

# Exploring the Cosmos: Hackable Innovations at the Allen Telescope Array

The image shows a large radio telescope dish in the foreground, with three smaller dishes visible in the background. The dishes are mounted on tripods and are situated in a flat, open field. The sky is a uniform orange color, suggesting a sunset or sunrise. The text is overlaid on the left side of the image.

Luigi Cruz

DEF CON 32 - Las Vegas, NV







# Allen Telescope Array

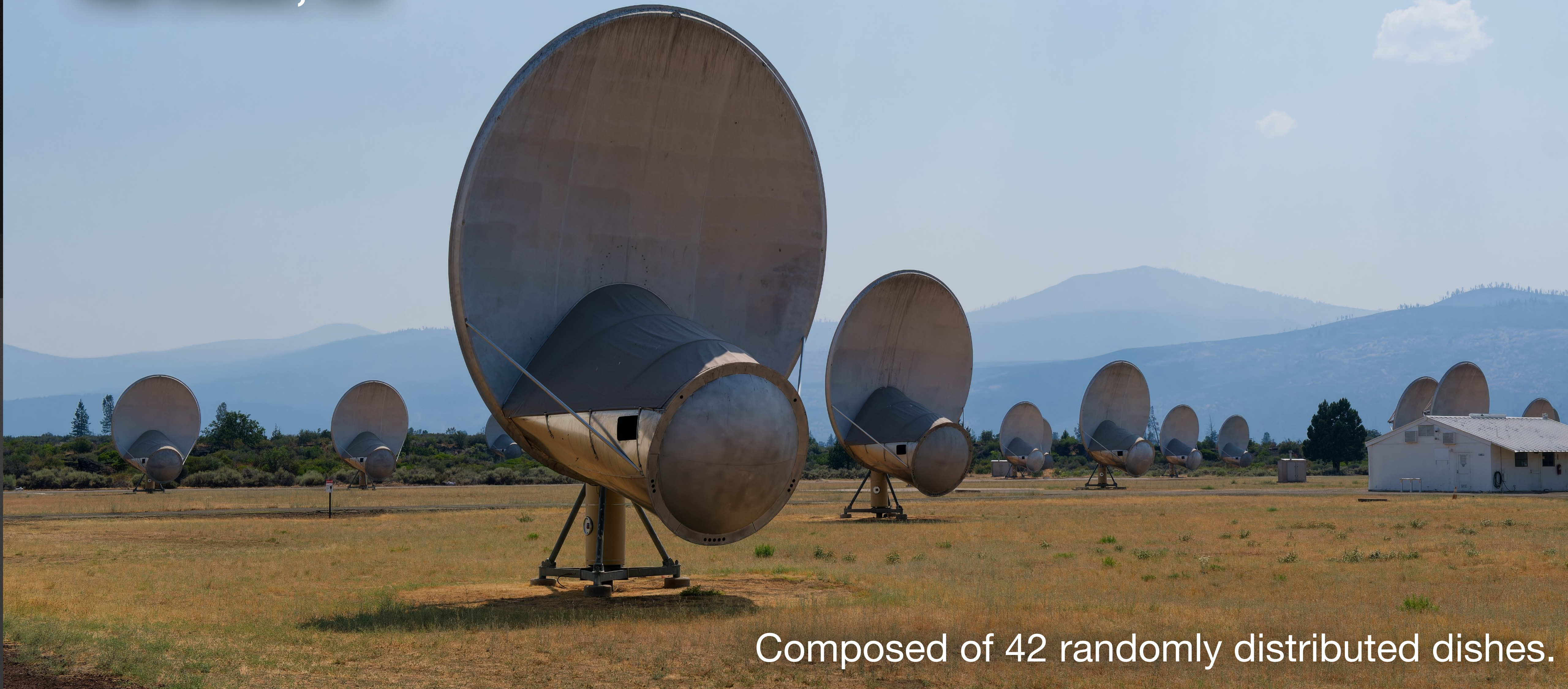
## Hat Creek, CA

- Radio-telescope located in northern California was built from 2002 to 2007.
- Designed to conduct astronomical observations and search for extraterrestrial intelligence (SETI).
- Named after Microsoft co-founder Paul Allen, who provided significant funding for the project.
- Recently refurbished for improved reliability and sensitivity. Thanks to generous private donations.



# Allen Telescope Array

Hat Creek, CA



Composed of 42 randomly distributed dishes.

# Allen Telescope Array

## Offset Gregorian Dish

- Each of the 42 antennas has 20 feet (6.1 meters) in diameter.
- Produce  $\sim 1.5$  GHz of bandwidth for each polarization ( $\sim 3.0$  GHz in total).
- The entire telescope equated to  $\sim 60$  GHz or  $\sim 1$  Tbps at 8 bits per sample.
- Connected to the DSP Room via RF over fiber.
- Ultra wide band reception from 900 MHz to 12 GHz.







