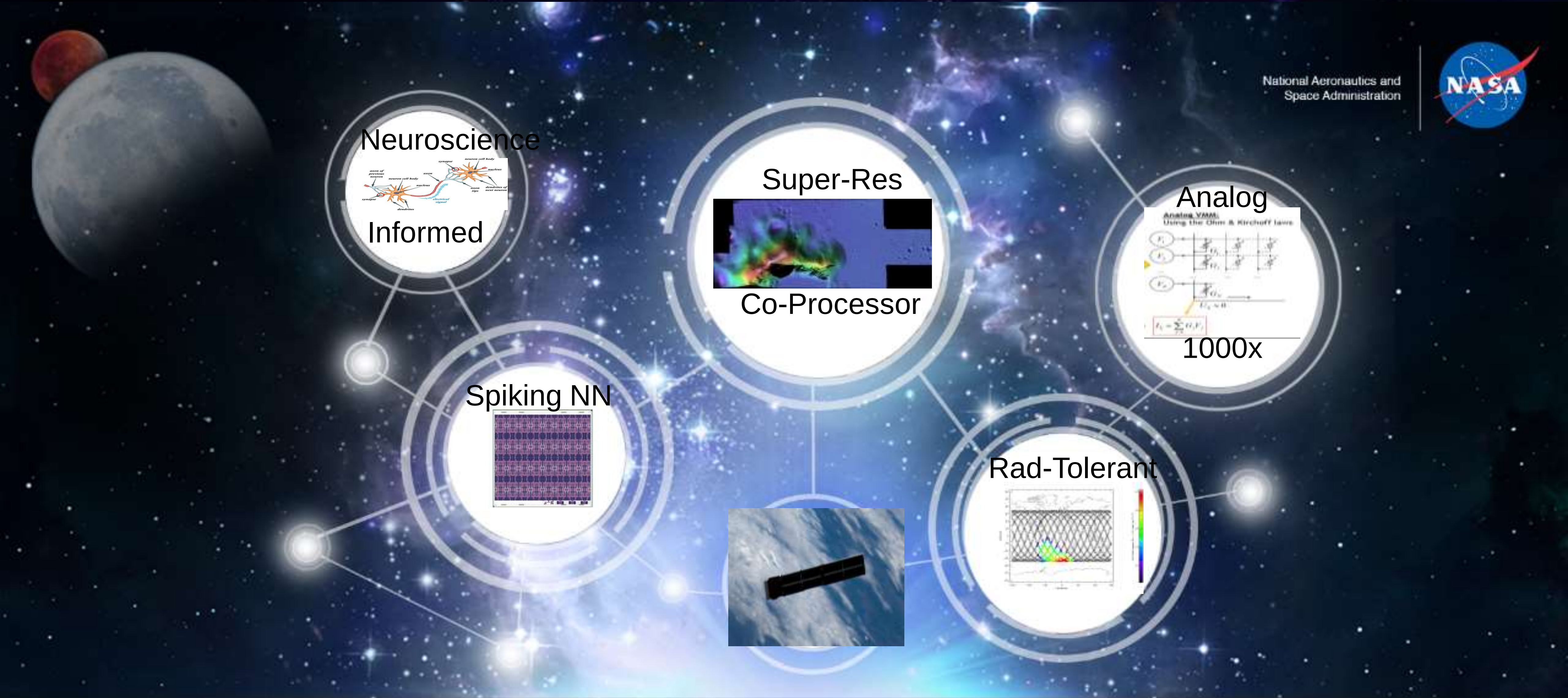


Space Technology Mission Directorate

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.

