National Aeronautics and Space Administration

Ames Research Center

BrainStack: A Platform for Artificial Intelligence and Machine Learning Collaborative Experiments of a Nanosatellite

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Logo:
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TechEdSat-N /Nano Orbital Workshop

Who we are:

- Innovative flight project focused on rapid design and innovation
  - 2-3 flights a year
  - Low cost, ISS standards
  - 90% experiment success rate
- Over 25 years developing platforms/concepts
  - Balloon: VAST, BEST-N
  - Sub-Orbital: SOAREX-N
  - Orbital: TES-N /NOW [Nano-Orbital Workshop]
  - Lunar/Mars exploration proposals

Key Innovations:

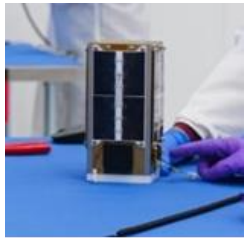
- Communication
  - Iridium for quick command and control
  - Custom Lunar and Mars SDR radios
- Exo-Brake
  - Exo-atmospheric braking device focused on targeted reentry
- Machine Learning
  - GPU and Neuromorphic processing test bed

Notable Missions:

- Active: TES-13 (3U)
- Upcoming: TES-11 (6U), TES-12 (3U), TES-14 (12U), TES-16 (12U)

Support: ARC, GRC, AFRL

TES-1: 1st off ISS



TES-7: In orbit

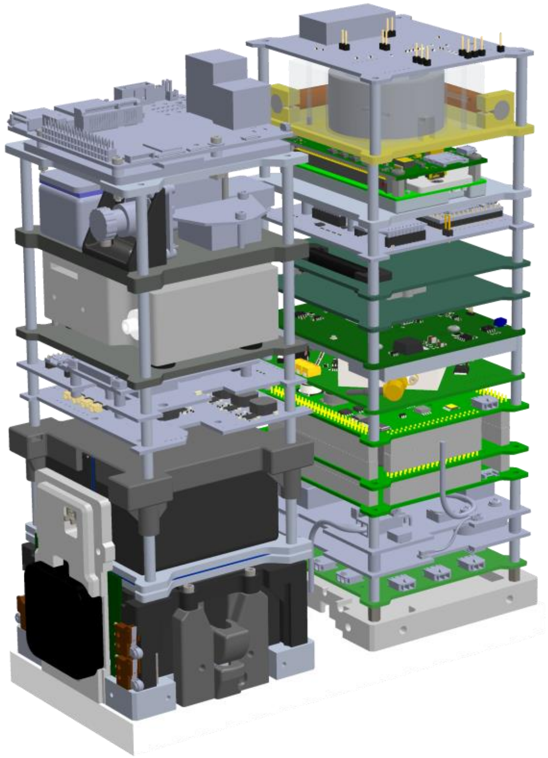
TES-10: Mission of the Year

Images courtesy of NASA

The BrainStack

Objective: Develop an orbital testbed for AI/ML processors and software

- An evolution of previous TES-n/NOW AI/ML experiments (GPUs, neuromorphic processors)
- Growing to a multi-element stack that incorporates various AI/ML experimental elements
- Initial emphasis on AI/ML plus sensor hardware accommodation and experiments
- Permit different software experiments on each layer of the stack
    - Spacecraft autonomy/prognostics
    - Radiation damage accommodation
    - Extension of EOL for the spacecraft
    - Celestial Navigation (Earth zenith pointing)
    - Earth surface object identification
    - Remote sensing optimization
    - Cognitive communication / autonomously scheduled data downlink



Initial BrainStack Flights: TES-8 and TES-10

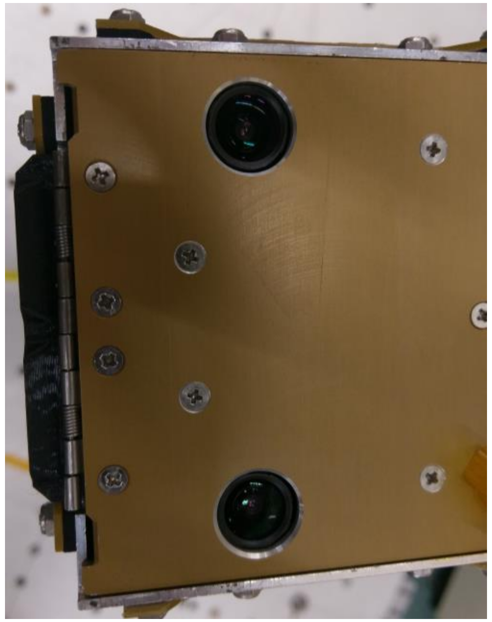
- TechEdSat-8 and TechEdSat-10 represented the first tests of an AI/ML payload for the program
- The payload selected was an NVIDIA Jetson TX2 connected to a stereoscopic camera system meant to record the ExoBrake ejection event from the ISS