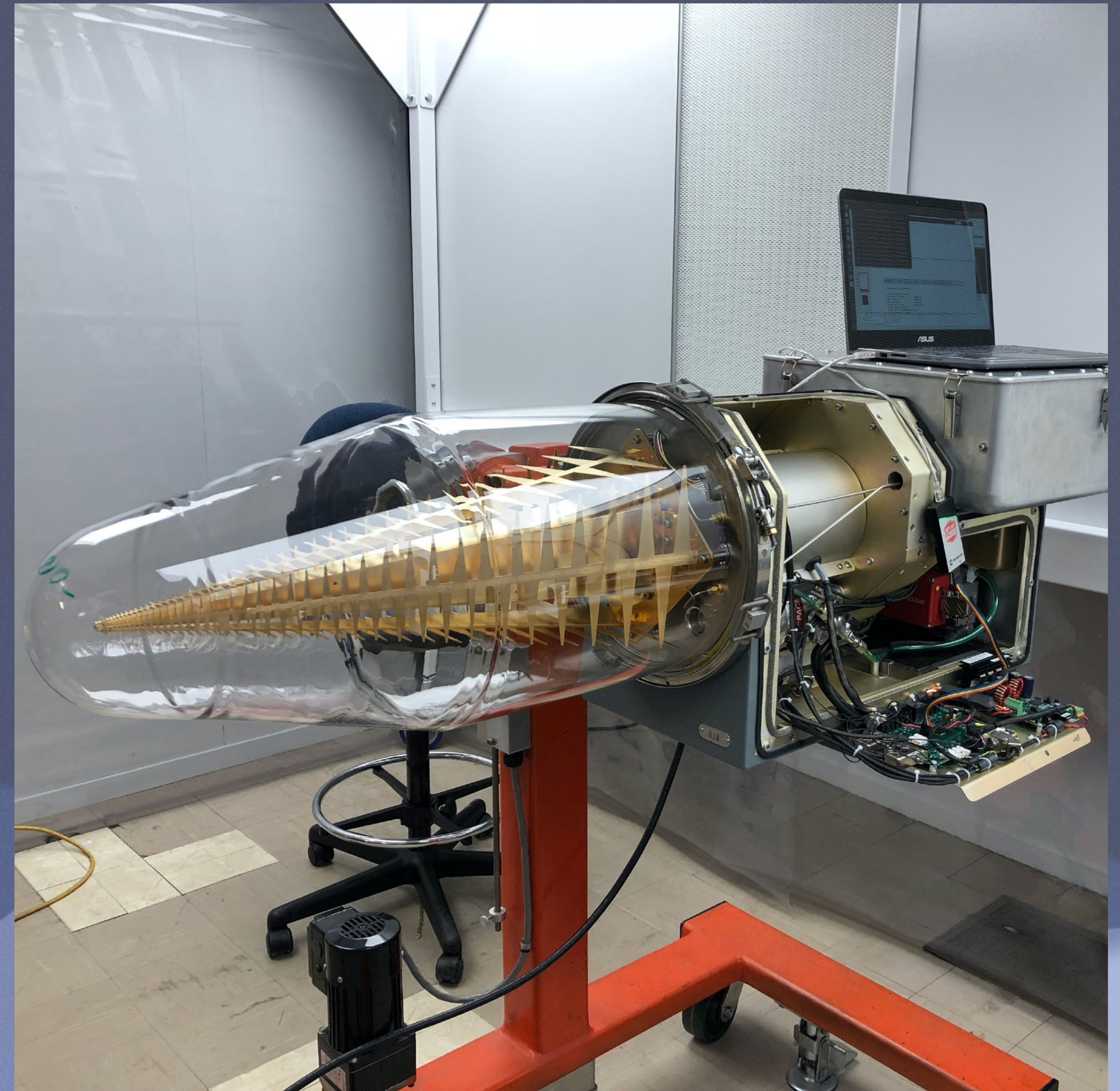
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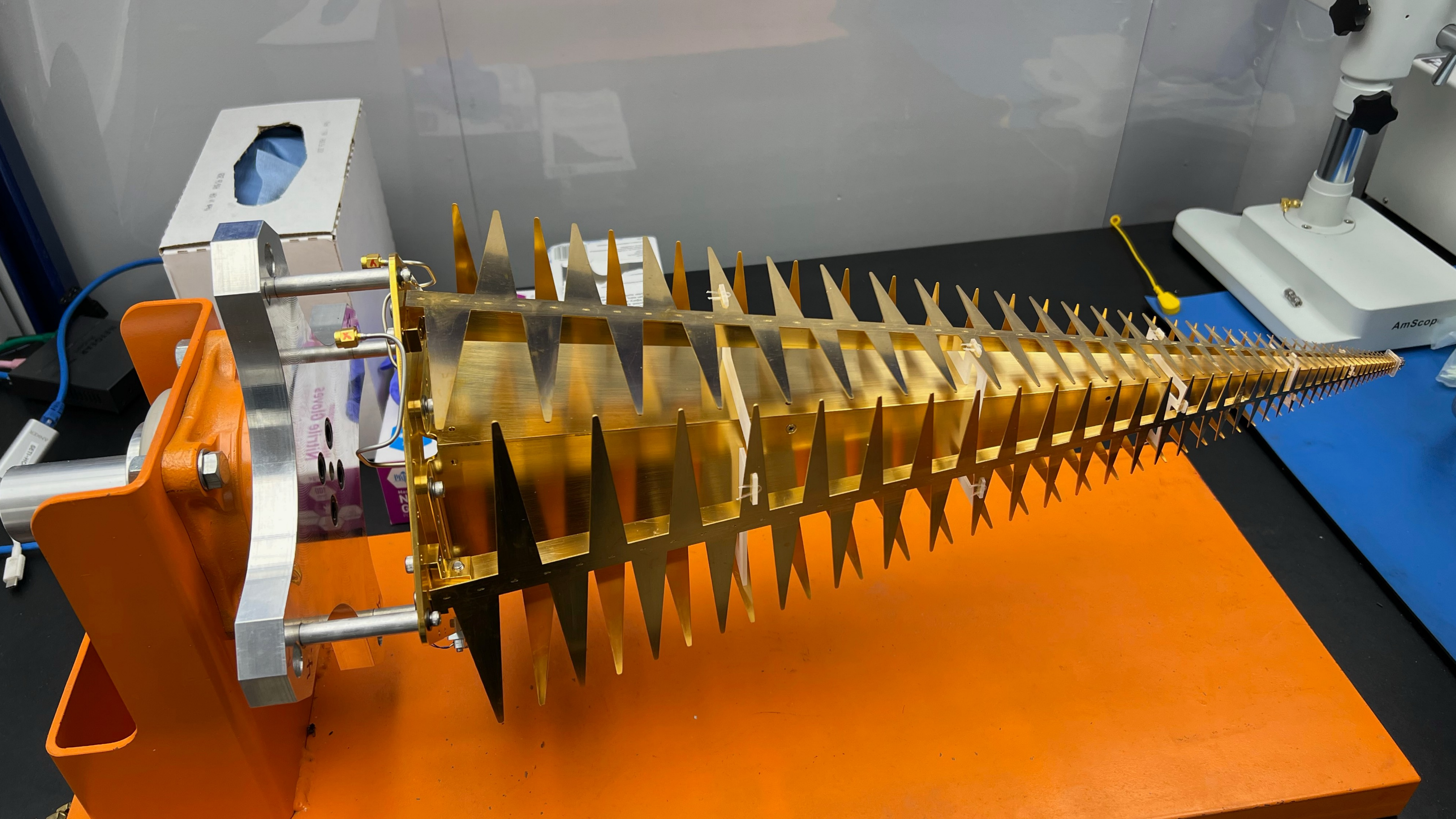


