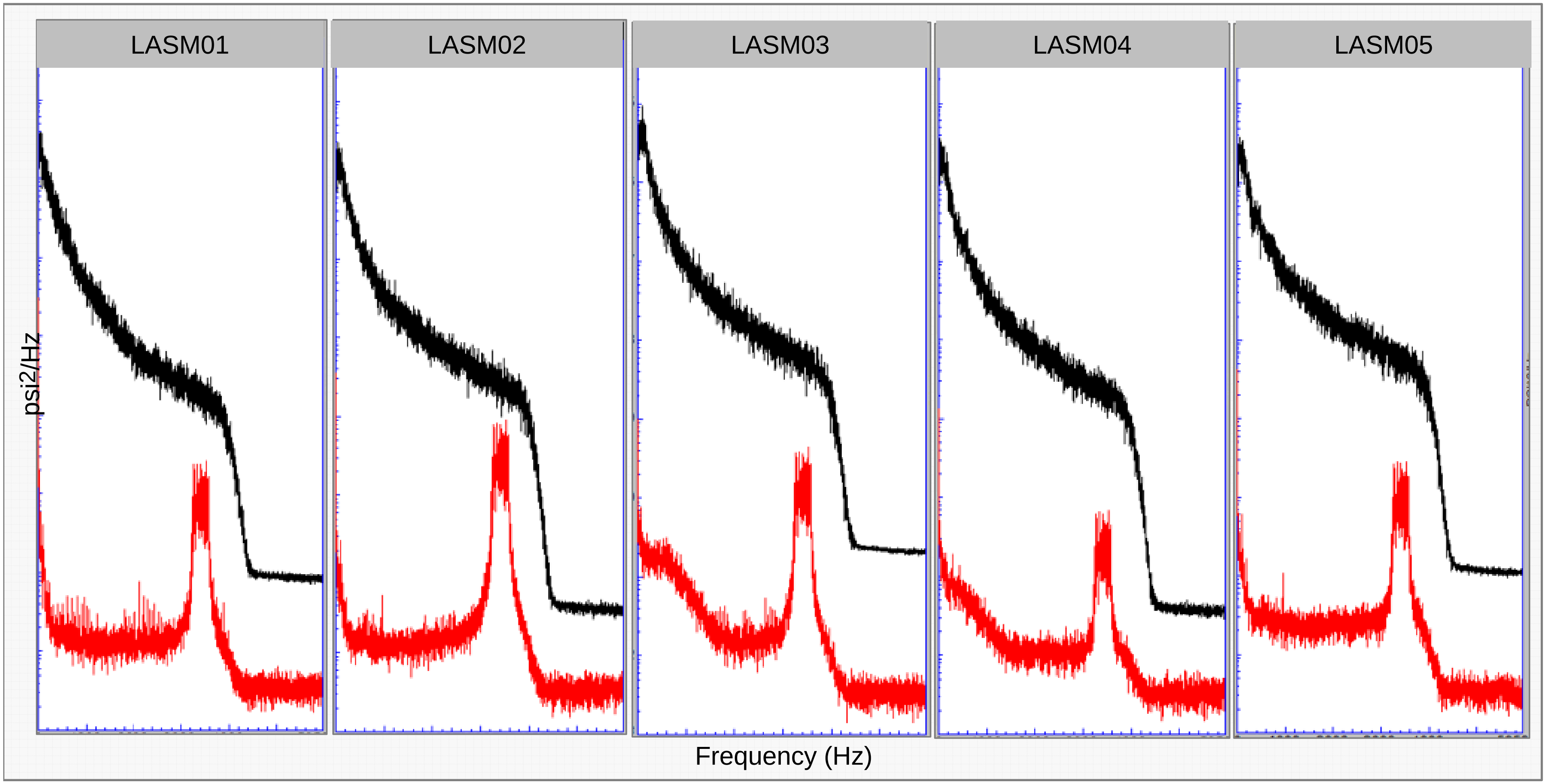
Example DAU with Cards (Slots)