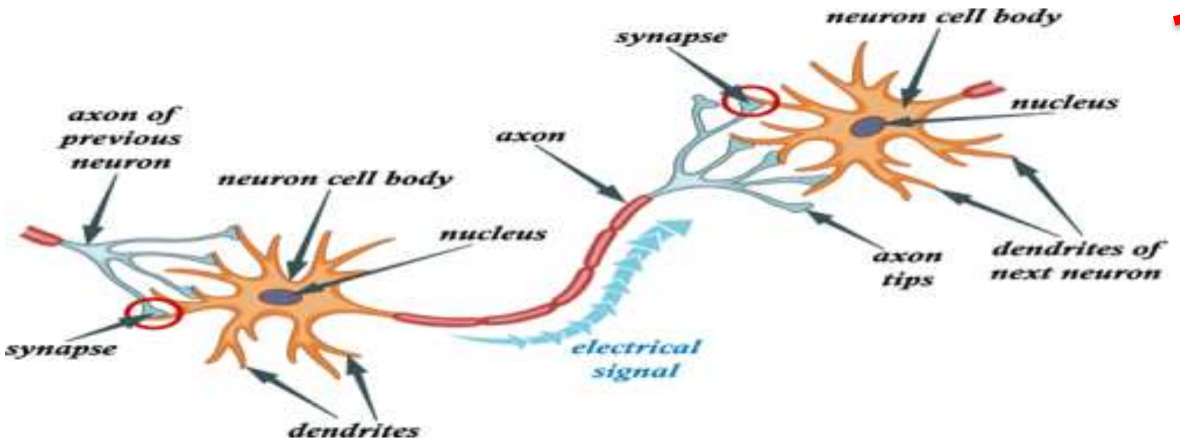
- **Exploration & Science Applicability**
  - The technology targets high-throughput and critical in-situ computing.
  - Fast traverse autonomous roving, lunar and planetary.
  - Perceptual processing for extreme access
  - Anomaly detection, FDIR, spacecraft health
  - Cognitive Radio
  - In-situ adaptation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

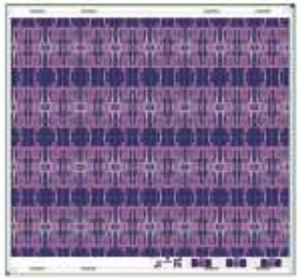
Why Rad-Tolerant Neuromorphic?