TechEdSat-8
- Launched in 2019 from the ISS
- First flight of the NVIDIA Jetson TX2 Image processing payload
- First flight of our in-house developed S-Band Lunar Radio

TechEdSat-10
- Launched in 2020 from the ISS
- Re-flight of the NVIDIA Jetson TX2 Payload from TES-8

TechEdSat-8 Avionics Stack

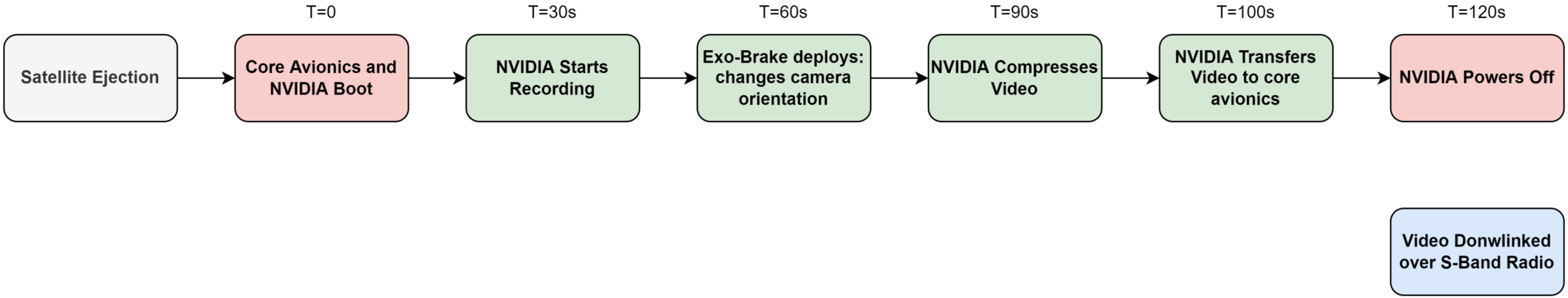
NVIDIA Jetson TX2 payload and Camera



Developed in conjunction with San Jose State University

TES-8 and TES-10 Results

TES-8 and TES-10 NVIDIA Concepts of Operations



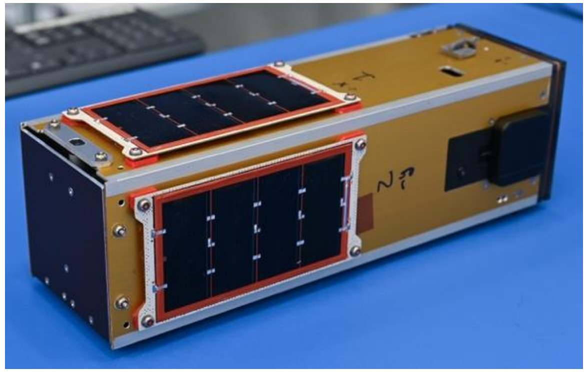
TES-8 and TES-10 Results

- Verification was received that the payload turned on, recorded the video, and transferred the video to the spacecraft’s Wi-Fi bus
- TES-10 recovered parts of the compressed video file through Iridium
- TES-8 and TES-10 played a key role is starting the development of interfaces needed to support an AI/ML processor

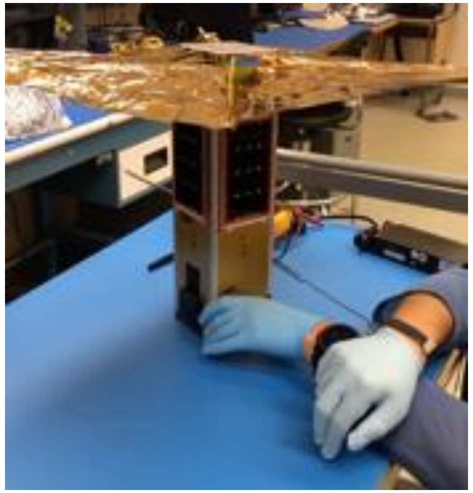
Neuromorphic BrainStack: TES-13

- Launched January 13, 2022
  - Virgin Orbit *Above the Clouds* mission
- Status:
  - Satellite is fully operational and has already achieved mission comprehensive success
- Experiments:
  - Updated Non-Targeting Exo-Brake design
  - Updated in-house S-Band lunar radio
  - Intel Loihi neuromorphic processor
- Objectives:
  - Establish the hardware, electrical, and software interfaces necessary to build an on-orbit neuromorphic platform
  - Run simple AI/ML applications that utilize the Intel Kapoho Bay