DAU	Sensor ID with Slot &Channels			
DAU1	LASM01 – Slot 26 – Channel 1 LASM02 – Slot 26 – Channel 2 LASM03 – Slot 26 – Channel 3 LASM04 – Slot 26 – Channel 4 LASM05 – Slot 26 – Channel 5			
DAU2	OM11 – Slot 13 – Channel 1 OM08 – Slot 13 – Channel 3 OM01 – Slot 13 – Channel 5	OM07 – Slot 14 – Channel 1 OM05 – Slot 14 – Channel 3 OM01*int* – Slot 14 – Channel 5	OM03 – Slot 15 – Channel 1 OM02 – Slot 15 – Channel 3	OM12 – Slot 16 – Channel 1 OM13 – Slot 16 – Channel 3
DAU3	OM15 – Slot 13 – Channel 1 OM10 – Slot 13 – Channel 3	OM16 – Slot 14 – Channel 1 OM14 – Slot 14 – Channel 3	OM09– Slot 15 – Channel 1 OM06 – Slot 15 – Channel 3	OM04 – Slot 16 – Channel 1 OM17– Slot 16 – Channel 3

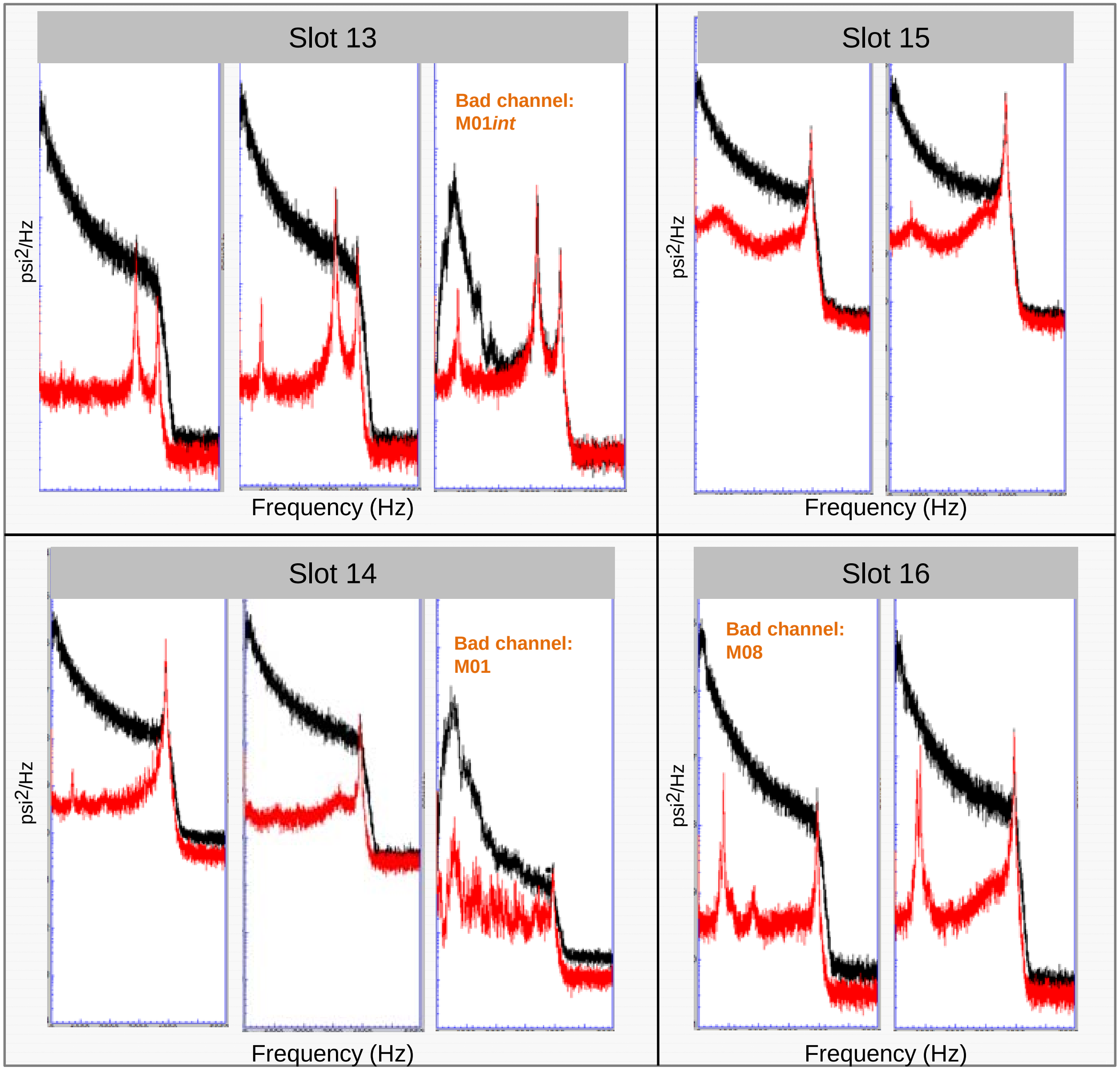
DAU1 Average PSDs

DAU1 Evaluation Conclusions (1 slot, sequential channels)

