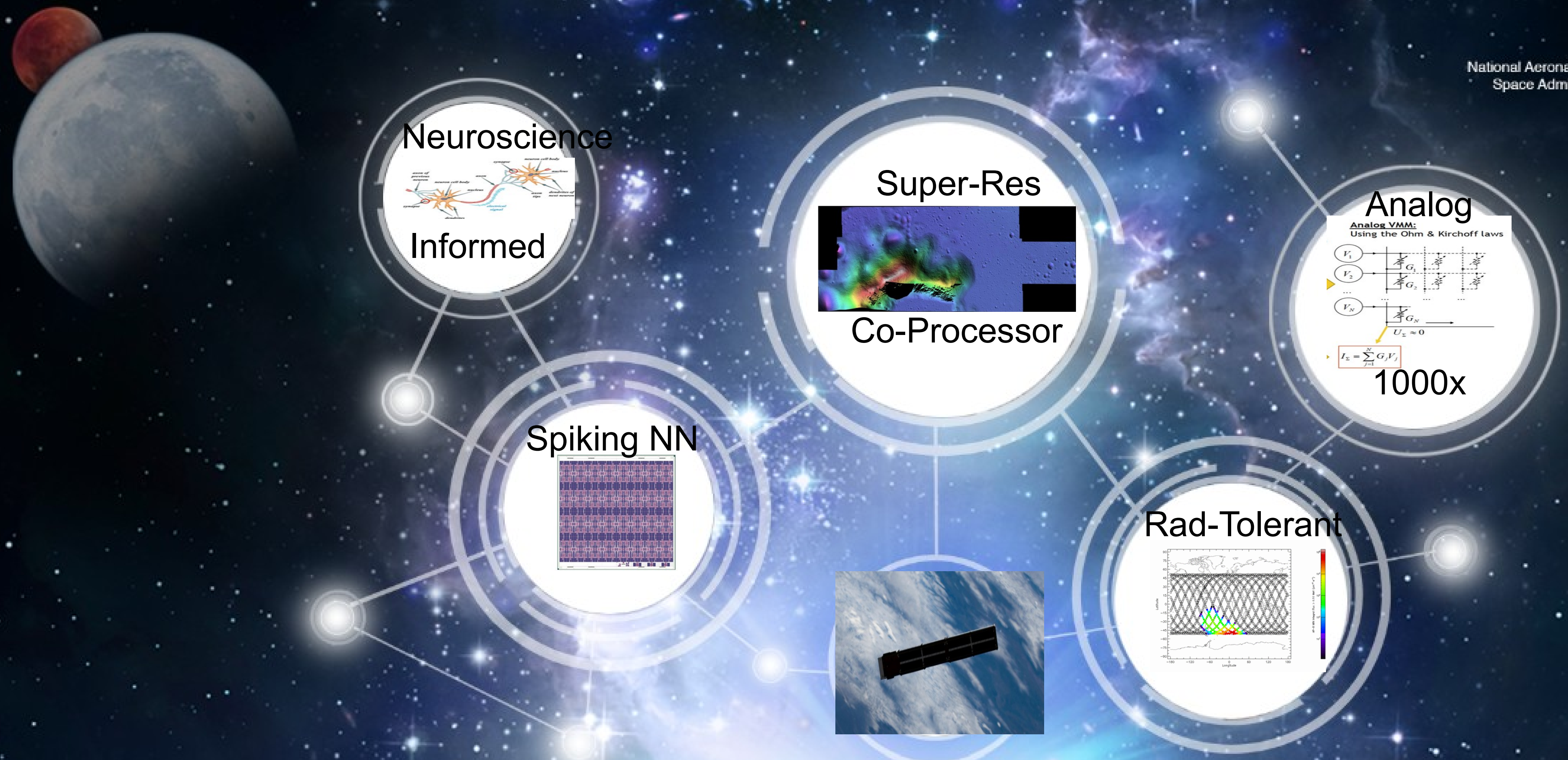
National Aeronautics and Space Administration



Space Technology Mission Directorate

Game Changing Development Program

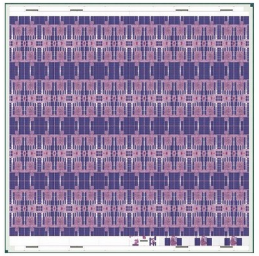
Dr. Michael Lowry| Dr. Eric Barszcz, Richard Alena | FY21 RadNeuro Annual Review Presentation

RadNeuro Overview

- **Technology Product Capability:** Radiation-Tolerant Neuromorphic Processor Project offers ***Power Efficiency and Radiation Tolerance*** for Artificial Intelligence and Machine Learning space capabilities – both as a co-processor and standalone. Neuromorphic maps neuroscience onto silicon to achieve Teraops (trillions per second) throughput with 100x to 1000x more power efficiency than general purpose CPUs.

- **Technical Capabilities**
  - Radiation Tolerance: Leveraging processor advances in terrestrial neuromorphic computing to space radiation tolerance through new device technology, redundancy management, new system architectures, and system software.
  - Technology maturation for space missions through experiments and demonstrations in increasingly relevant environments.

