TechEdSat-13: The First Flight of a Neuromorphic Processor

CubeSat Developers Workshop

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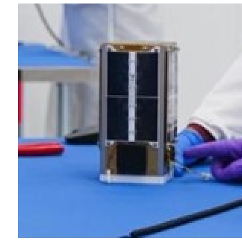
TechEdSat-N / Nano Orbital Workshop

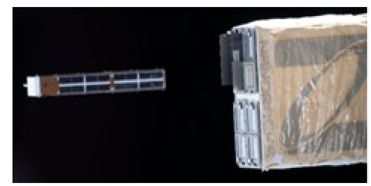
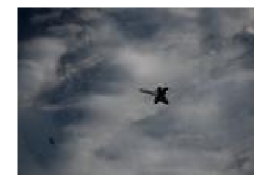
Who we are:
- Innovative flight project focused on rapid design and innovation
  - 2-3 flights a year
  - Low cost, ISS standards
  - 90% experiment success rate
- Over 25 years developing platforms/concepts
  - Balloon: VAST, BEST-N
  - Sub-Orbital: SOAREX-N
  - Orbital: TES-N /NOW [Nano-Orbital Workshop]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

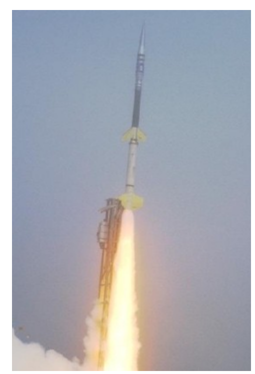
Key Innovations:
- Communication
  - Iridium for quick command and control
  - Custom Lunar and Mars SDR radios
- Exo-Brake
  - Exo-atmospheric braking device focused on targeted reentry
- Machine Learning
  - GPU and Neuromorphic processing test bed

Notable Missions:
- Active: TES-7 (2U), TES-13 (3U)
- Upcoming: TES-11 (6U), TES-12 (3U), TES-14 (12U)


TES-1: 1st off ISS


TES-7: In orbit



TES-10: Mission of Year, targeted de-orbit


SOAREX-7


MARVIN Cubesat Rover

Support: ARC, STMD/SSTP, GRC, AFRL

TechEdSat-13

Launched January 13, 2022

- Virgin Orbit Above the cloud mission

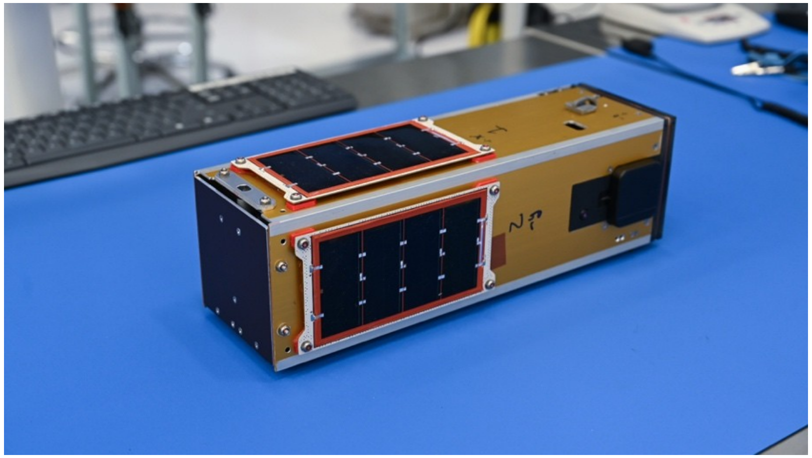
Status:

- Satellite is fully operational and has already achieved mission comprehensive success

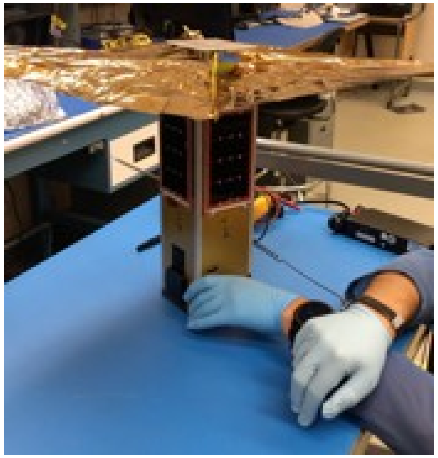
Experiments:

- Updated Non-Targeting Exo-Brake design
- Updated custom S-Band lunar radio
- Intel Loihi neuromorphic processor

Developed, tested, and integrated in 12 weeks



Virgin Orbit



Non-Targeting Exo-Brake

First AI/ML Neuromorphic Test

Interest:

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

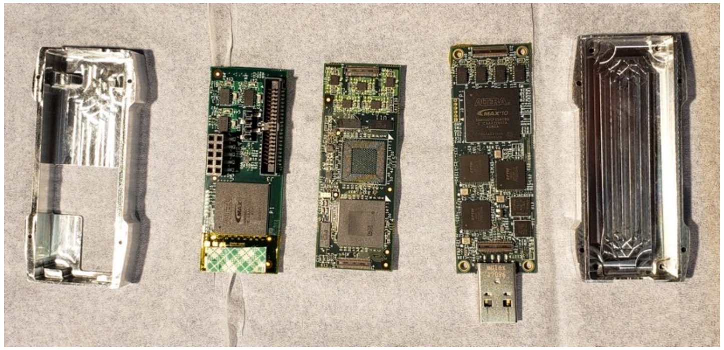
Processor: Intel Kapoho Bay

- 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

TES-13 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

Intel



Developing an AI/ML Payload

Crayfish-AI *(Command and data)*

- Interfaces TES with AI/ML payload
- Dedicated Iridium for command and control of payload, and downlinks a *short summary* of application results
- Memory to store payload data
- Temperature, IMU, Magnetometer sensors to monitor payload health

Up Squared *(Payload flight computer)*

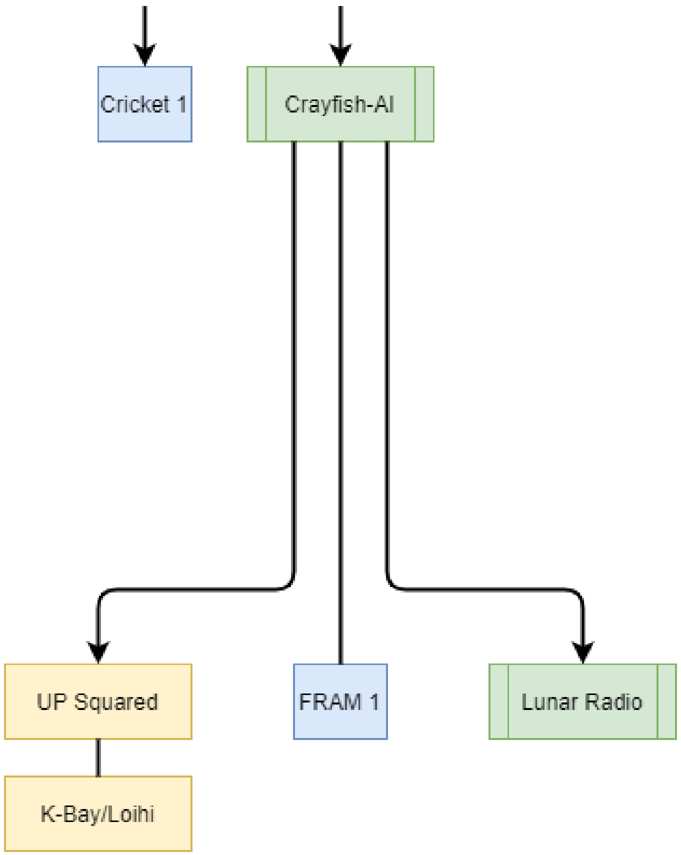
- Interfaces with the Kapoho
- Manages the AI/ML applications runs and post processes any data