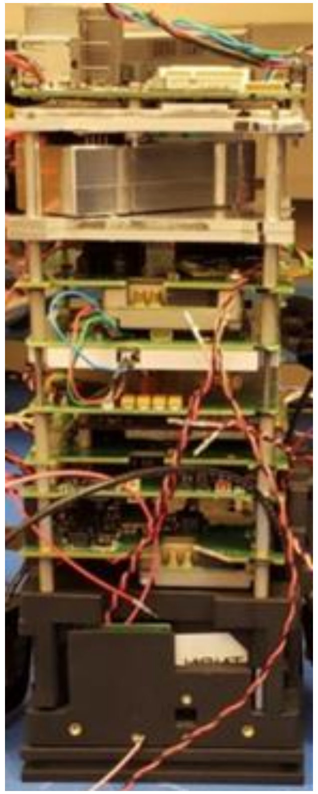
TechEdSat-13



Disposal Exo-Brake



TES-13 Avionics Stack



Images courtesy of NASA

Neuromorphic Processor: Intel Loihi

- Neuromorphic/Deep Neural Network (DNN) processors achieve 100x to 1000x power efficiency for AI and Machine Learning applications over CPUs, GPUs
  - Bringing higher performance learning to smaller spacecraft through high power efficiency
- Model biological brain processes on neuromorphic silicon

Processor: Intel Kapoho Bay

- Contains a Loihi neuromorphic chip modeled after the spiking behavior of neurons, characterized by very low power consumption and learning rules inspired by how the brain learns

Interest:

- Potential to greatly improve nano-satellite data processing while decreasing power consumption

Image courtesy of Intel, Inc.

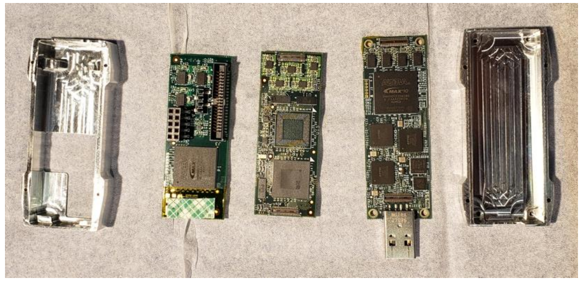
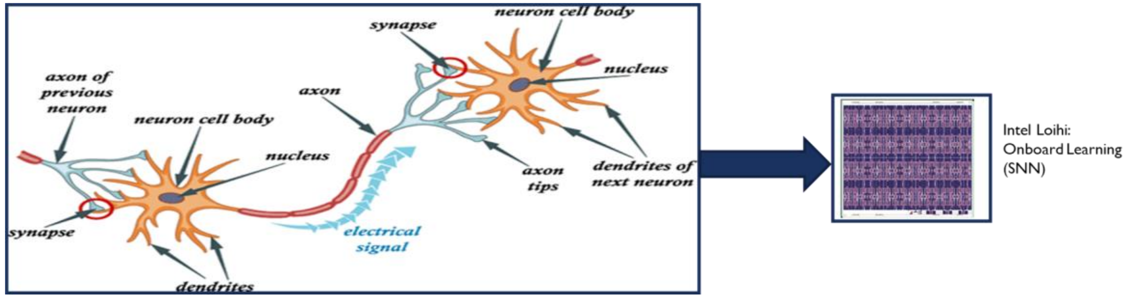


Image courtesy of NASA



Neuromorphic BrainStack Interface

Hardware Interface

Crayfish-AI *(Command and Data)*

- Interfaces TES with AI/ML payload and monitors payload health
- Dedicated Iridium for command and control of payload