- **Exploration & Science Applicability**
  - The technology targets high-throughput and critical in-situ computing.
  - Fast traverse autonomous roving, lunar and planetary.
  - Perceptual processing for extreme access
  - Anomaly detection, FDIR, spacecraft health
  - Cognitive Radio
  - In-situ adaptation and science.
  - Sentient small spacecraft

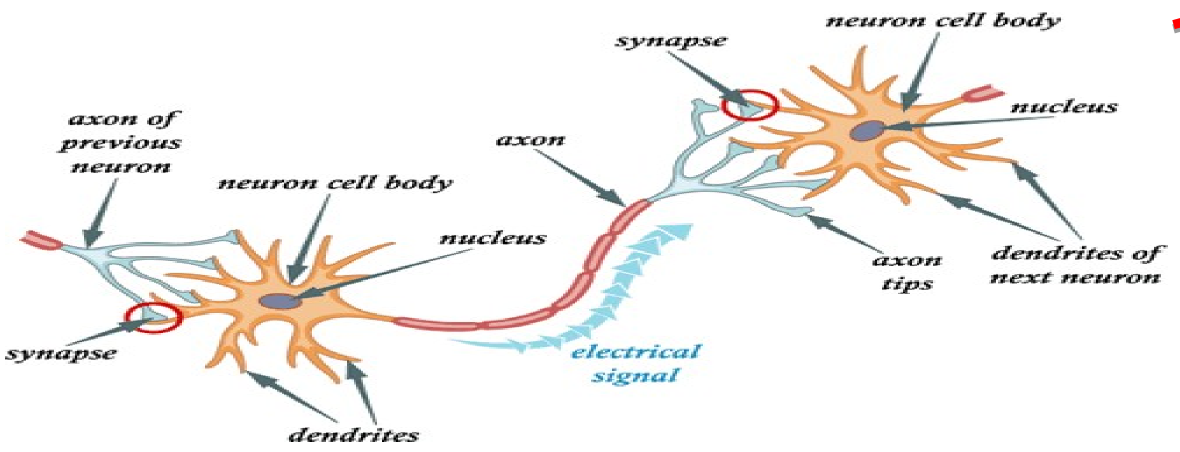


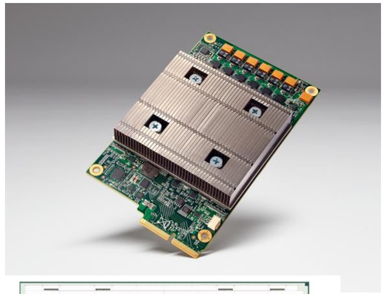
Top picture is an innovative analog neuromorphic chip from partner Mentium with extreme power efficiency. GCD is funding radiation hardening. The middle picture is a Tech Ed Sat nanosat mission. Tes13 passed environmental testing August 2021. Intel Loihi, bottom, is targeted to be first neuromorphic processor in space, launch early FY22.

Why Rad-Tolerant Neuromorphic?

- Neuromorphic processors have outstanding ***Power Efficiency (100x to 1,000x throughput per watt compared to a CPU)*** for Artificial Intelligence and Machine Learning applications. Radiation tolerance brings these capabilities to space missions. Rad-tolerant neuromorphic processors, both as a co-processor to a CPU and standalone processor for smart instruments and nanosats, will bring high-throughput and critical in-situ computing for capabilities ranging from fast traverse autonomous rovers to precision extreme access to in-situ adaptation and science.

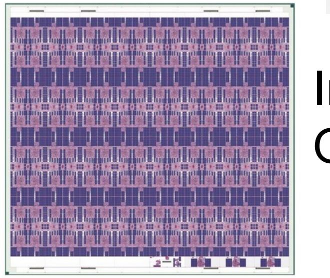
Neuromorphic: Map NeuroScience onto Silicon
Human Brain: Exascale+ processing @ 20 watts
(86 Billion Neurons, 150 Trillion Synapses)





Google Tensorflow Processing Unit
83x CPU ops/watt

Digital Systolic Array



Intel Loihi:
Onboard Learning

Mesh Network

Analog

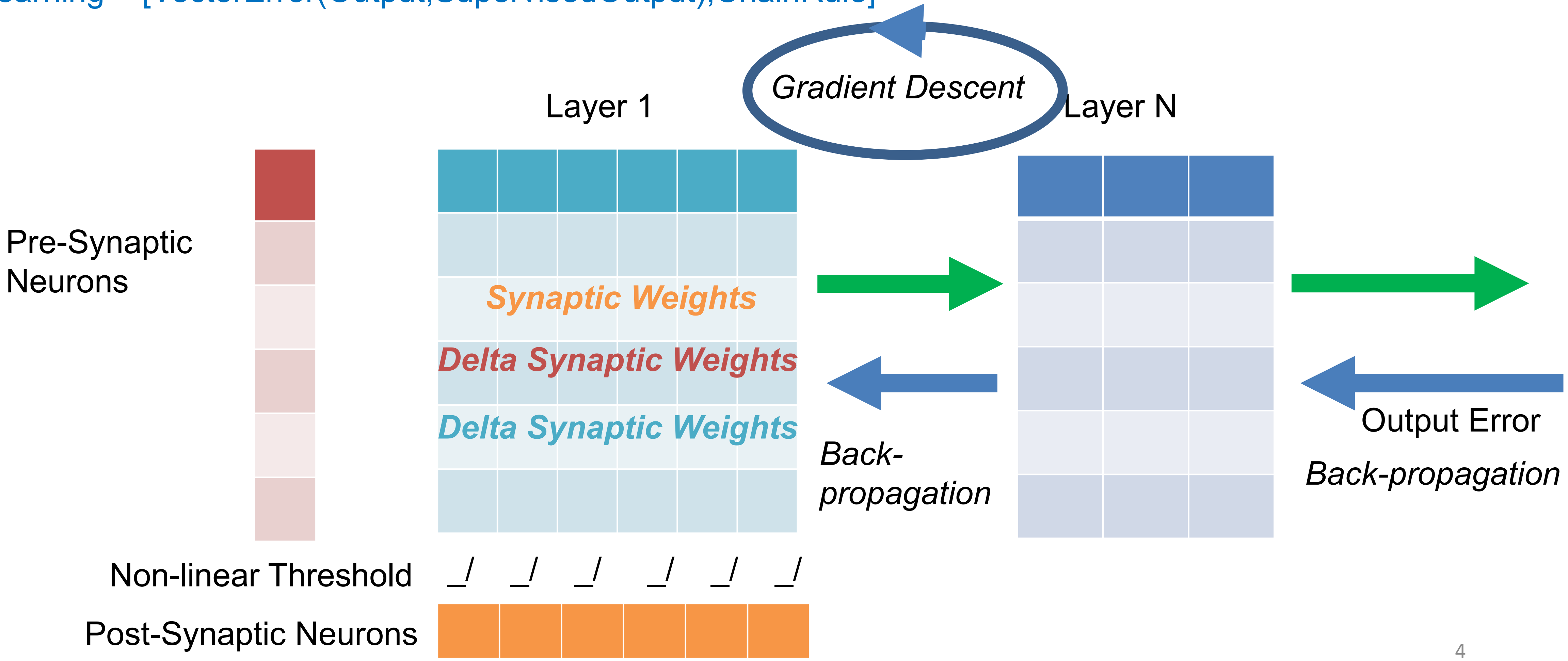
Mentium San Migual :Mixed Analog/Digital
10x Digital Efficiency *Analog Systolic Array*