- Looks as expected
- Ambient noise window has peak but below signal

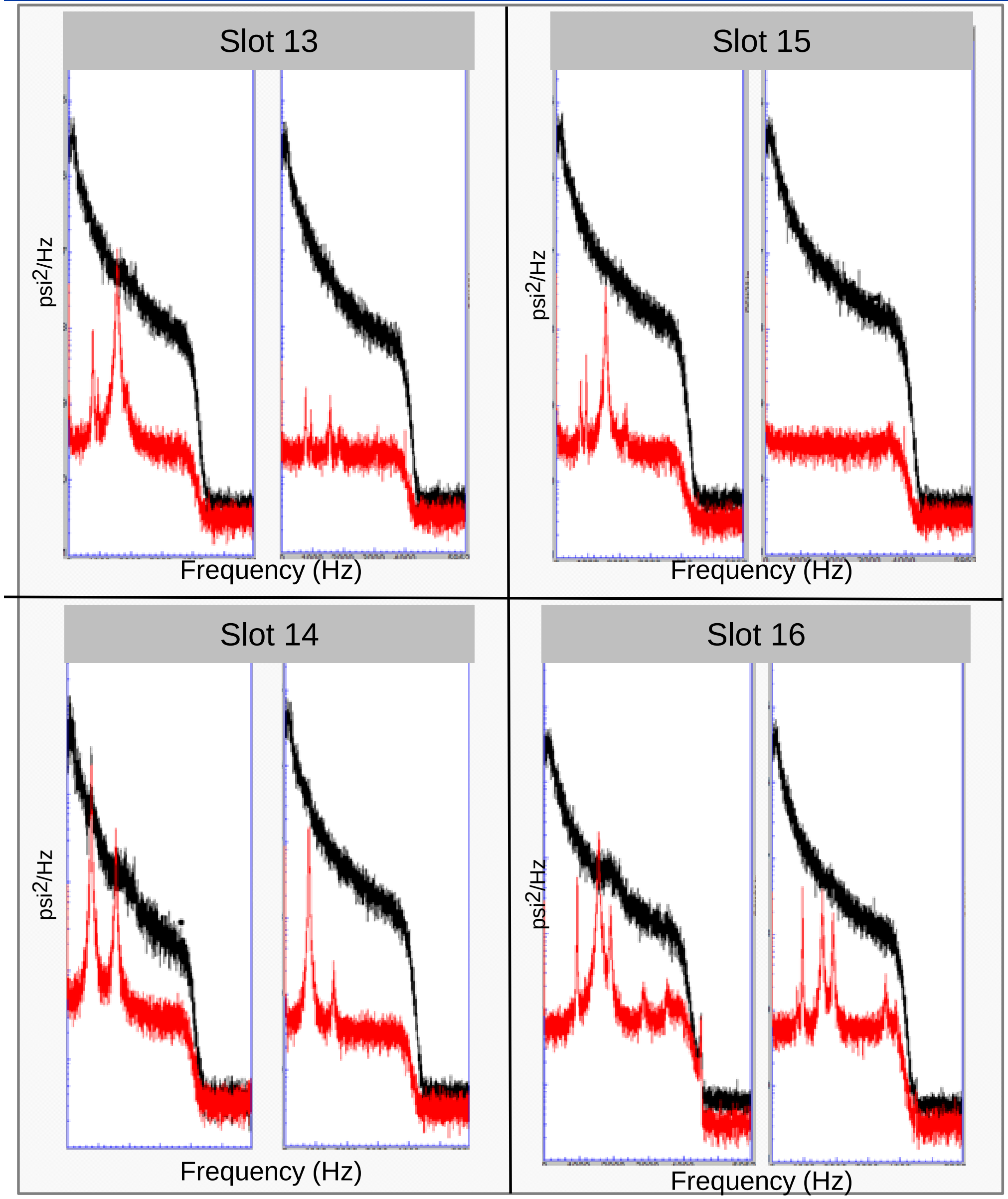


DAU2 Average PSDs



- **DAU2** Evaluations Conclusions (4 slots)
- Peaks in ambient and liftoff times seem to be slot dependent
- Noise to signal ratio of ambient to launch window peaks insufficient