- 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

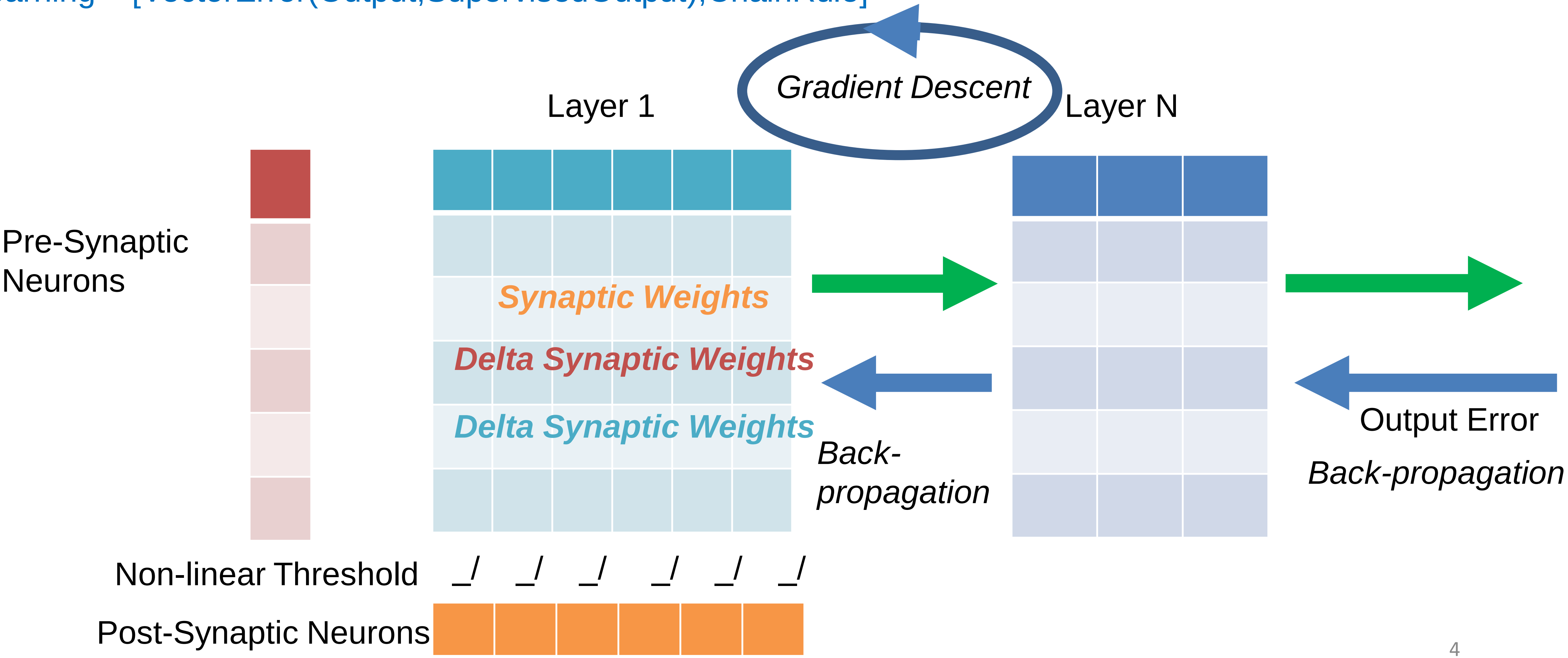


Intel Loihi:
Onboard Learning
Mesh Network

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)

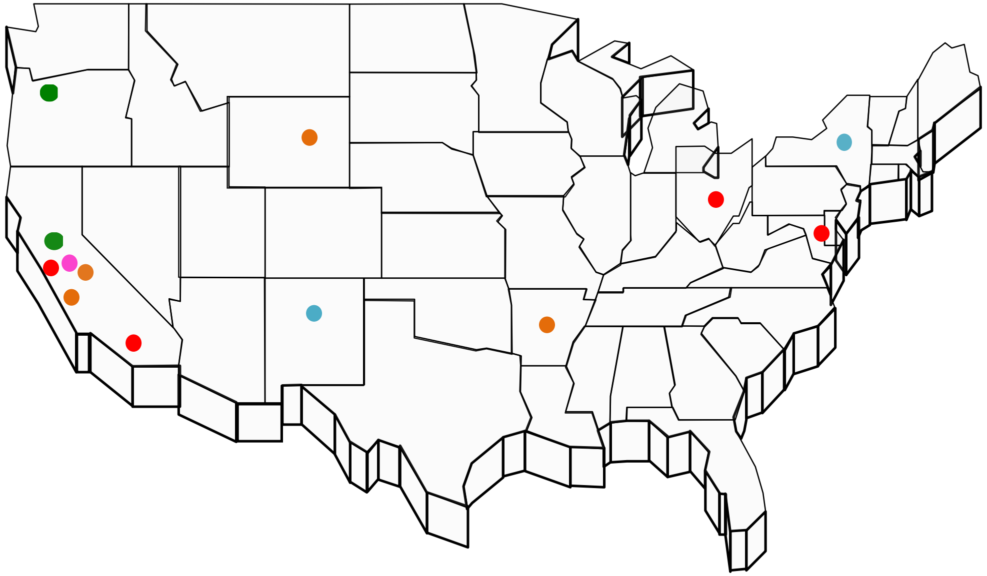
Public/Private Partnerships
- Intel Corporation Loihi Space Act Agreement

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.