Neuromorphic Vector Operations

Deep Inference = [RELU(DotProduct(,))] *

Hebbian Learning = TensorProduct(Pre,Post)

Deep Learning = [VectorError(Output,SupervisedOutput);ChainRule]*



Mission Infusion & Partnerships

NASA Centers
- Ames
- JPL
- Goddard (NEPP)
- Glen (Cognitive Radio)

Public/Private Partnerships
- Intel Corporation Loihi Space Act Agreement

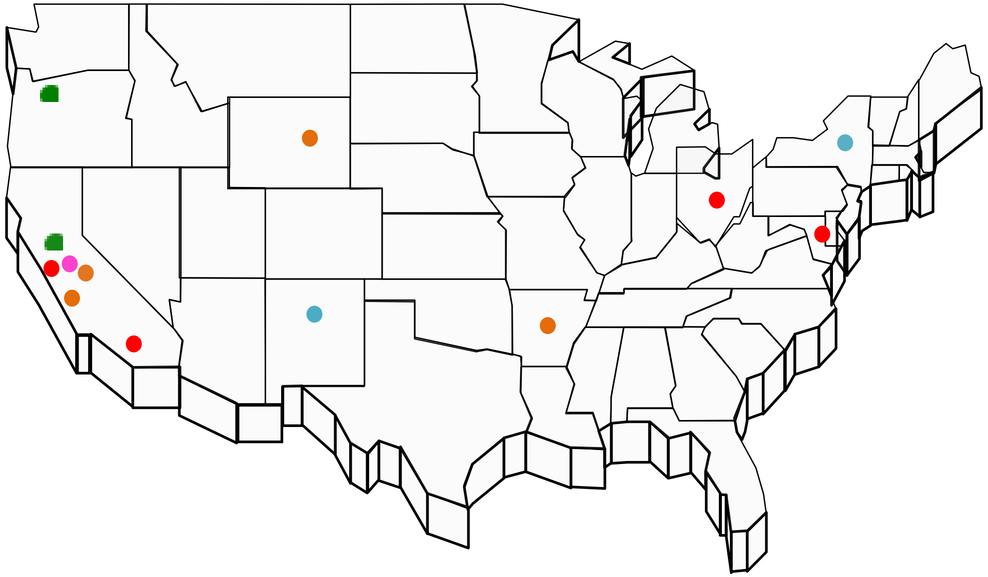
OGA Leveraging
- AFRL

SBIR/STTR
- Mentium
- Exploration Institute
- Nanomatronix
- Numem

NASA Programs
- SSTP Small Spacecraft Technology Program

Mission Infusion

- SSTP PACE4 mission with prototype rad-tolerant Neuromorphic processor(s)
- First-gen processors available for pacing missions with radiation tolerance.
- Radiation tolerant technology for Neuro conveyed to avionics community.
- Phase 2 proposal to GCD for full-scale Neuro
  - Solicit partners, downselect
  - Design, develop, verify, deploy



Collaborative multidisciplinary partnerships to leverage fiscal resources, ideas, knowledge & expertise.

RadNeuro Phase 1
Technology Goals & Project Objectives

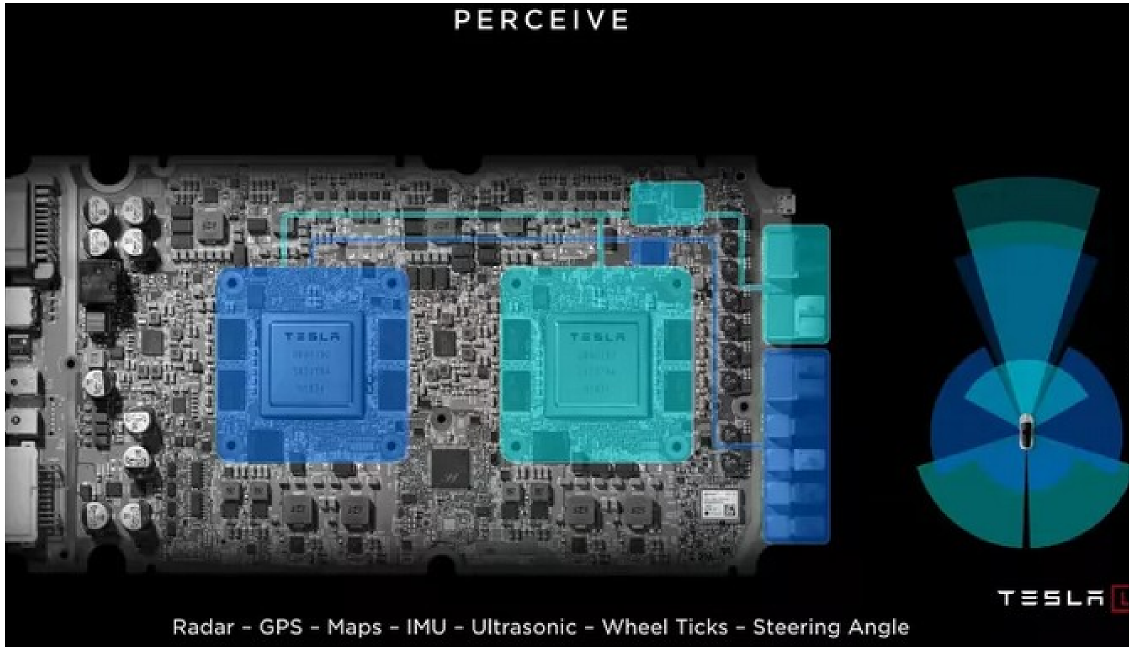
Technology Goals	
Goal #1	Enable space missions to use neuromorphic processors for in-situ autonomy.
Goal #2	Augment CPU space processors with rad-tolerant neuromorphic co-processor providing 100x ops/watt for high compute AI and Machine Learning tasks.
Goal #3	Ultra low-power standalone neuromorphic processor for small space assets and standalone instruments
Goal #4	Bridge gap between commercial industry and space rad-tolerant neuromorphic processors.