DAU3 Average PSDs



- DAU3 Evaluations Conclusions (4 slots)
- Peaks in ambient and liftoff times seem to be slot dependent
- Noise to signal ratio of ambient to launch window peaks insufficient
- Possible that documentation for channels in Slot 13 and Slot 15 is incorrect

Teq Calculation and Results

Definition of Fatigue-Weighted Duration

- Fatigue-Weighted Duration (T_{eq}) formula :

$$T_{eq} = \sum_i T_i \left(\frac{W_i(T_i)}{W_{max}}\right)^{\beta}$$

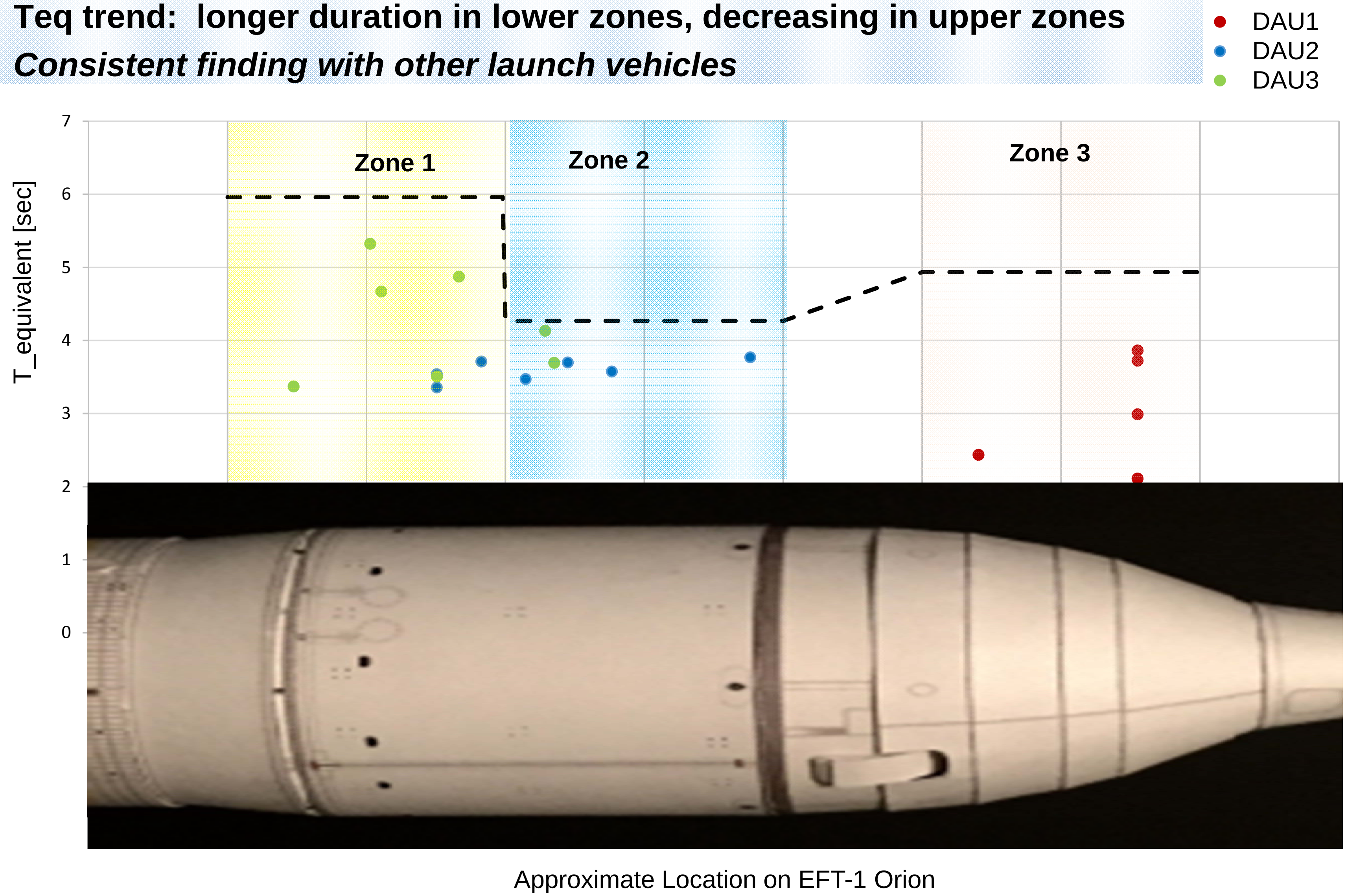
For EFT-1Teq
- Time step
  - Ti = 2* (t_2-t_1) = 0.086 sec