Up^2 *(Payload flight computer)*

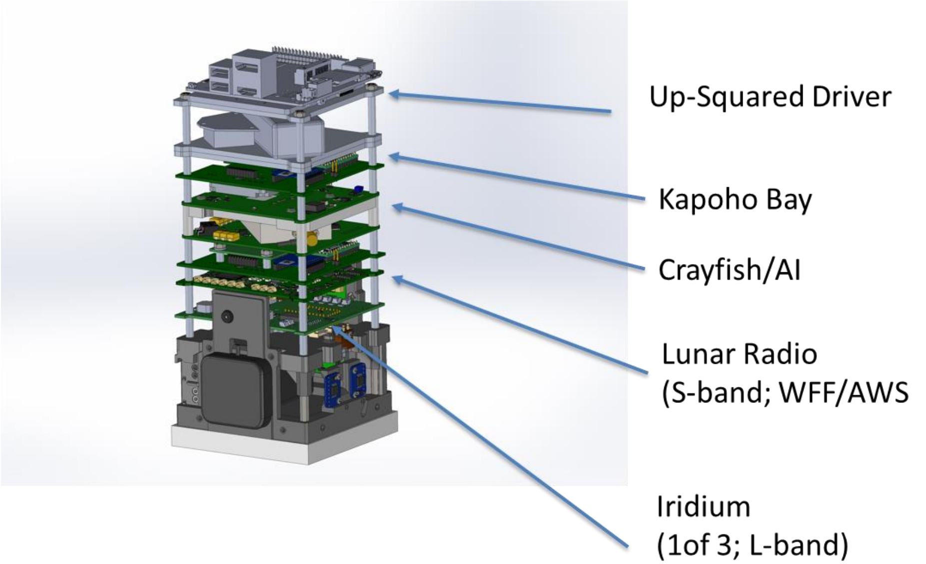
- Interfaces with the Kapoho Bay and manages the AI/ML applications

Intel Kapoho Bay *(Neuromorphic processor)*

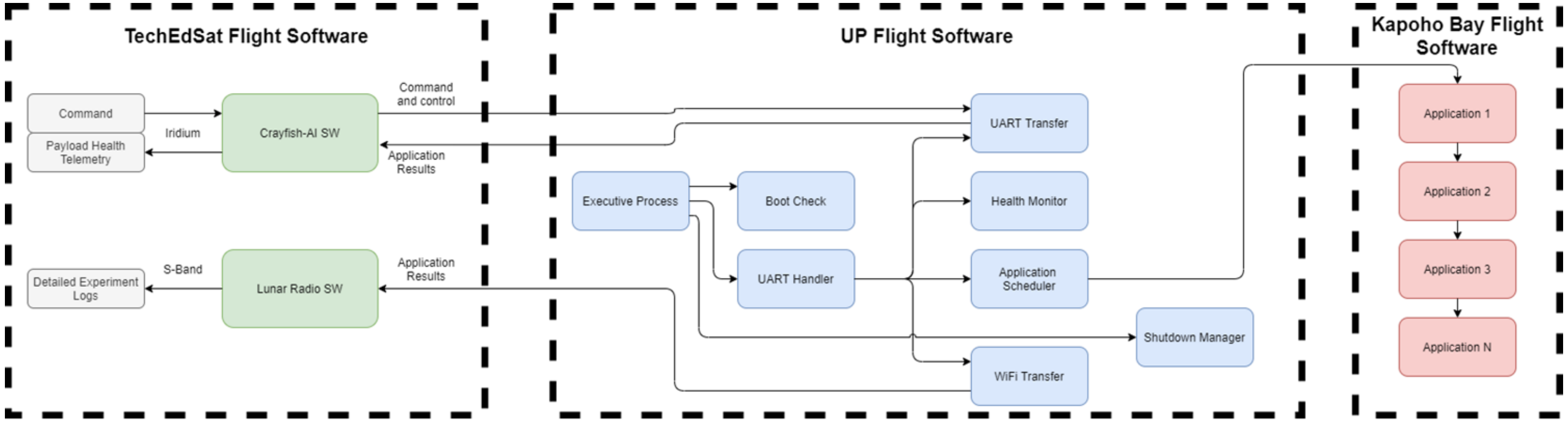
- Runs the AI/ML applications

Lunar S-Band Radio *(Data downlink)*

- Downlinks the complete AI/ML application result logs



Software Interface



Experiment Parameters:

- **Run Time**: total time to run AI/ML applications
- **UART Transfer Time**: transfer data time to Crayfish
- **WiFi Transfer Time**: transfer data time to Lunar Radio