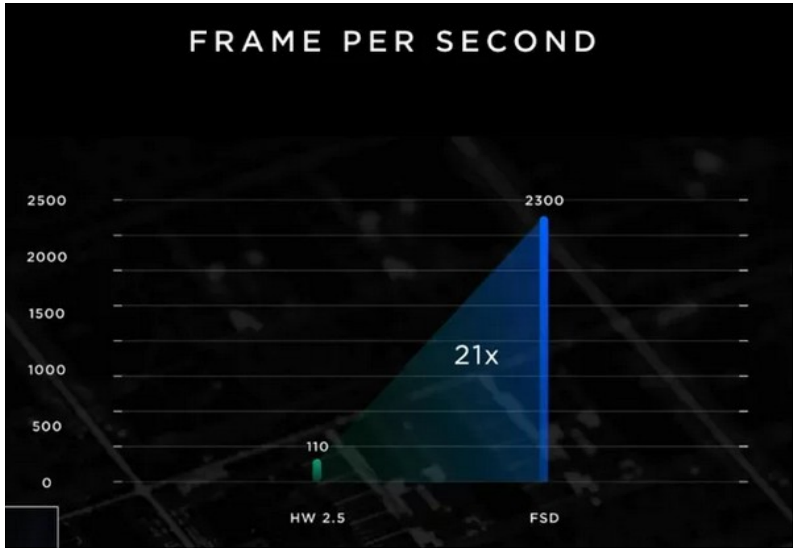
Project Objectives	
Objective #1	Trade-space analysis.
Objective #2	Mature TRL for neuromorphic processing in space from 2 to 4
Objective #3	Radiation test neuromorphic devices, circuits, and chips
Objective #4	Design and fabricate prototype rad-tolerant neuromorphic circuits and processors for space
Objective #5	Engage partner for Phase 2 design and fabrication of full rad-tolerant neuromorphic processor.

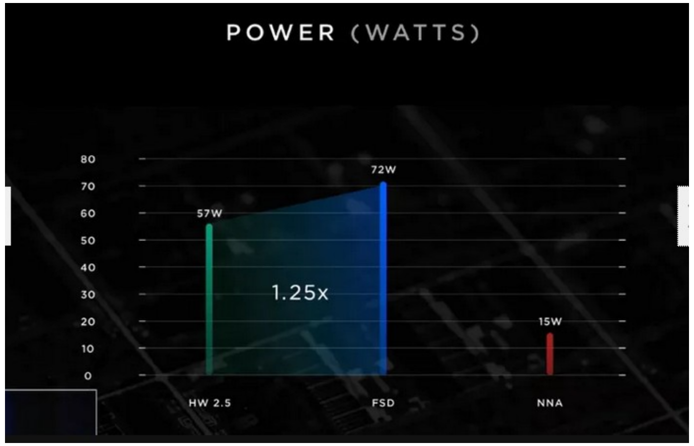
Force Multiplier Co-Processor for Space Autonomy

Example from Terrestrial Autonomous Cars

Tesla Full Self-Driving Chip (6B transistors 14nm FinFET)







Heavy lifting for vector processing off-loaded to Neural Net Accelerators
System Level: 21x perceptual processing for 1.25x power 17x ratio
Force Multiplier towards Autonomous Cars
Autonomy: Achieves SAE Level 2 (Hands-on human vigilance)
Specialized NNA: 72 Terops @ 15 Watts [12x ARM + GPU @ 60 Watts]

Sentient Small Spacecraft

Today's Small Spacecraft

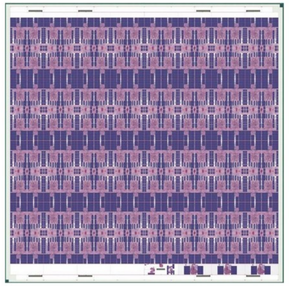
- Low mass, shared launch, affordable missions.
- Typically single-point sensor, bandwidth limited to Earth with minimal on-board processing, on-board processing limited by size and power.
- Typically either single-spacecraft missions or non-coordinated constellations.
- Typically LEO minimal radiation missions.

Next-Gen Small Spacecraft

- Small mass, shared or dedicated launch, affordable missions.
- High-throughput, low-power on-board processing enables sentient actions and data processing, compressed communication to Earth with high information content, opportunistic science.
- Swarms of distributed communicating small spacecraft provide synthetic large sensors (DSA).
- Widespread solar system exploration.