  - where $\beta = b/n = 4$ for this work (assuming solder joints; conservative)
  - Varying RMS level (W_i), within a given time step (T_i), and max level (W_{max})

- For launch vehicle / spacecraft applications, it is preferred to use sinusoidal vibration profiles for *W*
  - Mainly for component vibrations / accelerations
- Sound pressure levels or aero dynamic pressure can be used in place of vibration profiles
  - *Assumes that the external pressure environment is linearly driving the component level accelerations*
- Calculation process then needs the *W* profile over the flight phase of interest
  - For this work, the liftoff phase of flight is of interest. Liftoff phase (per action) includes:
    - Engine ignition – **not desired for random vibration / T_{eq} assessment**
    - Full thrust engine – **desired phase of flight**

Teq Results

Teq trend: longer duration in lower zones, decreasing in upper zones
Consistent finding with other launch vehicles



Conclusion

- Data processing has inherent challenges
  - Need good understanding of the data acquisition system in order to avoid false conclusions
- Teq calculations were completed for EFT-1
- EFT-1 launch data can be used for launch vehicles in design
  - Information is useful for SLS

Back up

EFT-1 Mission

Delta IV EFT-1 Mission

DELTA IV EFT-1 MISSION

A United Launch Alliance Delta IV Heavy will take the Orion spacecraft to the highest orbit for a spacecraft designed for humans since Apollo, then deliver it to a re-entry location for splashdown and recovery. Liftoff will occur from Space Launch Complex 37 at Cape Canaveral Air Force Station, FL.

The Orion Exploration Flight Test (EFT)-1 mission is an un-crewed launch of Orion to demonstrate the Service Module (SM) fairing and Launch Abort System (LAS) jettison events, the ability to perform controlled re-entry, and the effectiveness of the heat shield. The Orion spacecraft is built by Lockheed Martin and is comprised of four major elements: the LAS, the Crew Module (CM), the SM, (together, the LAS, CM, and SM comprise the Multi-Purpose Crew Vehicle (MPCV)), and the MPCV Stage Adapter (MSA).

The EFT-1 mission will orbit the Earth twice, reaching a maximum altitude of more than 3,500 miles on the second orbit prior to a starting a steep descent that approaches a lunar mission return thermal environment. The Orion CM will achieve a maximum speed of more than 19,770 mph (29,000 ft/sec) before entering Earth's atmosphere. Following a parachute-aided descent, the Orion spacecraft will be recovered by the U.S. Navy from the Pacific Ocean off the California Baja Peninsula.

Orion Spacecraft

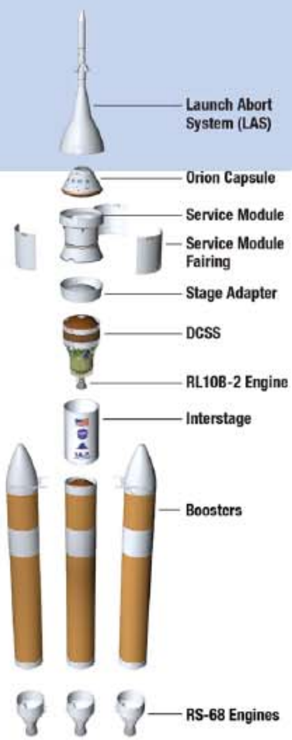
The spacecraft is comprised of the Launch Abort System, the Crew Module, the Service Module and fairings, and the Stage Adapter. The vehicle's height with Orion is approximately 243 ft.