Images courtesy of NASA

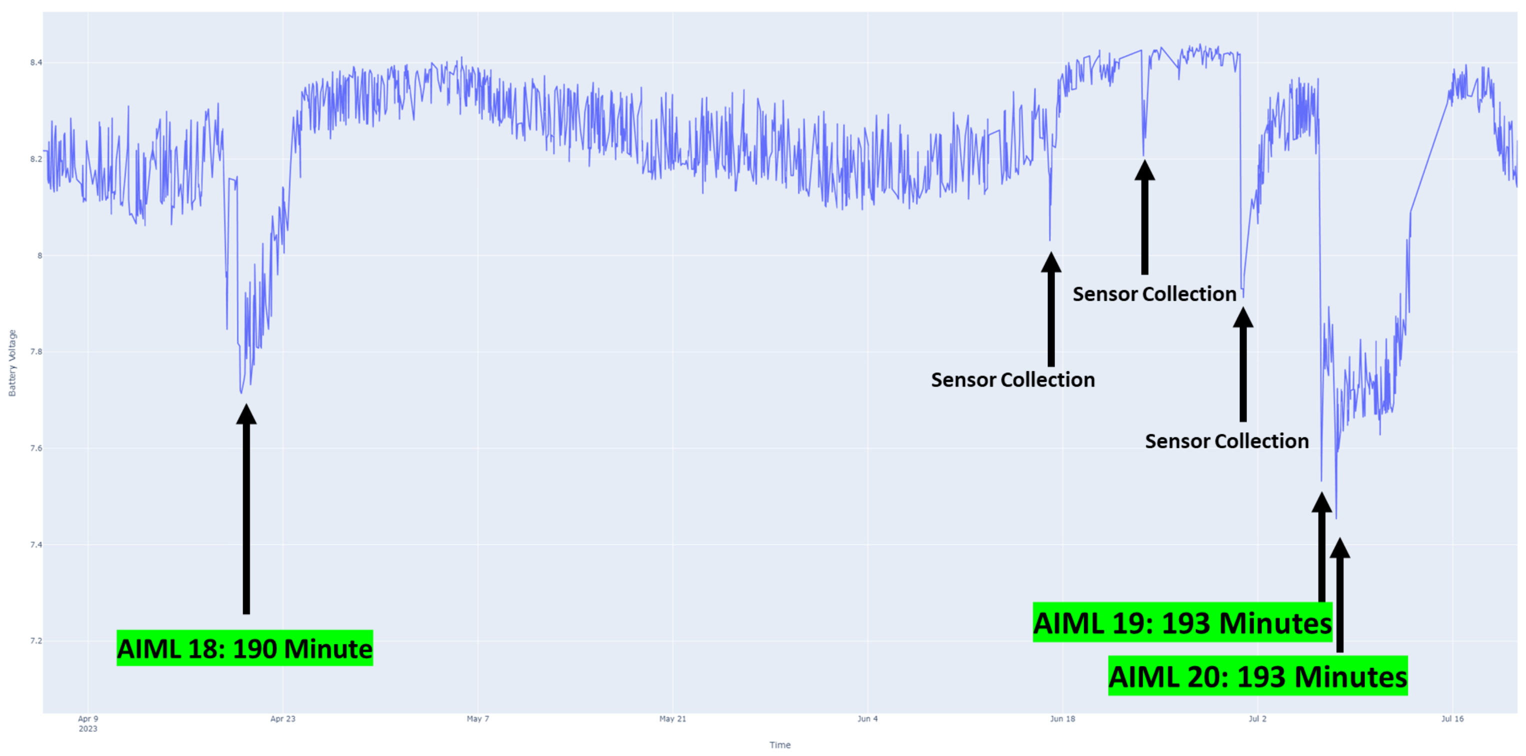
TechEdSat-13 Initial Results

Initial Experiment Runs

ID	Date	T_Sched	T_UART	T_WIFI	Tot Packets	Success Rate
1	1/14/2022	4	2	0	2	50%
2	1/14/2022	6	2	0	5	20%
3	1/16/2022	4	2	0	7	14%
4	1/17/2022	30	10	0	12	17%
5	1/18/2022	15	5	0	6	0%
6	1/19/2022	19	5	0	9	0%
7	1/21/2022	41	10	0	10	0%
8	1/24/2022	45	10	0	21	11%
9	1/25/2022	65	20	15	19	7%
10	1/30/2022	65	20	0	40	39%
11	2/7/2022	95	30	0	66	75%
12	2/10/2022	96	30	0	35	86%
13	2/12/2022	180	45	0	67	90%
14	2/22/2022	225	50	0	159	84%
15	3/4/2022	226	60	0	61	66%

Each application generates a status packet identifying if the application succeeded or failed
Success Rate: the number of successful application packets out of the total application packets received, disregarding any health packets