Accomplishments - Technical

Hokulele: First neuromorphic AI/ML system ready for space launch



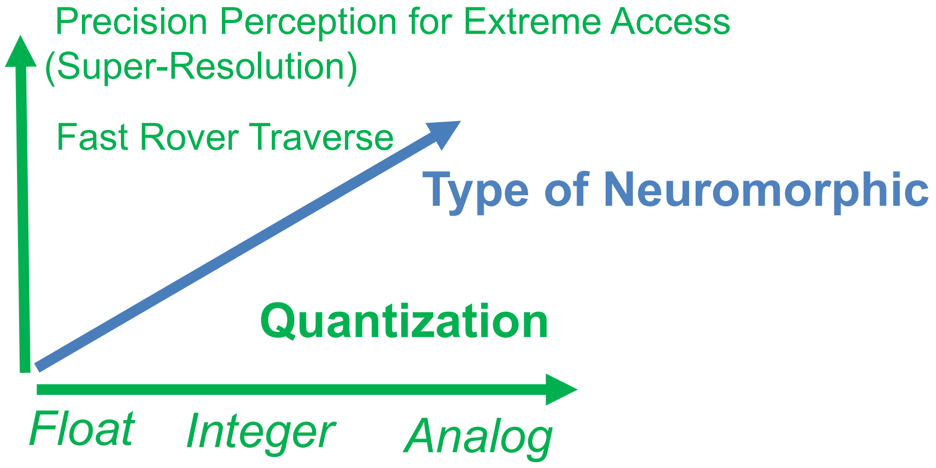
- Hokulele (meteor) system consists of Intel Loihi spiking neural net Gen 1 processor and supporting avionics
- Tes13 3U nanosat now packaged for launch on Virgin Orbit fall 2021, environmental and functional tests complete, launch Nov15 +, parallel orbit to ISS, likely months of operations.
- Tes13 is a collaboration of RadNeuro, Cognitive Radio, Small Spacecraft Technology Program, SBIR companies and AFRL contribution
- Hokulele requirements are defined as a progression of increasing success criteria
- Hokulele software consists of C&DH, scheduling and execution framework, 7 AI/ML applications, and robust reset strategy for hardware faults
- Software was designed, developed, peer-reviewed, and verified by RadNeuro in collaboration with SBIR Exploration Institute and Blaze computing.
- Loihi hardware was debugged in collaboration with Intel Neuromorphic Research Laboratory, hangs isolated to auxiliary USB circuitry with mitigation by Hokulele software
- **Hokulele Incorporates in-situ learning capability: 6 baseline classes for anomaly detection already learned during test and checkout**
- Hokulele deployment experiment operational policies and procedures have been defined, including nominal and extended modes, and 'war plans' for potential fault conditions
- **Once success criteria have been achieved - expected within first 30 days using Iridium 100-byte communications- longer mission will validate in-situ learning with S-band 'lunar radio' 10s of MBytes data downloads, and characterize Loihi hardware space performance.**

Accomplishments - Technical

- **Tradespace:**
  Throughput and Quantization tradespace defined for NASA Applications

Throughput And Sizing

TOPS/Watt – efficiency
Onchip synaptic storage



Energy for Multiply (synapse)	*4pJ @ 14nm Finfet*	*0.5pJ Estimated*	*0.2 pJ@ 14nm Finfet*	*Appx. 0.05pJ*	*4.5 x 10^8 ATP per spike appx. 0.045pJ per synapse*
64bit FP High Precision Simulation	32bit FP Digital Signal Processing	BFloat16 Deep Learning	Int8 Edge Inference	4-6 bit Analog	2-4 bit Biological Synapse *Rolls et al*

Analysis Estimates
TOP = 10^12 operations/sec

750 TOPS	Human Vision
600 to 800 TOPS	Perception for Extreme Access
200to 400 TOPS	Fast Rover Traverse
74 TOPS	Tesla FSD SAE L2 Hands On Constant Monitoring

Accomplishments - Technical

- Radiation Test Procedures
  - Extended TID testing defined for synaptic weight shifts
  - Engagement with Intel for radiation-testing Loihi
  - Testing procedures defined and written for Neuromorphic Devices:

    Analog NOR Flash, Memristors, STT-MRAM

Neuromorphic Radiation Tolerance

Traditional (Digital ASIC) – redundancy leads to reduction of power and area efficiency:

ECC	Bigger Transistors	Slower Clock	TMR	Self-Checking Pairs	Warm/Cold Backups
x 1.5-2	x 3-5	x 2-4	x 3x+	x 2	x 2

Neuromorphic Rad-Tolerance: Traditional Approaches + *more*

Device Level Radiation Tolerance

	NOR Flash	ReRAM	STT-RAM
SEL/SEU Immune	No	Yes	Yes
TID tolerance	< 100k	< 10M	>1M
Commercial Standard	Mature, Special Library	~ 2023 (Today: Special Arrangement)	~ 2023 (Today: Special Arrangement)

Architecture Level Radiation Tolerance

Redundant NN (uncompressed)
Sparing rows, columns for TID
Reduce voltages, e.g., for writing
Reduce capacitive reservoirs, e.g.
Analog / Digital converters

6

Prototype Radiation Tolerant Processors

Three broad processor classes as defined by layout and architecture.

RadNeuro will leverage these classes with Radiation & Fault Tolerance.

Systolic Array for Artificial Neural Net

San Miguel (California mission) – FY22Q2
Radneuro-Mentium collaboration for rad-tolerance

Mesh Network for Spiking Neural Net

Hoku-pa'a (Hawiaan Northstar) – FY22Q2

Radneuro-intel collaboration rad-tolerance with Loihi baseline architecture

FPGA Neuromorphic

Freya (Norse clairvoyant shapeshifter goddess) – FY23Q1

Radneuro-Brainchip collaboration

Prototype RadNeuro Processor Validation

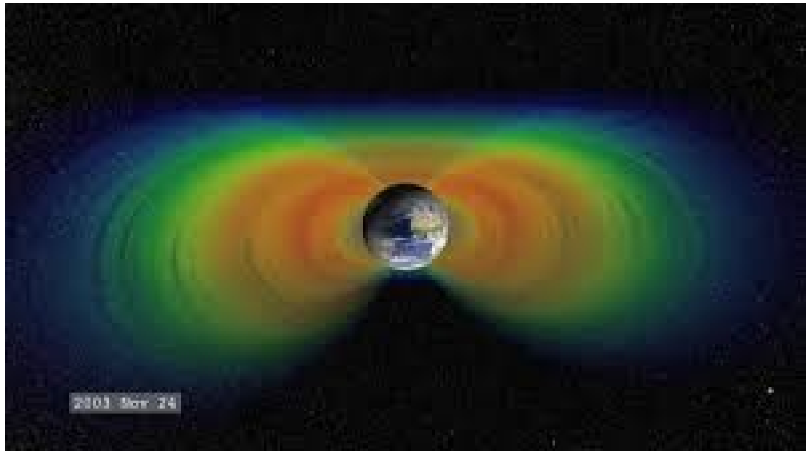
Radiation TID/Beam test prototype neuromorphic processors (FY22, FY23 Q1)