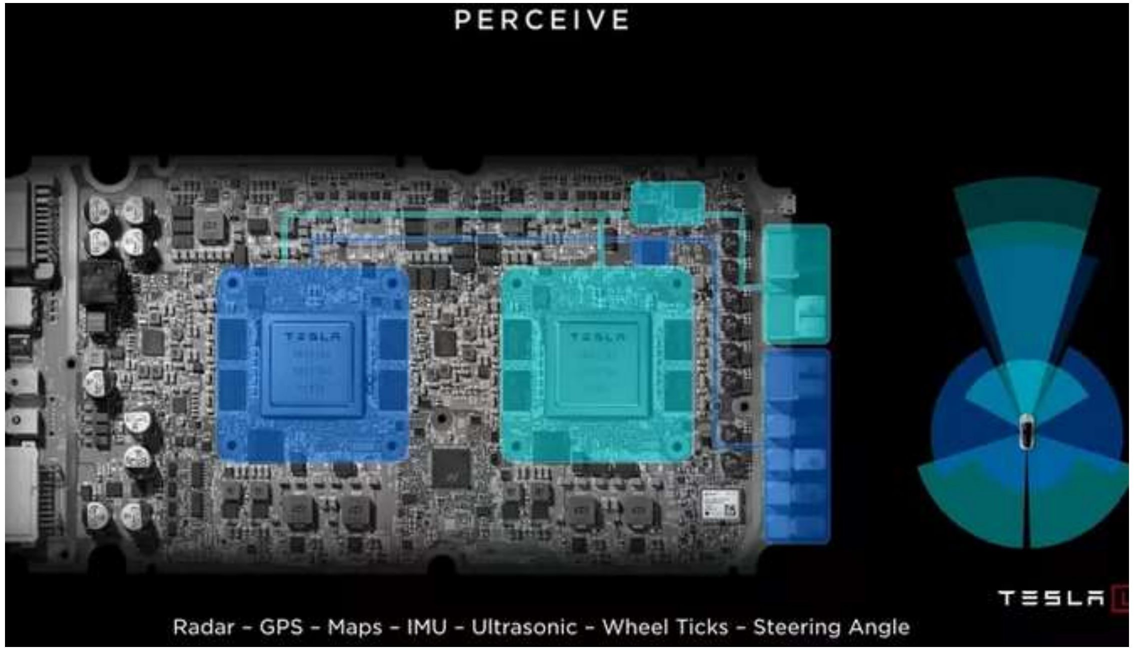
Project Objectives

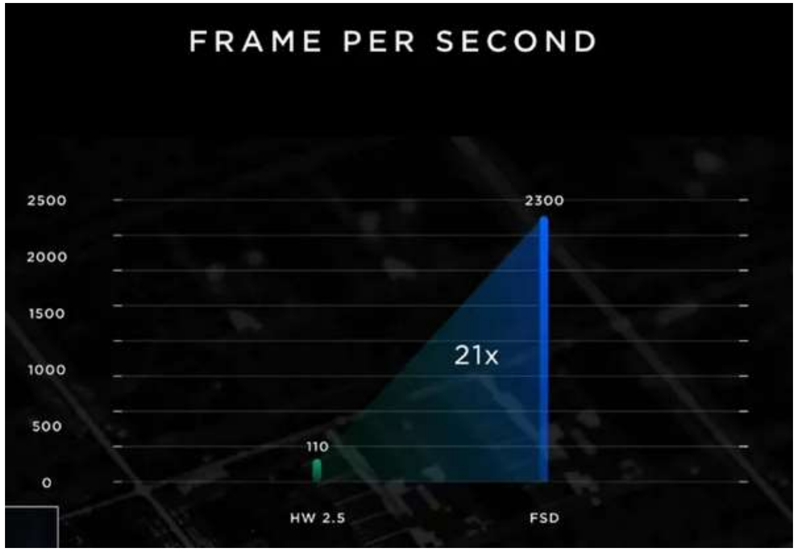
Objective #1	Trade-space analysis.
Objective #2	Mature TRL for neuromorphic processing in space from 2 to 4
Objective #3	Radiation test neuromorphic devices, circuits, and chips
Objective #4	Design and fabricate prototype rad-tolerant neuromorphic circuits and processors for space
Objective #5	Engage 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.**