TechEdSat-13 Battery Voltage 4/1/23 – 7/20/23



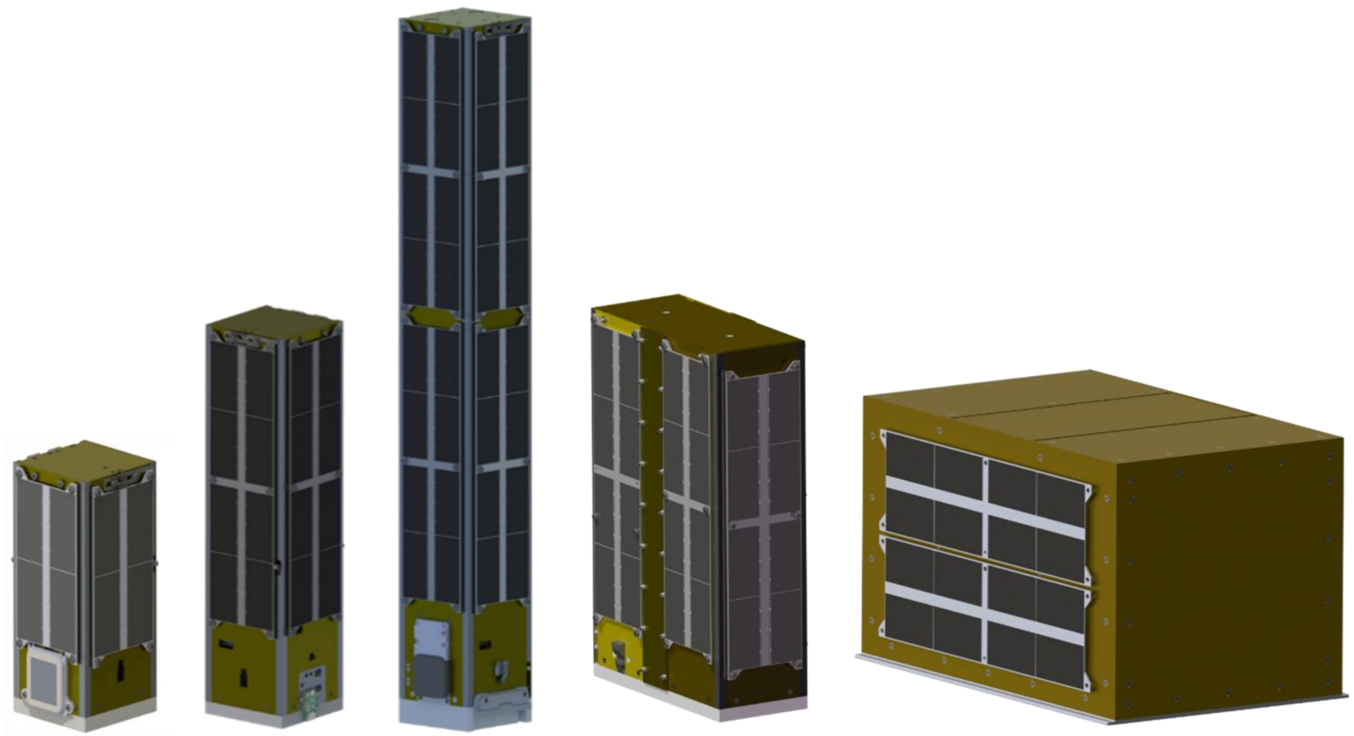
TechEdSat-13 and the AIML Payload are still healthy and operating nominally

Future BrainStack Options

AI/ML Architectures					
Processor	Developer	Dimensions	Power	Supported APIs	Comments
Tegra X2	NVIDIA	256-core NVIDIA Pascal™ GPU architecture with 256 NVIDIA CUDA cores	15W	TensorFlow (TF), CUDA	Flown on TES-8/10 Ready for TES-11 flight
Loihi 1 Kapoho Bay	Intel	128K neurons per chip in 2D mesh of 128 neural cores	<1.5W	NxSDK	TES-13 in orbit (first test flight) TES-12 in dev.
Loihi 2	Intel	1M+ neurons per chip in 3D mesh of 128 neural cores	<1W	LAVA	TES-17 in dev. Core capacity significantly higher than Loihi 1
Akida	Brainchip	1.2 million neurons, 256 nodes	<4W	TF, Keras, BrainChip MetaTF	Minimal CPU intervention needed, mini PCIe board with Brainchip
Movidius™ Myriad™ X Vision	Intel	16 SHAVE cores (916 billion operations per second)	1.5W TDP	Flic Hub SDK	14mm x 14mm x 0.84mm 105°C max & -40 °C min
Coral TPU	Google	85x56mm	2 TOPS/W	TFLite	Low power usage
Apple A16 Bionic	Apple	16 Apple neuron Engine cores	17 TOPS 8W TDP	Swift	iPhone GPU, not tested for flight, very small size
HPSC	NASA	8x X280 at 4.6TOPS/c 4x TBD RISC-V cores	7W	TFLite, ROS	Scalability: less than 1W or up to 10 cores 2025 delivery