Downselect Prototype Neuromorphic Processors (FY23 Q1)

Agneya Baptism by Fire (Sanskrit, Hindu Goddess) Summer 2023

RadTolerant AI/ML system on PACE4 Mission

GeoTransfer Orbit with repeated exposure to Earth's Natural Synchrotron – the Van Allen Belts



2mm AL SHIELDING									
Mission	Trapped Solar Particles				Solar Flares			GCR	Total Dose
	Proton Dose	Electron Dose	Brem Dose	Total Trapped	Dose/SPE	Annual SPE	Total SPE	Proton, He	Rads (Si)
LEO Zero	12	0	0	12	30	4	120	5	137
LEO 51˚	200	1000	10	1210	30	4	120	5	1335
LEO Polar	150	1000	10	1160	30	4	120	5	1285
GEO	10000	100000	1000	111000	30	4	120	10	111130
GTO (max rad)	10000	10000000	10000	10020000	30	4	120	10	10020130

Objectives Status Summary

Project Objectives	
Objective #1	Trade-space analysis. *70% complete*
Objective #2	Mature TRL for neuromorphic processing in space from 2 to 4. *Hokulele system checkout testing has achieved TRL 3* *Hokulele space launch on Tes13 nanosat will achieve TRL 4* *Agneya RadTolerant AI/ML on PACE 4 nanosat will achieve TRL 5*
Objective #3	Radiation test neuromorphic devices, circuits, and chips *Test procedures defined for extended TID / Synaptic Weight radiation stability*
Objective #4	Design and fabricate prototype rad-tolerant neuromorphic circuits and processors for space *San Miguel tapeout November 2021, following Santa Barbara and Santa Cruz processors*
Objective #5	Engage partner for Phase 2 design and fabrication of full rad-tolerant neuromorphic processor. *OGA, 8 SBIR companies, 2 large tech companies interested*

RadNeuro Maturation Timeline

August 2021: Neuromorphic processor successfully integrated into 3U nanosat, 9K SLOC, functional and environmental checkout – ready for launch on Virgin Orbit. 6 classes learned in-situ. TRL 3

December 2021: Intel Loihi operational in LEO. Ground command through Iridium for successive executions of 7 Loihi applications, including in-situ learning for anomaly detection. Evaluation against success criteria. Data acquisition through S-band of Loihi operational profile in orbit. TRL 4

FY22 Q1, Q2: Radiation testing of neuromorphic synaptic devices – high TID – MRAM, Memristors, Analog NOR. TRL 2

March 2022: Tape-out of San Miguel rad-tolerant Analog Systolic array. Radiation and functional testing through June 2022. TRL 3

August 2022: Rad-tolerant firmware for SNN developed with Intel for Loihi. Radiation and functional testing through November 2022. TRL 3

November 2022: Rad-tolerant FPGA neural cores developed with selected partners (e.g., Brainchip). Integration with radiation-tolerant configuration and synaptic memory. Radiation and functional testing through January 2023.

February 2023: downselect rad-tolerant prototype Neuromorphic processors for PACE *Baptism by fire.*

RadNeuro Maturation Timeline

March 2023: integration onto PACE4. TRL 4 rad-tolerant prototype processors

July 2023: PACE4 nanosat mission through Van Allen belts. TRL 5.

September 2023: Publication of data and rad-tolerant technology capabilities from radiation labs and Agneya mission.

If approved, Phase 2 RadNeuro for development of full rad-tolerant neuromorphic processor.

Solicit and Downselect partners (+ 4 months)

- **Initial tapeout of processor (+ 18 months)**
- **Radiation, throughput, and power efficiency verification and debugging (+24 months)**
- **Fabrication of full-scale Rad-Tolerant Neuro Processor (+36 months)**

Technical Assessment

Technical Elements	TRL			
	Entry	Current[1]	Exit	Verification
Trade-Space Analysis	**2**	**3**	**4**	**Milestone ID K1**
Radiation Tolerance	2	3	5	Milestone ID K2
Technology Maturation	2	3	5	Milestone ID: C2
Prototype Rad-Tolerant Neuromorphc Processors	2	2	4	Milestone ID: C3

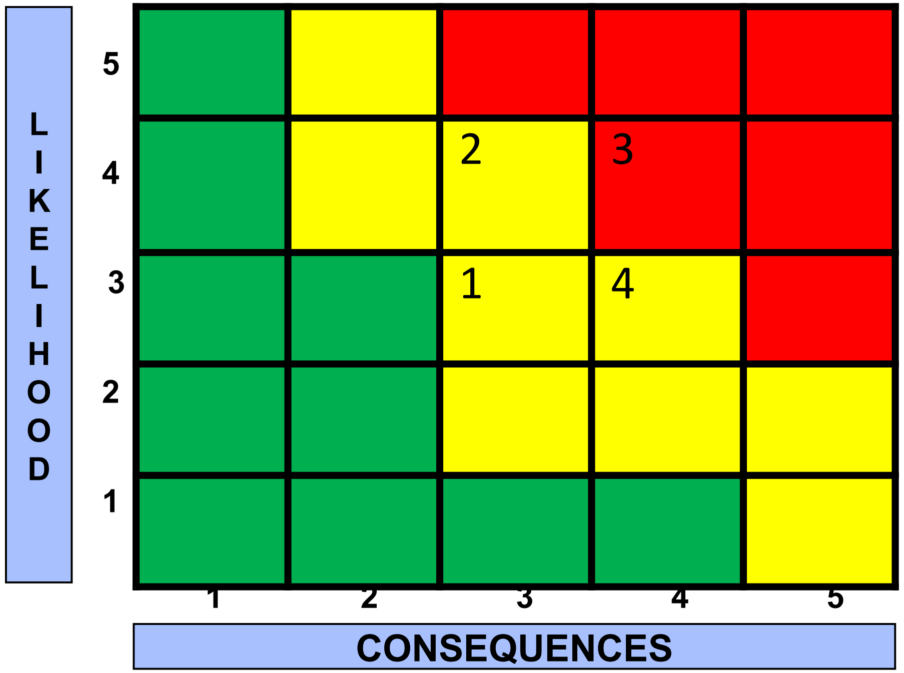
Date of last Technical Assessment was August 2021 for PCD Approval by GCD Chief Engineer