Delta Cryogenic Second Stage (DCSS)

The DCSS stage propellant tanks are structurally rigid and constructed of isogrid aluminum ring forgings and spun-formed aluminum domes. It is a cryogenic liquid hydrogen/liquid oxygen-fueled vehicle, and uses a single RL10B-2 engine that produces 24,750 lb of thrust. The DCSS cryogenic tanks are insulated with a combination of spray-on and bond-on insulation, and helium-purged insulation blankets. An equipment shelf attached to the aft dome of the DCSS liquid oxygen tank provides the structural mountings for vehicle electronics.

Boosters

The Delta IV booster tanks are structurally rigid and constructed of isogrid aluminum barrels, spun-formed aluminum domes and machined aluminum tank skirts. Delta IV booster propulsion is provided by the RS-68 engine system which burns cryogenic liquid hydrogen and liquid oxygen which delivers 663,000 lb of thrust at sea level. Booster cryogenic tanks are insulated with a combination of spray-on and bond-on insulation and helium-purged insulation blankets. The boosters are controlled by the DCSS avionics system, which provides guidance, flight control.



The ULA team is proud to be the launch provider for the Lockheed Martin Orion Exploration Flight Test (EFT)-1 mission. The EFT-1 mission represents the next step U.S. crewed space exploration beyond Earth orbit, testing critical interfaces on the Orion and further refining the design that will take astronauts to the moon and beyond.

The ULA team is focused on attaining Perfect Product Delivery for the EFT-1 mission, which includes a relentless focus on mission success (the perfect product) and also excellence and continuous improvement in meeting all of the needs of our customers (the perfect delivery).

My thanks to the entire ULA team and our mission partner, Lockheed Martin, as well as major suppliers of ULA for their hard work and commitment to mission success.

Go Delta, Go EFT-1!

Jim Sponnick
Vice President, Atlas and Delta Programs

United Launch Alliance

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DELTA

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MISSION OVERVIEW

- 90th ULA Launch
- 8th Delta IV Heavy Launch
- 1st Commercial Delta IV Heavy Launch

United Launch Alliance

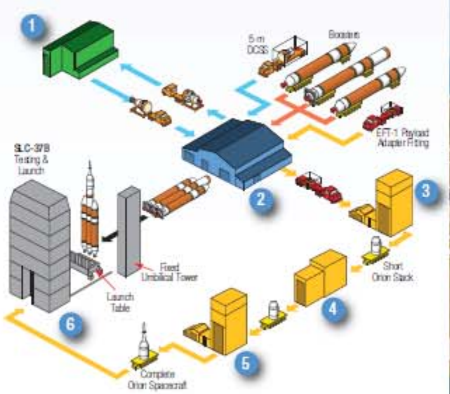
LOCKHEED MARTIN

Delta IV EFT-1 Mission

DELTA IV PRODUCTION AND LAUNCH

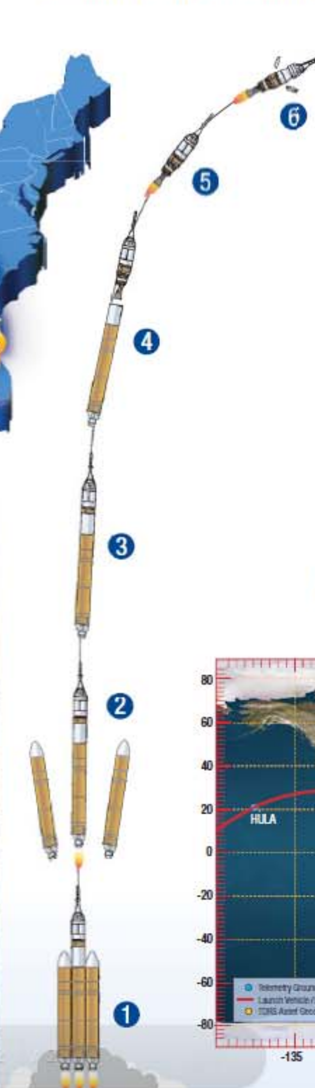
1. De Soto, CA
   – RS-68 Engine Fabrication at Aerojet Rocketdyne
2. Denver, CO
   – ULA Headquarters & Design Center Engineering
3. Decatur, AL
   – Boosters, & Second Stage Fabrication
4. West Palm Beach, FL
   – RL10 Engine Fabrication at Aerojet Rocketdyne