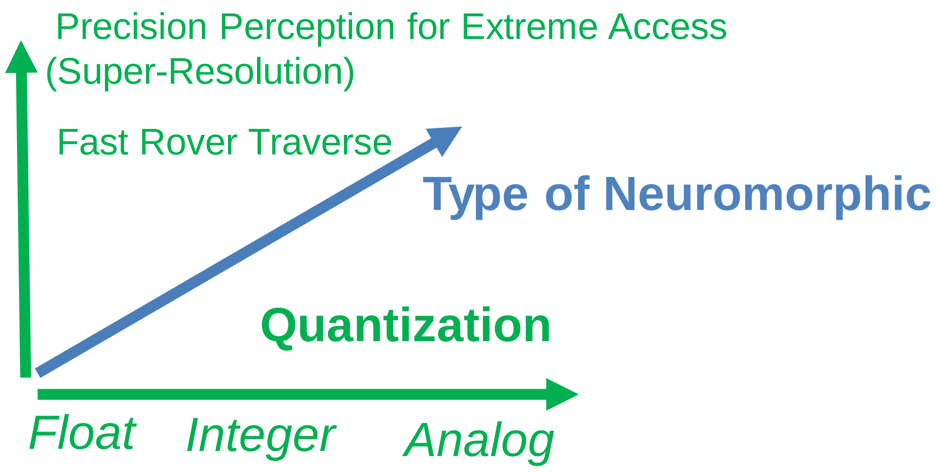
Accomplishments - Technical

- Tradespace:
  Throughput and Quantization tradespace defined for NASA Applications

Analysis Estimates
TOP = 10^12 operations/sec

Throughput
And Sizing

TOPS/Watt – efficiency
Onchip synaptic storage



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

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*

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

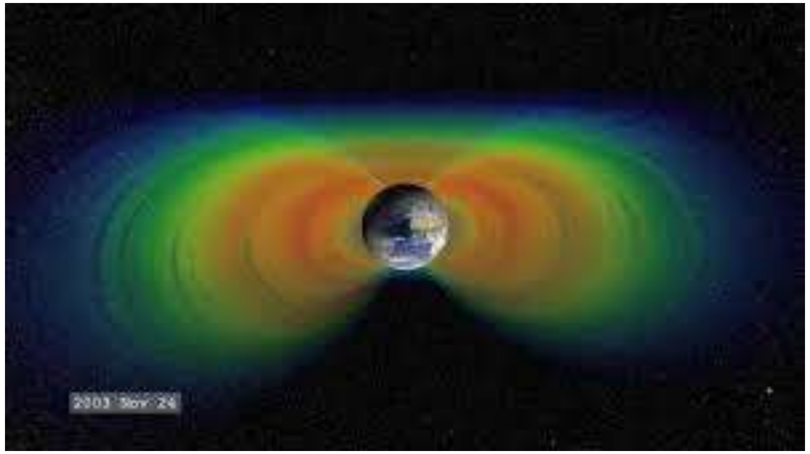
Prototype RadNeuro Processor Validation

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	1002013 0

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

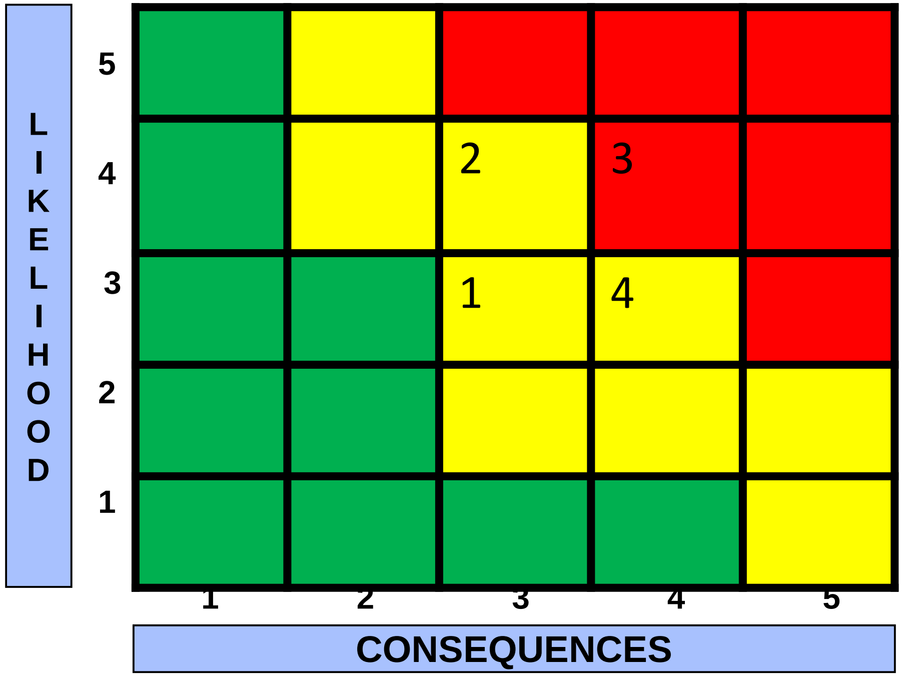
Notes:

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.