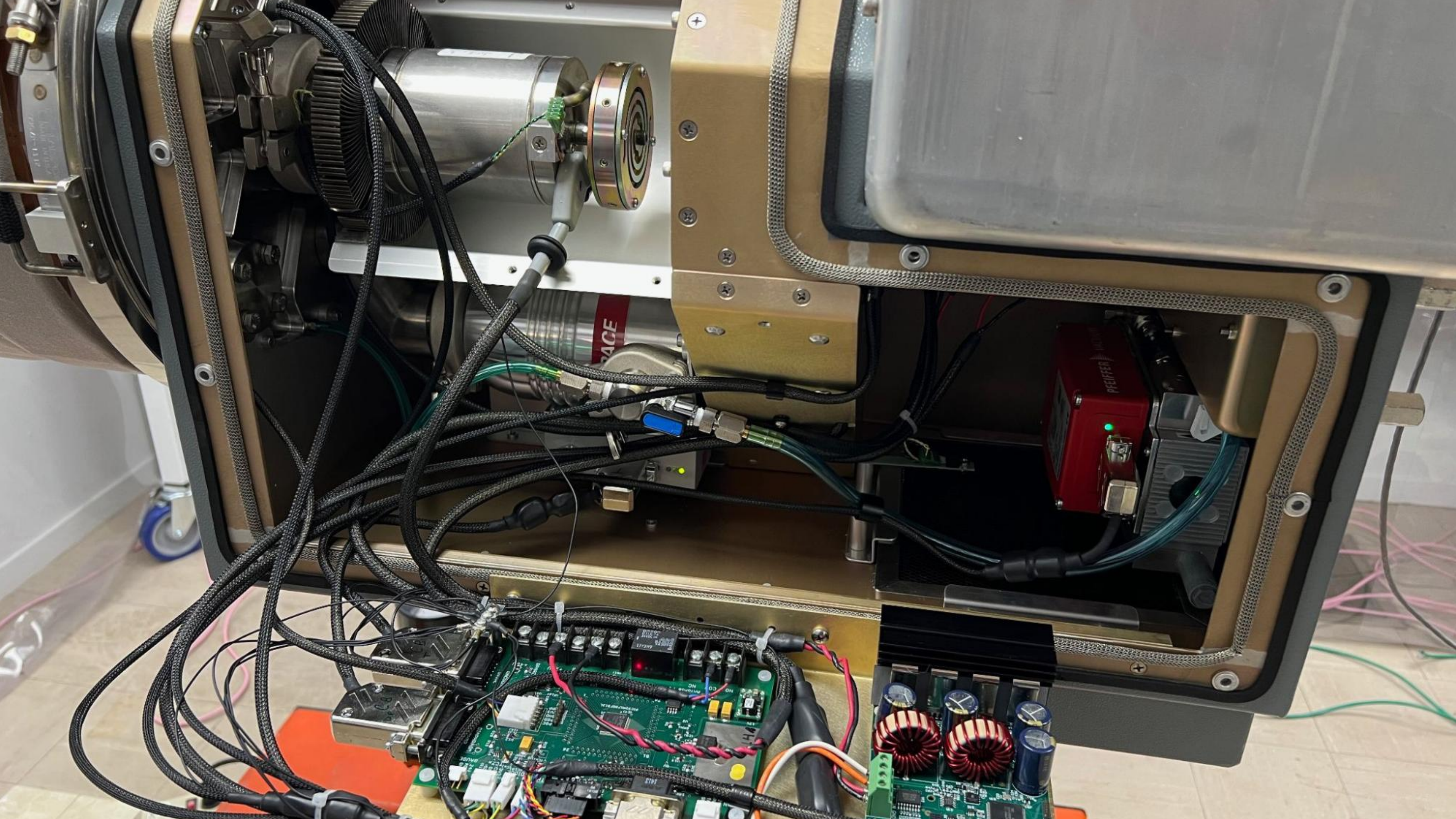
# Allen Telescope Array

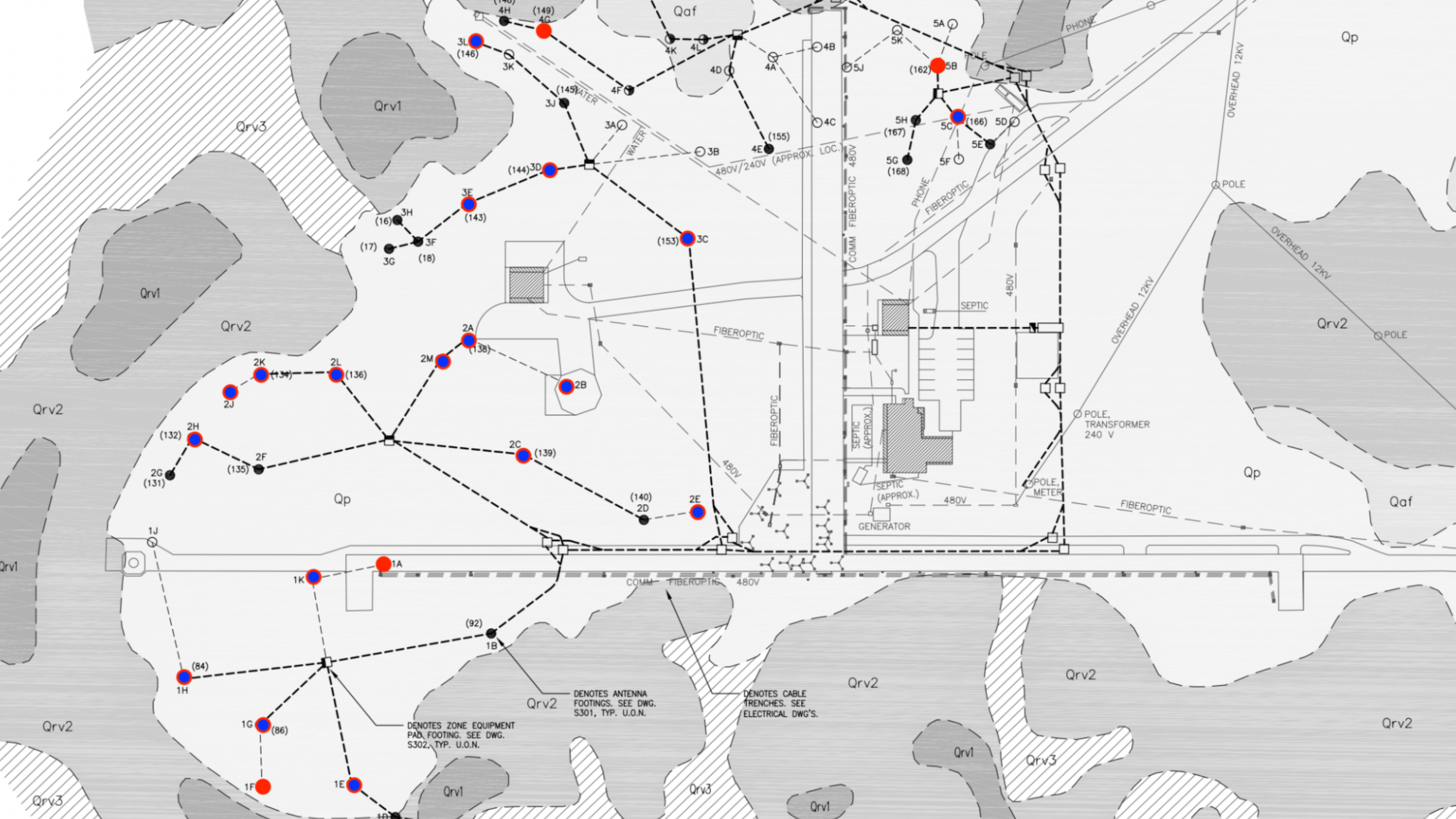
## Log-periodic Feed

- Ultra wide band capabilities are made possible by the log-periodic feed-horn.
- Cryocooled to improve the sensitivity of higher frequencies.
- New Antonio feed is surrounded by a glass dome to help maintain the vacuum and shield it from moisture.