Intel Kapoho Bay *(Payload processer)*

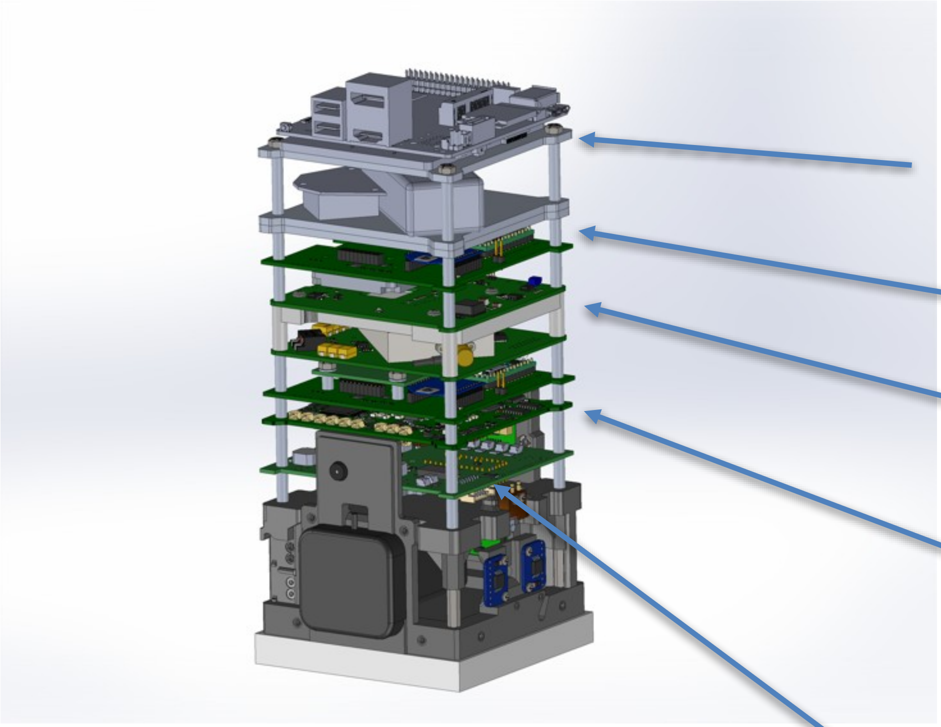
- Runs the AI/ML Applications

Lunar S-Band Radio *(Data downlink)*

- Downlinks the *fully detailed* AI/ML application result logs



Hardware and Avionics Interface



Up-Squared Driver

Kapoho Bay

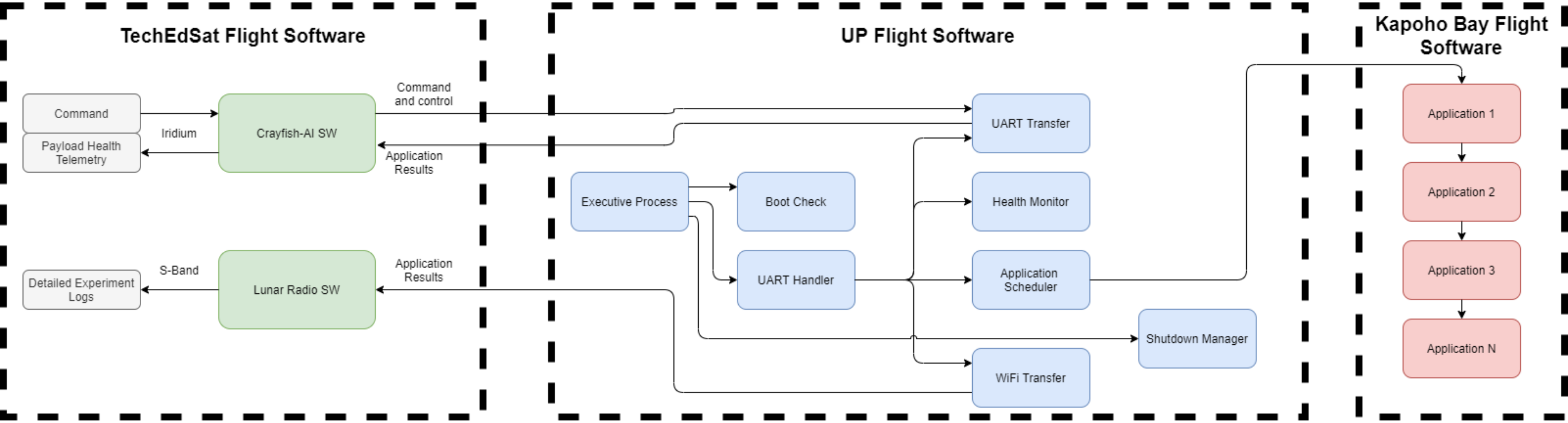
Crayfish/AI

Lunar Radio
(S-band; WFF/AWS

Iridium
(1of 3; L-band)

(S. Zuniga)

Software Interface



(E. Barszcz et. al)

Crayfish-AI interfaces with the Up board over a UART connection
Lunar Radio interfaces the Up board over a local WiFi connection

Experiment Parameters:

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

Software Environment

Up Board and Kapoho Bay

- OS: Linux (Ubuntu 18.04)
- Two virtual environments
  - One for running AI/ML applications
  - One for monitoring the power
- Three programming languages and about 11K lines of code (Including comments and white space)
  - Shell Script, C, Python

(E. Barszcz et. al)

Crayfish-AI

- Environment: Arduino
- Two programming languages and about 1K lines of code
  - C/C++