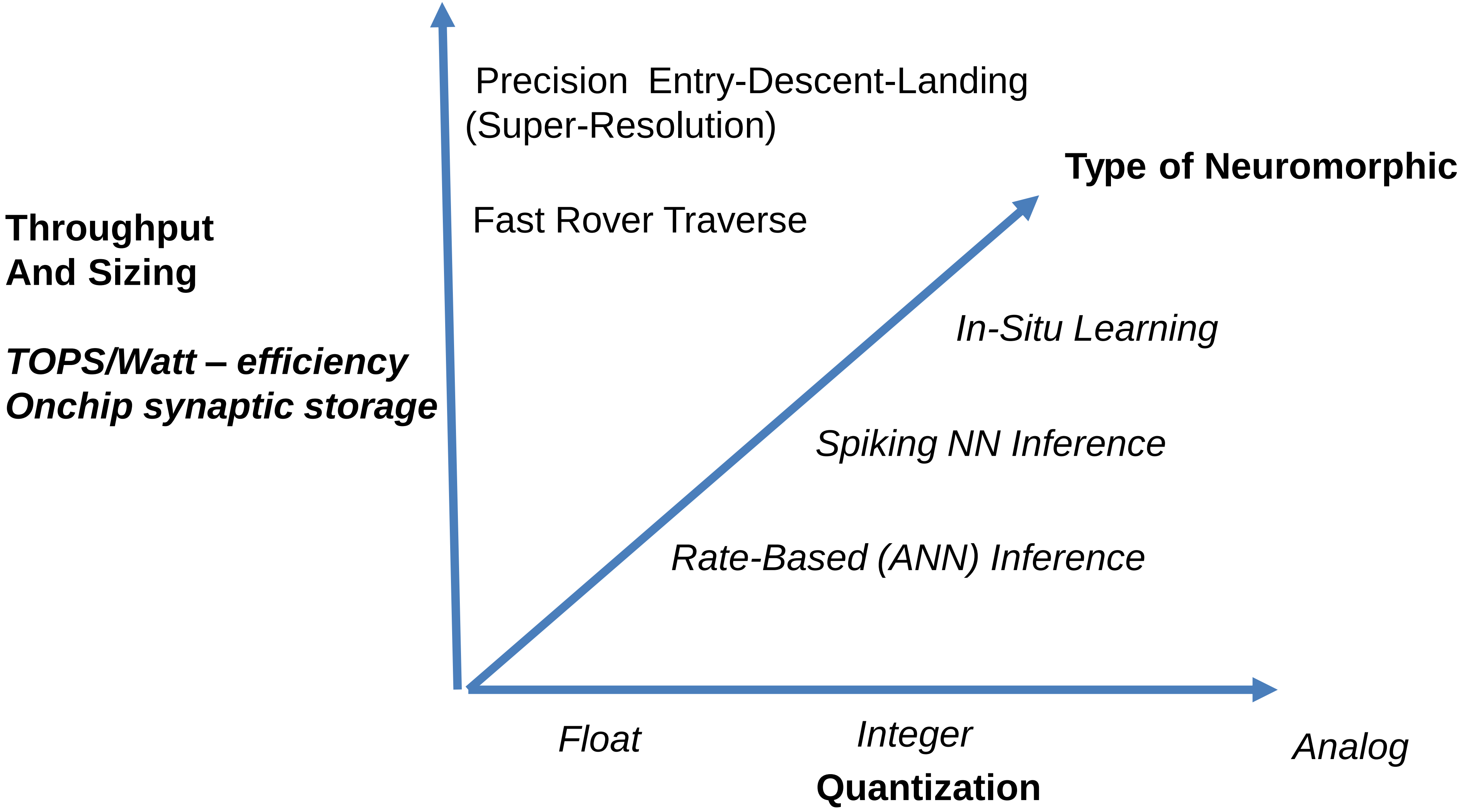
Nominal Success: Verify the UP/Loihi successfully executes at least 5 Loihi applications in Nominal mode and downlinks them to ground via Irridium.

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