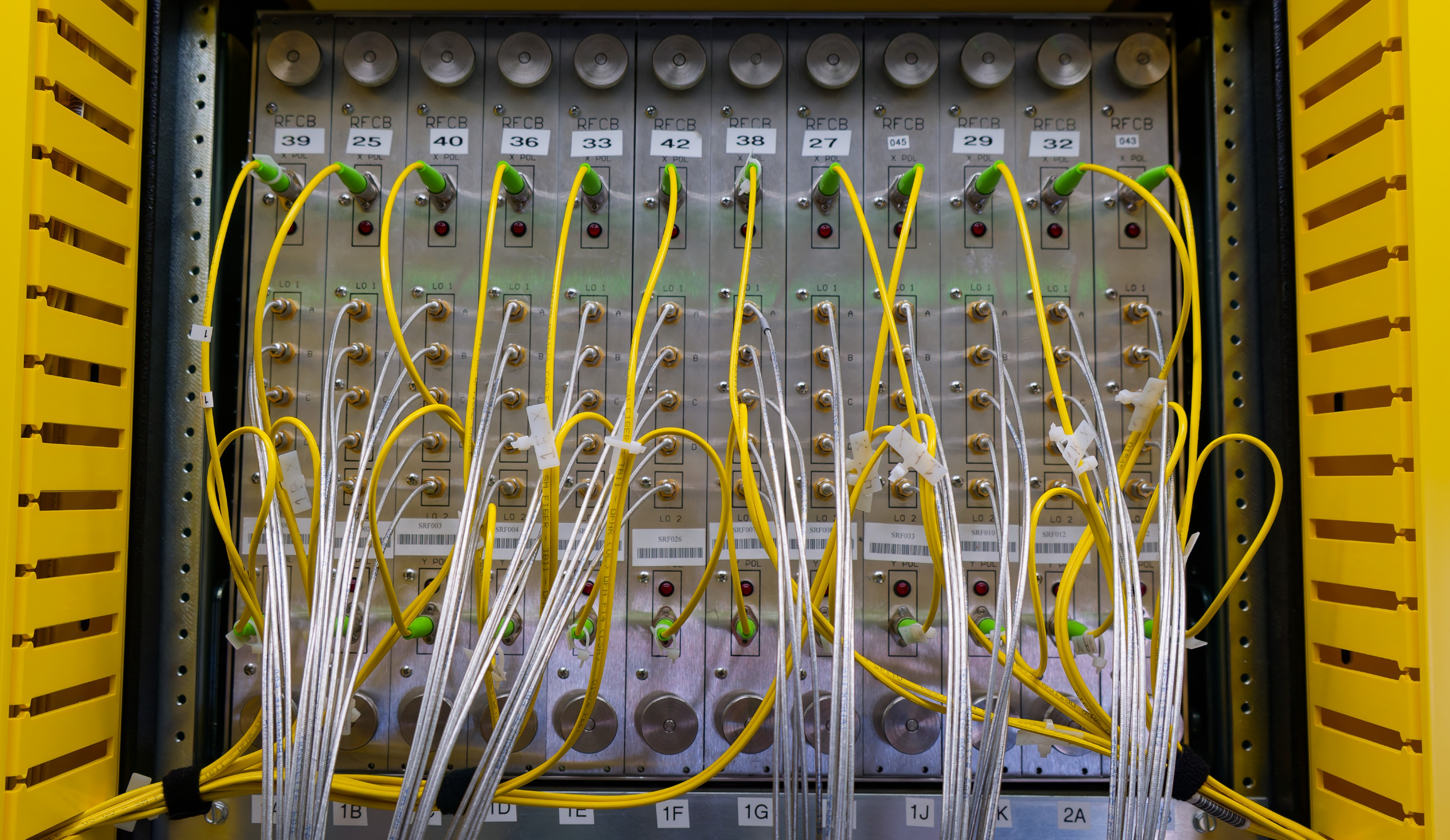


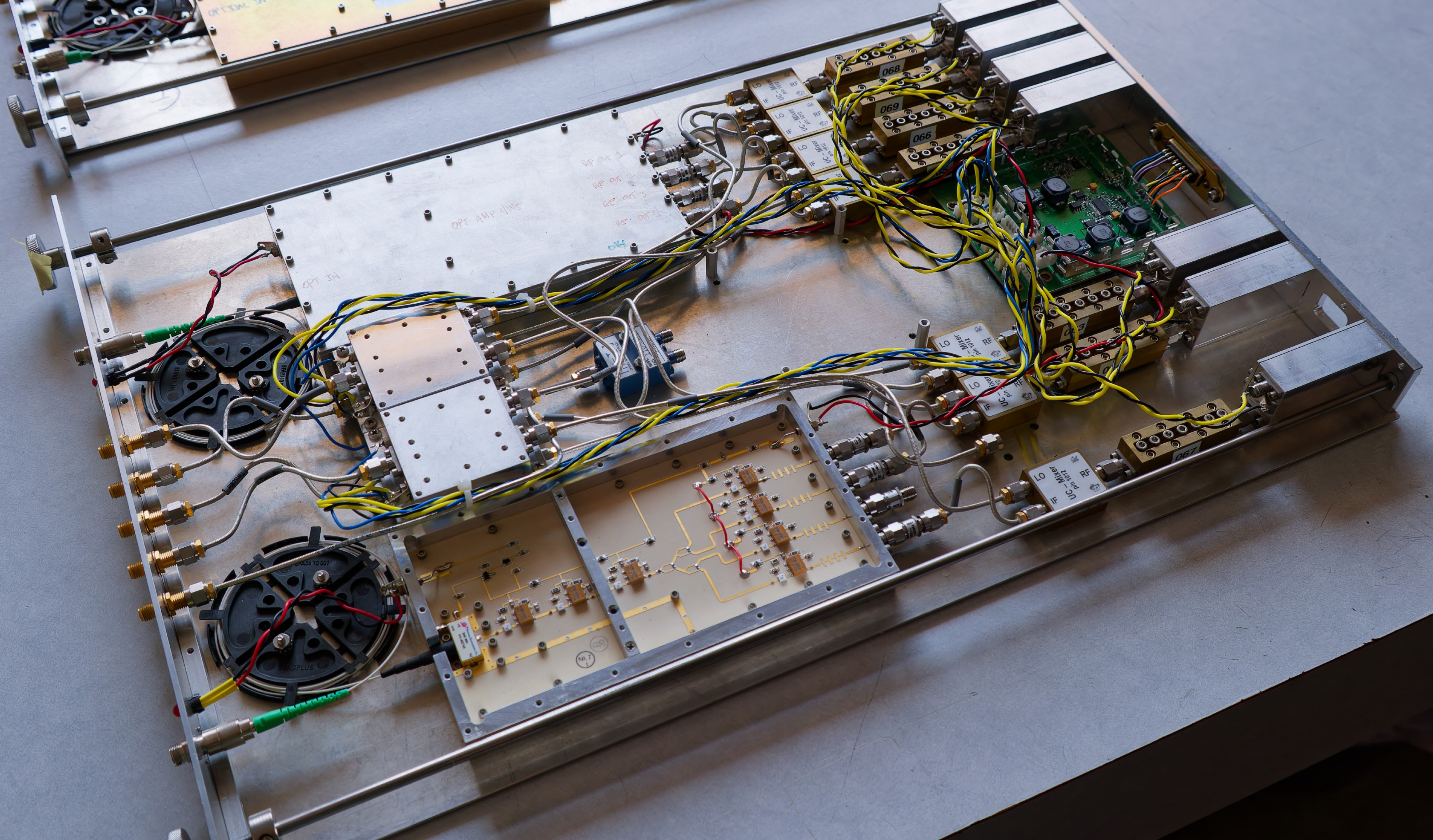


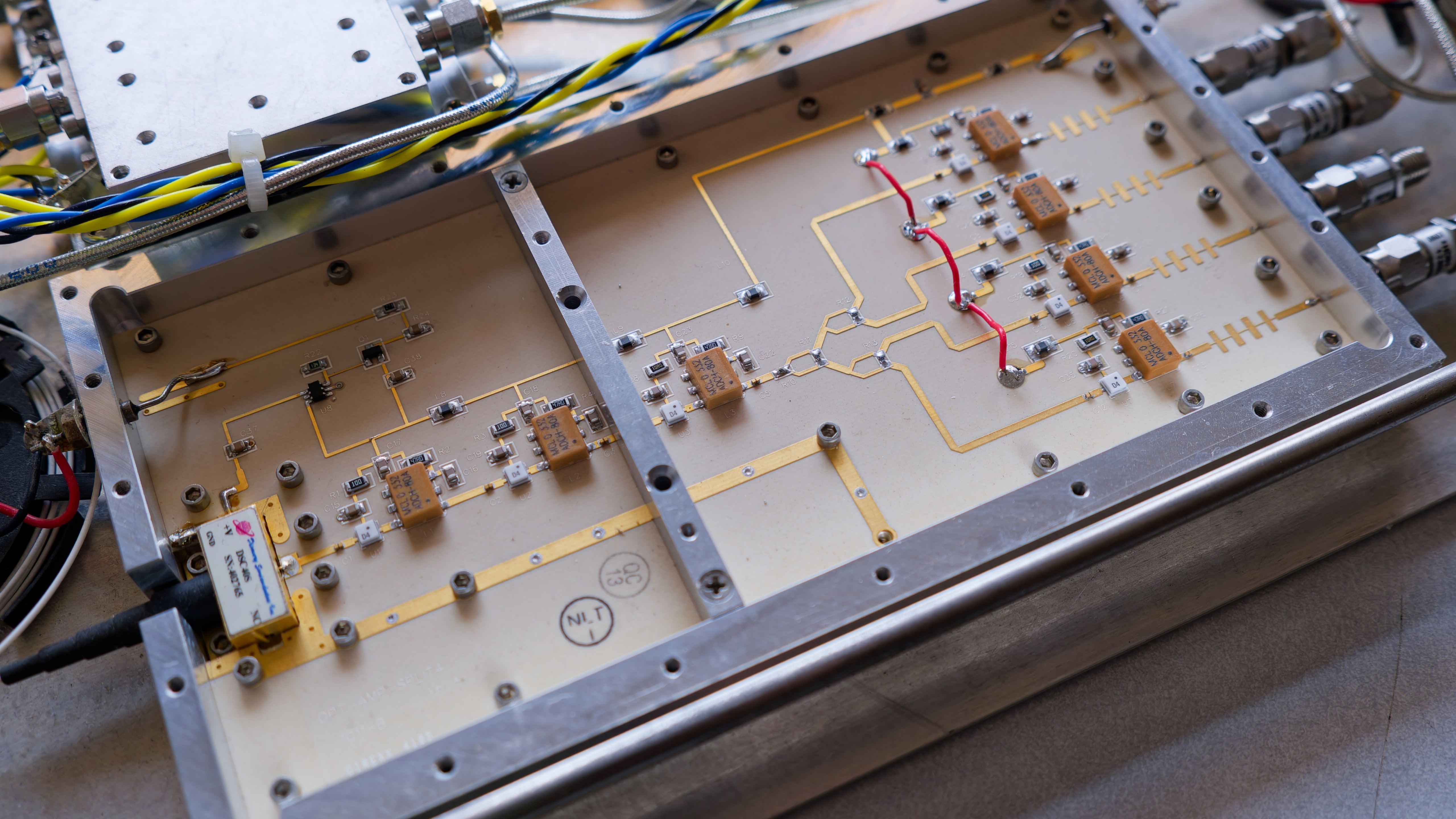