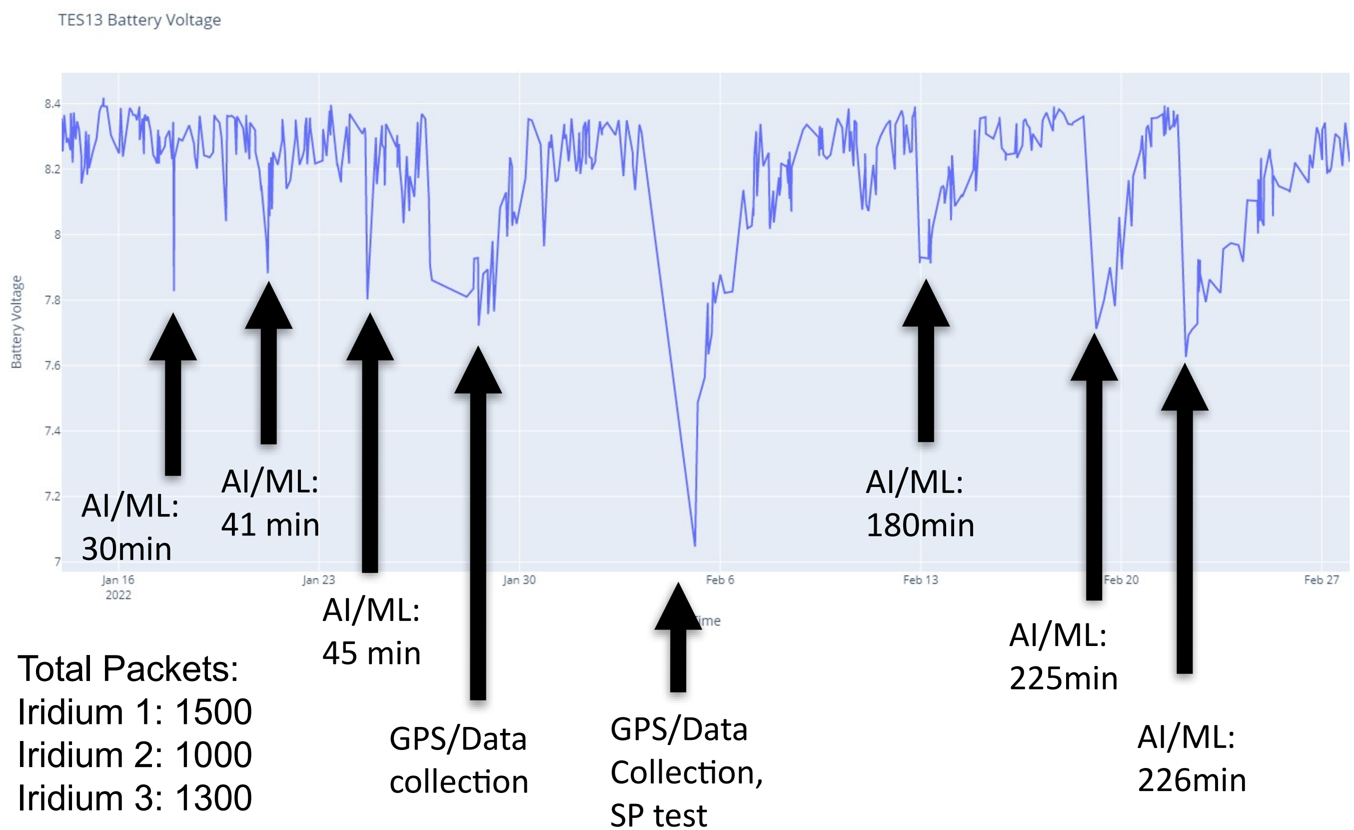
AI/ML Applications

ID	Processor	Execution Time	Description
A	Kapoho Bay	5.22 Minutes	Y but on Kapoho Bay
B	Kapoho Bay	.5 Minutes	Cognitive radio online learning
C	Kapoho Bay	.6 Minutes	Cognitive radio on simulated data
O	Kapoho Bay	13.8 Minutes	Online learning on spacecraft anomaly data
T	Kapoho Bay	0.5-4 Minutes	Online learning with spacecraft health
W	UP	0.5-4 Minutes	Validates any data generated with T