1. **Delta Operations Center (DOC)** | Launch Control Center and Mission Director's Center
2. **Horizontal Integration Facility** | Receiving, inspection and integration
3. **Neil Armstrong O&C Building** | Orion spacecraft assembly and testing
4. **Payload Hazardous Servicing Facility(PHSF)** | Orion spacecraft fueling
5. **Launch Abort System Facility (LASF)** | Launch abort system installation on Orion spacecraft
6. **Mobile Service Tower** | Launch vehicle integration and testing, spacecraft mate and integrated operations



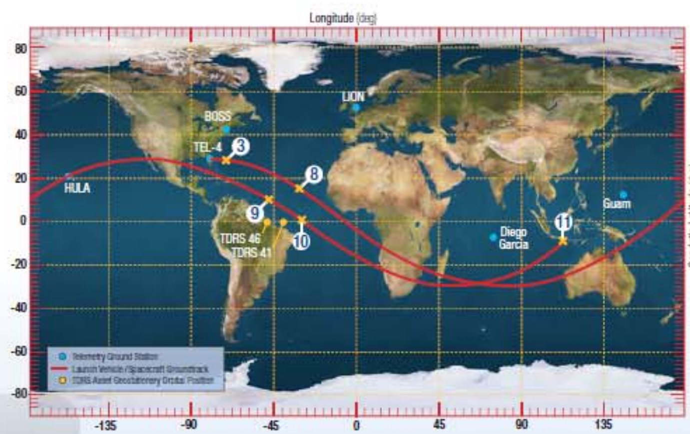
1. **Mobile Service Tower** (MST)
2. **Launch Vehicle**
3. **Launch Table**
4. **Fixed Umbilical Tower** (FUT)
5. **Lightning Protection Towers**
6. **LH2 Storage Tank**
7. **LO2 Storage Tank**

MISSION PROFILE AND GROUND TRACE



	Event	Time (seconds)	Time (hr:min:sec)
1	RS-68 Engine Ignition	-5.0	-00:00:05.0
	Liftoff (Thrust to Weight > 1)	0.0	00:00:00.0
	Begin Pitch/Yaw Maneuver	13.0	00:00:13.0
	Mach 1	82.2	00:01:22.2
	Maximum Dynamic Pressure	82.2	00:00:82.2
2	Port and Starboard Booster Jettison	238.3	00:03:58.3
3	Main Engine Cutoff (MECO)	330.9	00:05:30.9
4	First-Stage Separation	338.0	00:05:38.0
5	Second-Stage Ignition	351.0	00:05:51.0
6	Service Module (SM) Fairing Jettison	376.0	00:06:16.0
7	Launch Abort System (LAS) Jettison	381.0	00:06:21.0
8	First Cutoff—Second Stage (SECO-1)	1,037.1	00:17:17.1
9	First Restart—Second Stage	6,920.5	01:55:20.5
10	Second Cutoff—Second Stage (SECO-2)	7,202.5	02:00:02.5
11	Orion Separation	12,216.0	03:23:36.0

Perigee Altitude: -16.1 nmi | Apogee Altitude: 3,126.4 nmi | Inclination: 28.8 deg | Flight Azimuth: 95.0 deg



All Values Approximate

Delta IV Heavy and SLS with Orion

DELTA IV HEAVY

Orion's Flight Test

CAPABILITY TO LOW-EARTH ORBIT (LEO):
26 metric tons

PAYLOAD:
Basic Orion test structure

OBJECTIVE:
Acquire data at beyond-Earth orbit reentry velocities

DISTANCE FROM EARTH:
3,600 miles

DURATION:
5 Hours

SLS

Exploration Mission One (EM-1)

CAPABILITY TO LOW-EARTH ORBIT (LEO):
70 metric tons

PAYLOAD:
Full Orion

OBJECTIVE:
System readiness for astronauts to travel farther than humans have ever gone before

DISTANCE FROM EARTH:
Will break the distance record reached by the most remote Apollo spacecraft, and then 30,000 miles farther out (275,000 total miles)

DURATION:
22 Days