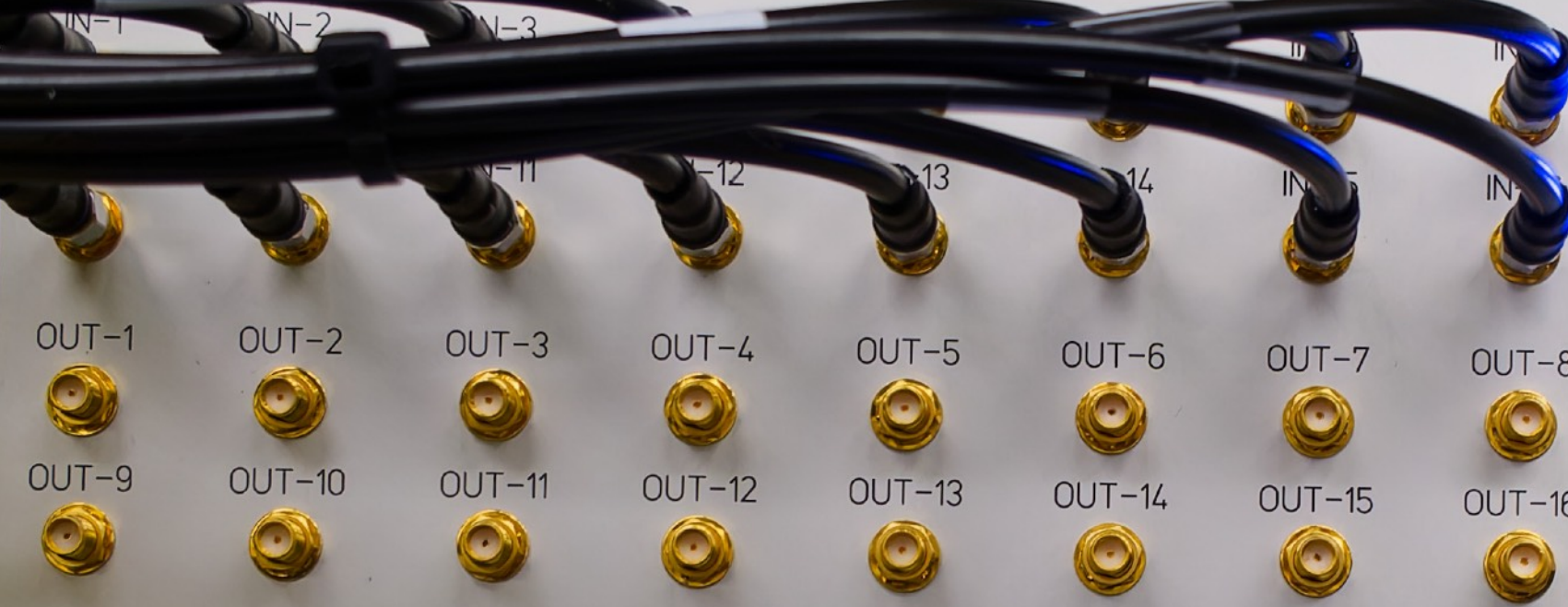








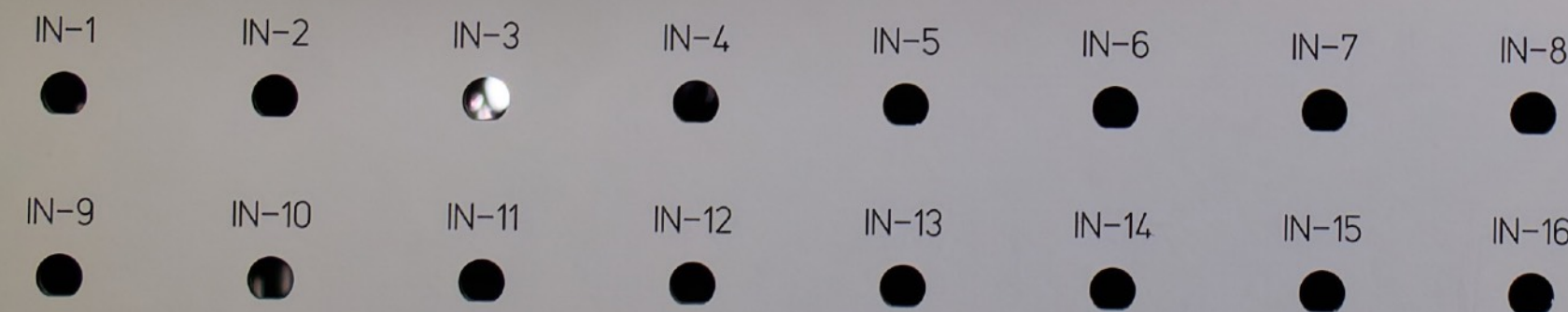