X	Up	1.56 Minutes	Y but without SNN
Y	Up	4.8 Minutes	Simulated SNN on a CPU
Z	Kapoho Bay	.9 Minutes	SNN anomaly detection on test spacecraft data

(M. Mercury et. al)

SNN – Spiking Neural Network

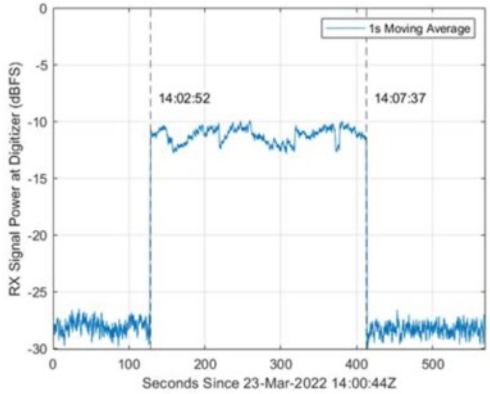
Initial Results: Spacecraft Health



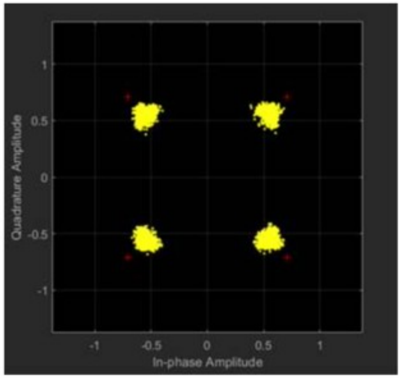
Successfully run the AI/ML experiment for 225 minutes or ~2.5 Orbits

Initial Results: Lunar Radio Downlink

TES-13 data received through AWS connection.