RadNeuro Key Performance Parameter (KPP) Status

Key Performance Parameters								
Parameter	**Units**	**State of the Art (SOA)**	**Threshold Value**	**Project Goal**	**Current Value To Date**	**TBoE for the provided Current Value**	**Expected Exit Value**	**TBoE for the provided Expected Exit Value**
Compute Power Efficiency	Tera ops /sec/watt	2(1)	10	20	4	Estimate for Analog	10 to 15	Benchmarks
Total Ionizing Dose	Kilorad	20	100	200	20	Previous TID tests(2)	120	Preliminary data on Neuromorphic Devices
Fault Recovery	Seconds	Latchup	10	1	Undef	N/A	2	Verified
Machine Learning Capability	InSitu Timeliness	Pretrained	Batch Learning	Adaptive Learning	Ground Adaptive Learning	Tes13 Checkout	Adaptive Learning	Verified

Notes:
Technical Basis of Estimate (TBoE)
(1) SOA comparison to Google Tensorflow Edge Processor
(2) Previous tests on Magnetic STT-RAM conducted by Ames at JSC

Risk Summary



Risk ID	Affinity/ Approach	Description/Status	Trend
1	T /A	Launch failure of Nanosat Mission	Unch
2	T/ R	Unforeseen Radiation vulnerability of Prototype Processor	New
3	S / W	Schedule slip of Nanosat Mission	Dec
4	S /W	Schedule slip of Prototype Processor Development	Unch

Criticality
- High
- Med
- Low

L x C Trend
- Decreasing (Improving)
- Increasing (Worsening)
- Unchanged
- New Since Last Period

Approach
- M - Mitigate
- W - Watch
- A - Accept
- R - Research

Affinity: **T**-Technical **C**-Cost **Sc**-Schedule **Sa**-Safety

Project Assessment Summary

Project Name	Performance				Comments
	C	S	T	P	
Mid Year					Technical – Tes13 nanosat mission in development, Intel and Mentium prototypes Cost – COVID19 expense rebaseline request pending Schedule – COVID19 rebaseline request pending Programmatic – RTOW package submitted
Annual					Technical – Tes13 nanosat passed checkout and environmental testing Cost – rebaseline request accepted Schedule – rebaseline request accepted Programmatic – RadNeuro lab re-opened under COVID19 protocols

EPO Update

- Upcoming significant events
  - Tes13 nanosat launch (November or December)
  - Hokulele Machine Learning system success fullfillment (December or January)
  - San Miguel analog neuromorphic fabrication (March or April)
- Conferences
  - International Conference on Neuromorphic Systems July 2021
  - Space Computing August 2021

Plans Forward and Infusion Plan

Tes13 Launch
Hokulele Machine Learning system success criteria fullfillment on Nanosat Tes13

Prototype Rad-Tolerant Neuromorphic Processors, Radiation Lab Testing

- **San Miguel Analog Systolic Array**
- **Hoku-pa'a - rad-tolerant mesh network for Spiking Neural Network**
- **Freya – FPGA neuromorphic**

Baptism by Fire – PACE4 GTO nanosat with Agneya RadTolerant AI/ML system
Infusion into STMD Small Spacecraft Technology Program
Infusion of Radiation-Tolerant Technology into Neuromorphic Processor Community

- **Data, Analysis, and Guidebook**
- **Direct Partnerships with both small companies and large companies**

Phase 2 RadNeuro proposal for development of full-scale Rad-Tolerant Neuro Processor

- **Solicit and Downselect partners (+ 4 months)**
- **Initial tapeout of processor (+ 18 months)**
- **Radiation, throughput, and power efficiency verification and debugging (+24 months)**
- **Fabrication of full-scale Rad-Tolerant Neuro Processor (+36 months)**

Summary – Accomplishments 2021

- Trade-space analysis: *70% complete*
- Mature TRL for neuromorphic processing in space from 2 to 4:
  Hokulele system checkout testing has achieved TRL 3
  Hokulele space launch on Tes13 nanosat will achieve TRL 4

- Radiation Testing:
  Test procedures defined for extended TID / Synaptic Weight radiation stability

- Design and fabricate prototype rad-tolerant neuromorphic circuits and processors for space:
  San Miguel tapeout November 2021, following Santa Barbara and Santa Cruz processors

- Engage partner for Phase 2 design and fabrication of full rad-tolerant neuromorphic processor: *8 SBIR companies engaged, 2 large tech companies interested, OGA discussions*

Technical Capability End State Phase 1

- Maturation of TRL for neuromorphic processing in space from 2 to > 4
- Individual KPPs achieved at component level on one or more prototypes (not integrated)
  - Teraops per watt
  - Synaptic circuit radiation tolerance
  - Rapid recovery after upset
  - Adaptive learning demonstrated

- Prototype Rad-Tolerant Processors verified in radiation labs and validated in GTO 'Baptism by Fire'. Prototypes potentially useful in selected missions as force-multiplier co-processors and sentient small spacecraft.

- Technical capability for leveraging terrestrial neuromorphic industry to space missions through radiation tolerant devices, circuits, and architectures.