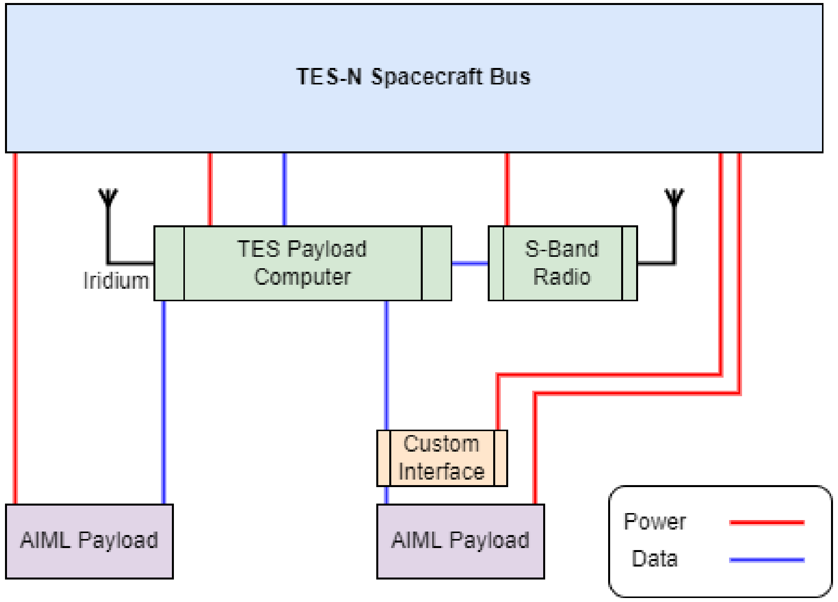
Future BrainStack Architecture: Hardware

Exo-Shell Options



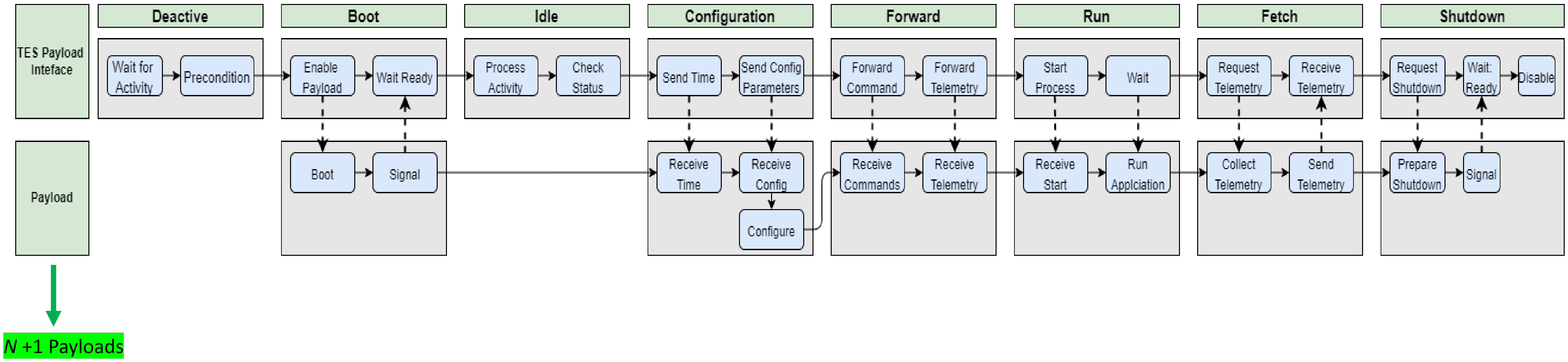
Representative TechEdSat configurations available. From left to right: 2U, 3U, 6U, 6U, and 12U

Electrical Interface



- Each AIML Payload will connect to the TES payload computer to interface with the TES Avionics Bus
  - If a direction connection cannot be made a custom interface board will be developed
- General Payload health will be transferred through iridium while full results will be transferred through the S-Band radio

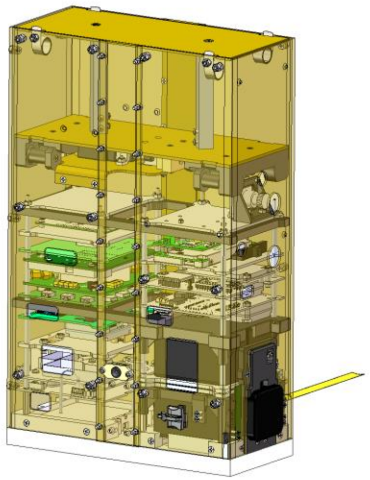
Future BrainStack Architecture: Software