(A. Gannon et. al)



(C. Priscal)

- **Successful Phase1 OPS**
  - Analyzing data to extract key radio/link parameters including S/N, data rate
  - Demodulation and data transfer protocol being developed
  - Passes limited to 50MB. (data per pass dependent on derived data rate; 1-1.2 Mbs; 400Mb requires 330-400s)
  - Commercial S-band data downlink experiment through Amazon Web Services (AWS) Ground Station
  - One 5-minute pass has downlinked 51MB of data
- **Operation plan for next few passes**
  - Evaluate current data set
  - Commence production experimental runs (a 2.5 orbit/225 min run/Extended Run will generate about 5MB of data)

Initial Results: Application statistics

ID	Date	T_Sched	T_UART	T_WIFI	Tot Packets	Num H	Num A	Num B	Num C	Num O	Num T	Num W	Num X	Num Y	Num Z	Success Rate
1	1/14/2022	4	2	0	2	-	-	-	-	-	-	-	1	-	-	50%
2	1/14/2022	6	2	0	5	-	-	-	-	-	-	-	1	-	-	20%
3	1/16/2022	4	2	0	7	-	-	-	-	-	-	-	1	-	-	14%
4	1/17/2022	30	10	0	12	-	-	-	-	-	-	-	1	1	-	17%
5	1/18/2022	15	5	0	6	1	-	-	-	-	-	-	-	-	-	0%
6	1/19/2022	19	5	0	9	2	-	-	-	-	-	-	-	-	-	0%
7	1/21/2022	41	10	0	10	3	-	-	-	-	-	-	-	-	-	0%
8	1/24/2022	45	10	0	21	3	-	1	1	-	-	-	-	-	-	11%
9	1/25/2022	65	20	15	19	5	-		1	-	-	-	-	-		7%
10	1/30/2022	65	20	0	40	4	1	5	2	-	2	2	-	-	2	39%
11	2/7/2022	95	30	0	66	7	2	6	4	-	13	13	-	-	6	75%
12	2/10/2022	96	30	0	35	-	3	6	5	-	-	-	6	4	6	86%
13	2/12/2022	180	45	0	67	-	5	12	9	5	-	-	10	8	11	90%
14	2/22/2022	225	50	0	159	15	4	18	17	-	34	34	-	-	14	84%
15	3/4/2022	226	60	0	61	-	5	5	5	2	-	-	9	8	6	66%

(E. Barszcz et. al)

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

Next Steps

Summary:

- TES-13 **may represent the first AI/ML flight test** of the Intel Loihi neuromorphic processor
- All AI/ML applications have successfully executed on the Kapoho Bay, including online machine learning using SNN
- TES-13 will operate on orbit for the next few years and the team will continue to conduct AI/ML experiments to better characterize the hardware
- Advances in computing represented by AI/ML neuromorphic processors is a harbinger of the future applications and makes it very suitable for power constrained systems.
- Experiment verified TES-13's compatibility with AWS which will be leveraged for future experiments (Cognitive Communications; UIS/User Initiated Service)

Observations:

- First generation Kapoho chip takes time to warm up and operate successfully
  - Starting experiment temperature is around -5 deg C
- Future versions of the software should incorporate timekeeping and better use of command scheduling

Future Flights:

- TES-11 (Late Summer 2022), and TES-12 (Early 2023) will fly the next version of this experiment
  - Includes several software and electrical improvements
    - Improved TES Interface board and next generation Intel Kapoho Bay module
    - Cognitive Communications – fully automated User Initiated Service (UIS) with two commercial providers (AWS and Iridium), this allows a spacecraft to schedule on-demand communications services with a ground station or space relay.