BACKUP

Success Criteria for Hokulele AI/ML System on Tes13

Pre-flight Minimum Success: successful end-to-end EDU tests with ground Irridium transfers and packets received, hangs are minimal and recovered automatically.
+ Exploration Institute NSFM monitored checkout and environmental testing, identified 6 classes of nominal operation.
Already achieved.

Flight Minimum Success: Verify the UP Loihi was turned on, one Loihi application succeeds and packet is received on ground via Irridium.

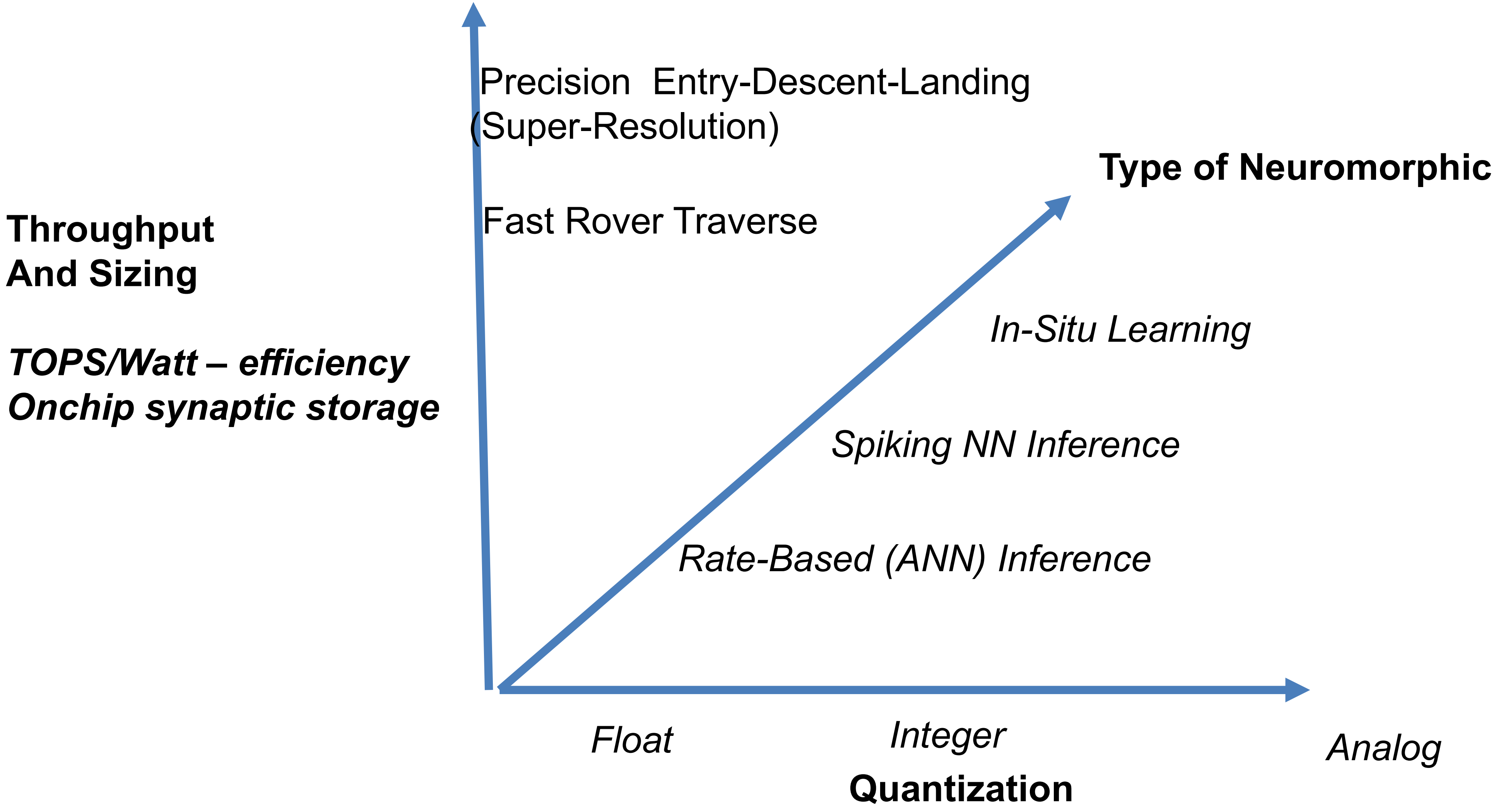
Nominal Success: Verify the UP/Loihi successfully executes at least 5 Loihi applications in Nominal mode and downlinks them to ground via Irridium.

Comprehensive success: Nominal executions routinely succeed, and SIMULATED learning in-situ is demonstrated with pre-recorded data.

Interstellar success: in-situ learning demonstrated with data from flight.

Additional success: functionality of S-band/Lunar Radio

Neuromorphic Trade Space



Quantization of Arithmetic

Energy for Multiply (synapse)

4pJ @ 14nm Finfet

0.5pJ Estimated

0.2 pJ@ 14nm Finfet

Appx. 0.05pJ

4.5 x 10^8 ATP per spike appx. 0.045pJ per synapse

64bit FP
High Precision
Simulation

32bit FP
Digital Signal
Processing

BFloat16
Deep Learning

Int8
Edge Inference

4-6 bit
Analog

2-4 bit
Biological
Synapse
Rolls et al

1 bit
NN

Simulate Chaotic Systems
AI Chip doubles as
Supercomputer for CFD
and other PDE

Resolve Poles
Near Unit Circle
AI chip doubles as
DSP chip

Inference +
Deep Learning
Google cloud
Servers TPU v2, v3

Google Edge TPU
Tesla FSD

Sufficient for
Typical Feed
Forward ANN

Biological
Neural Circuitry
is Robust despite
Noisy Neurons and
Synapses

Radiation Tolerance

CMOS RHBD and TMR

SRAM -> STT-RAM

Floating Gate TMR
ReRAM

Fast-Traverse Autonomous Rover SOS
NN Architecture Extrapolated from Autonomous Car