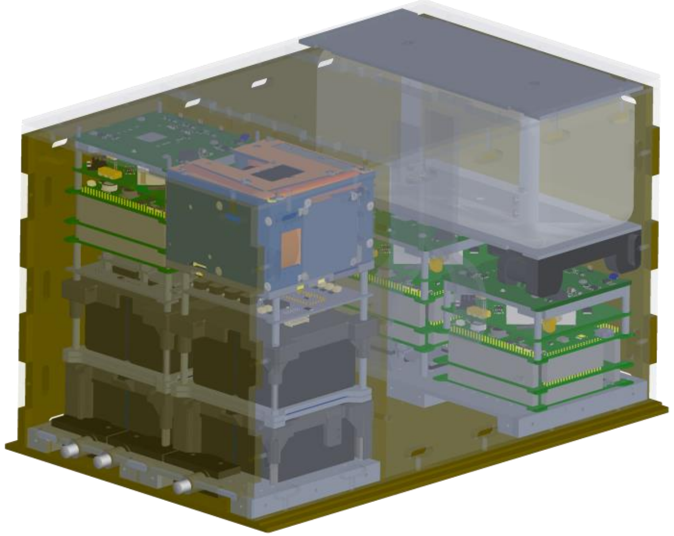
- An updated software interface has been developed based on the initial TES-13 Interface
- Each AIML Payload can expect to go through eight phases that are controlled by the TES interface computer
- The Configuration phase allows the payload to be configured before an experiment to control which applications can run
- The new Forward phase allows the passing of spacecraft sensors and telemetry data to the AIML processor for integration in potential applications

BrainStack 2.0: TES-11, TES-16, and Beyond

TechEdSat-11
- 6U satellite Scheduled for 2024
- BrainStack Payload: NVIDIA Jetson TX2 running an image interference algorithm



TechEdSat-16
- 12U satellite Scheduled for 2024
- BrainStack Payload:
  - Intel Loihi – Applications running learning using spacecraft engineering and sensor data
  - Nvidia TX2 – Image detection applications



TechEdSat-N
- Proposed satellite Scheduled for 2025
- BrainStack Payload: Intel Kapoho Point

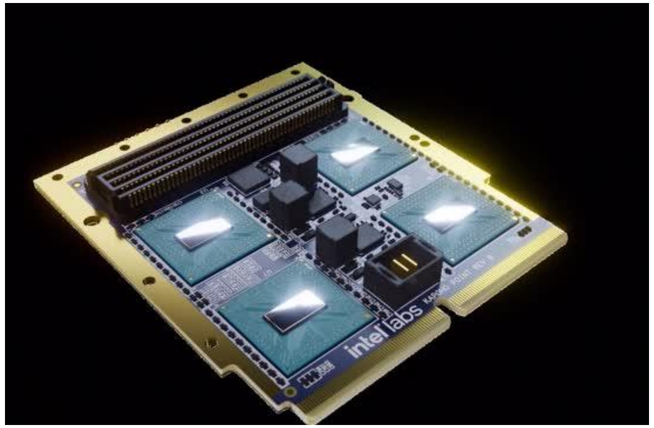


Image courtesy Intel Corp.

Software provided by NASA Ames, NASA Goddard, Exploration Institute, and University of Dayton, and other future collaborators

Summary

1. TES-n/NOW is developing payloads advancing various pertinent nano-sat subsystems. These include:
   - AI/ML (BrainStack)
   - Advanced COM
   - Innovative power systems (150-300W-hr)
   - Cryocooler/optic systems
   - De-orbit devices (Exo-brake)

2. BrainStack provides a versatile orbital laboratory (including mechanical, electrical, and software interfaces) for testing both software and processor payloads

3. Initial flight of Nvidia Jetson TX2 GPU and the Intel Loihi Neuromorphic processor have been tested and recovered valuable flight data

4. Future flights will include some of the processors discussed in the table (e.g. Kapoho Point) permitting a variety of different software ecosystems and applications – with a variety of collaborative teams

Outline

- TechEdSat Program Overview
- BrainStack Overview
- Proto BrainStack: TechEdSat-8 and TechEdSat-10
- Neuromorphic BrainStack: TechEdSat-13
- Future BrainStack flights
  - TechedSat-11, TechEdSat-16, TechEdSat-N
  - Updated BrainStack Interfaces
  - Potential BrainStack candidates
- Summary and Conclusion