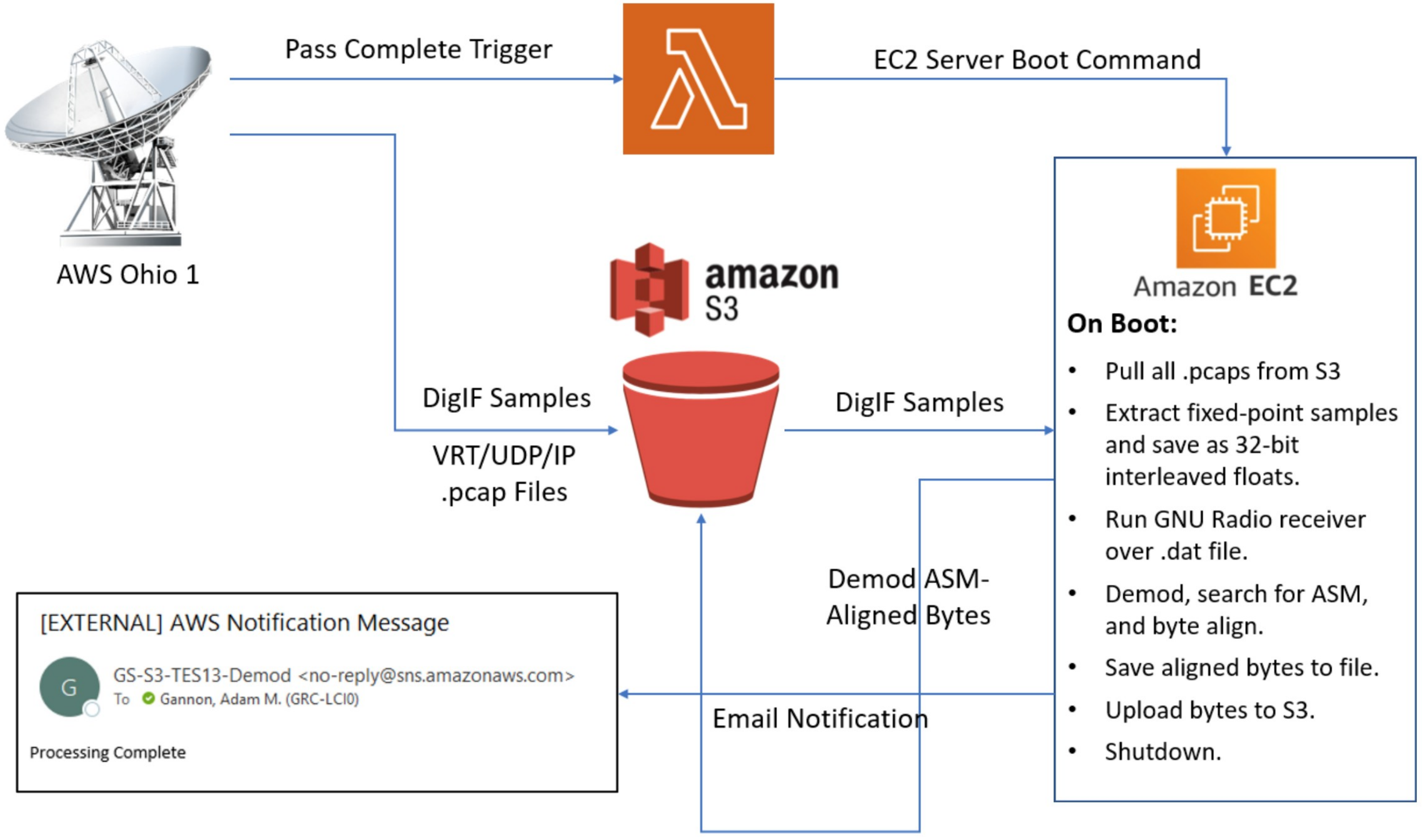
Thank You!

Marcus Murbach, , Alejandro Salas

Add team masked members!

Back-Up Slides

AWS Processing Flow



Abstract

Neuromorphic processors, inspired by the wiring of the brain, permit certain classes of Artificial Intelligence/Machine Learning (AI/ML) algorithms to run far more efficiently. Ultimately, such systems will make the small- and nano-satellite platforms even more useful in terms of greatly improved power, communication and internal data management. In addition, on-board processing of images and data will help to not only rapidly interpret the information, but also reduce the amount of data that needs to be transmitted to ground stations. This initial flight experiment uses the Intel/ Loihi processor combined with a custom interface board and three communication channels to run the AI/ML scripts. These will vary with increasing length and complexity during the course of the mission. The algorithms will use the (at first) limited sensor data to 'learn' - with comparisons to similar architecture in comparable ground experiments. Some of the applications for successor flights in the TES-n flight series include Cognitive Communications, whereby the overall communication system is optimized per overflight – by optimizing timing and data transmission functions. Lastly, the performance of the Loihi 14nm process technology will be monitored for performance in the LEO radiation environment, thus looking for induced hardware and software errors. This information will help guide future radiation protection techniques to extend the lifetime and overall utility. The TES-13 is a 3U nanosat successfully launched by the Virgin Orbit Launcher-1 on January 13, 2022, and will presage more flights and AI/ML applications to come.

TES10, TES7, TES11, TES13, TES-n
[Nano-Orbital Workshop: NOW!]

Objectives

- I. Advanced 'open' flight development platform with facile interfaces (NOW).
- II. Accurate Drag-based de-orbit (Exo-Brake modulation targeting) and subsequent EDL experiments; **Disposal Exo-brake**
- III. Advanced COM/Avionics/GPU platform (Lunar/ Mars radios),
- IV. Training platform for Next Gen NASA/Industry.
- Technology Need:
  - Open flight development platform to easily include 'Experiment/Sensor/Sub-systems for NASA, SSTP, and Gov/academic partners ['Umbrella' SAA in place]
  - Unique targeted de-orbit (safe/non-propulsive) for sample return, EDL material/concept testing.
  - Advanced COM/Avionics permits NEN-compatible COM architecture, Iridium/Globalstar test, large on-board processing/compression (NVIDIA/TX2 with 200:1 compression (Virtual Reality exp; AI in the sky/ML proposal). 150W-hr power system) - highest of NASA nano-sats
  - Education Outreach through university participation, internships, critical young-career dev.

Significant Accomplishments

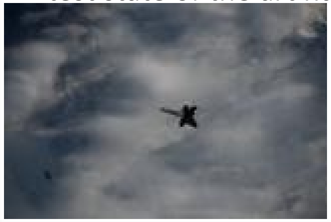
- **TES-10** achieved **comprehensive success**: Series of successful NOAA transmissions, PhoneSat successfully took a picture. **March 15, 2021 End of mission SMALLSAT MISSION OF THE YEAR**
- **TES-7**: COMP Success; **VO 1-17, 2021 – OPS Extended**
- **TES-11**: CDR, in-development; ILC Sept 22, 2022
- **TES-13**: **COMP Success – OPS Extended**
- **TES-12**: In-development; MMO 28Bravo Mission Dec, 2022

Upcoming Major Activities

- **TES-15**: Firefly Launch - Mid May, 2022

Approach

- Leverage the TechEdSat team to deliver satellites in a cost effective rapid manufacture approached
- Utilized the expertise of senior Engineers and PIs to develop and test state of the art hardware and race TRLs .



Project Incremental Flights (In Current Flight Order; Approved Slots)

TES10: July 15 [6U] ; CAL-Sat. [VO BALLAST OPPORTUNITY TES9 WAS 'LOST']
NVIDIA GPU; Lunar Radio/NEN-radio compatible at 5Mbs; Mars radio/NOAA; Internal wifi **COMP SUCCESS**
July 13, 2020 deployment from ISS; OPS under way;

TES7: January 17, 2021 [2U; CSLI Virgin Orbit; 500km 45° orbit]. **In Orbit!**
FIRST 'disposal' Exo-Brake' from 500km; possible debris soln; high alt Iridium test; laser diode test
Launch from Virgin Orbit (First payload flight on VO);

TES11: June 15, 2021 –[6U-W; CSLI L9EFS 500km Polar]. **ILC Sept 22, 2022**
NOAA/Mars Radio-3; NVIDIA GPU; AFOSR COM test; Adv COM experiment/DVBS-2; Encrypt
Constant-Q propulsion; X-band radio proposal

TES-13: Jan 13, 2022 launch [3U on AFRL VOX flight] AI/ML Success
Advanced COM/ML (GRC); adv exo-brake; Autonomous guidance experiment

TES-15: May X, 2022 [Firefly Vberg; 200°/300km circ]
Advanced COM/ML (GRC); HOT exo-brake; Autonomous guidance experiment-2