ATA Attenuator Module



- 5 V 1-2
- 5 V 2-2
- CLK
- DATA
- LE

- V
- C
- POWER

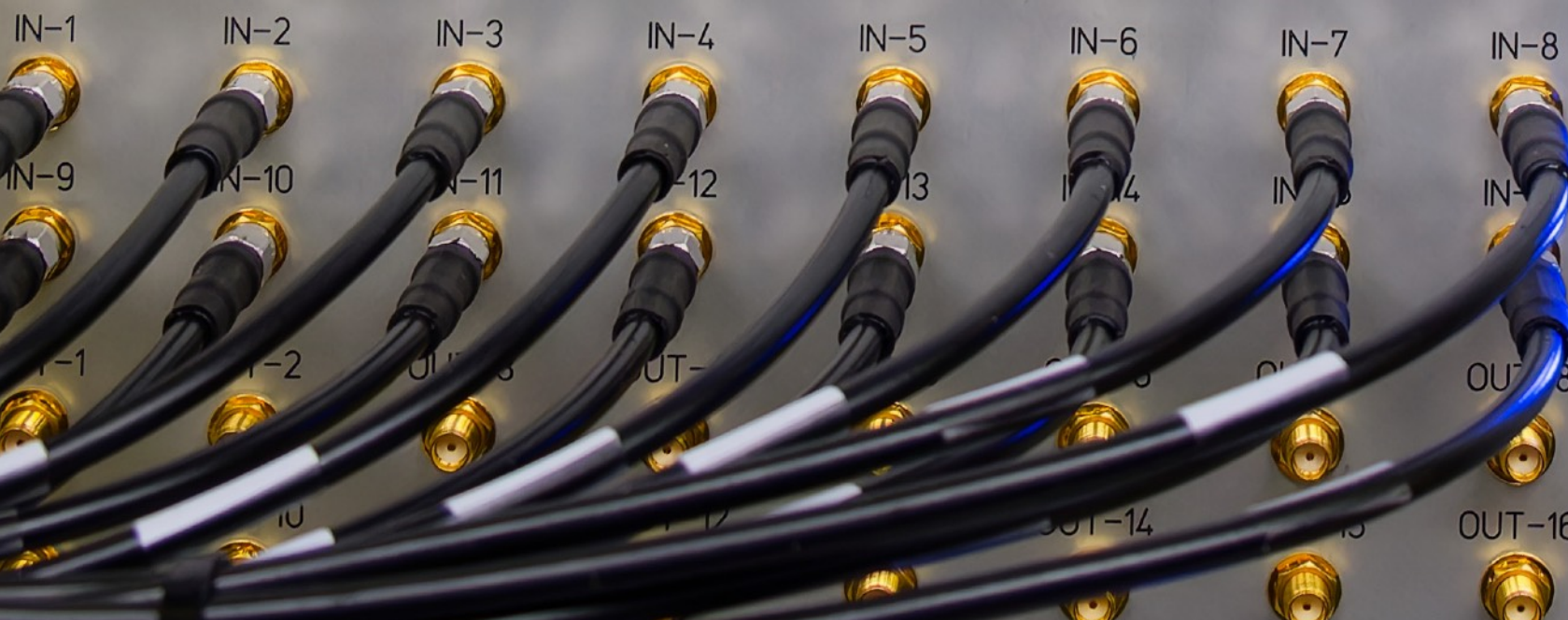
ATA RFSoc Digitizer



- 12 V
- 5 V
- Prog.
- 10 MHz
- 1 PPS

- POWER
- AV

ATA Attenuator Module



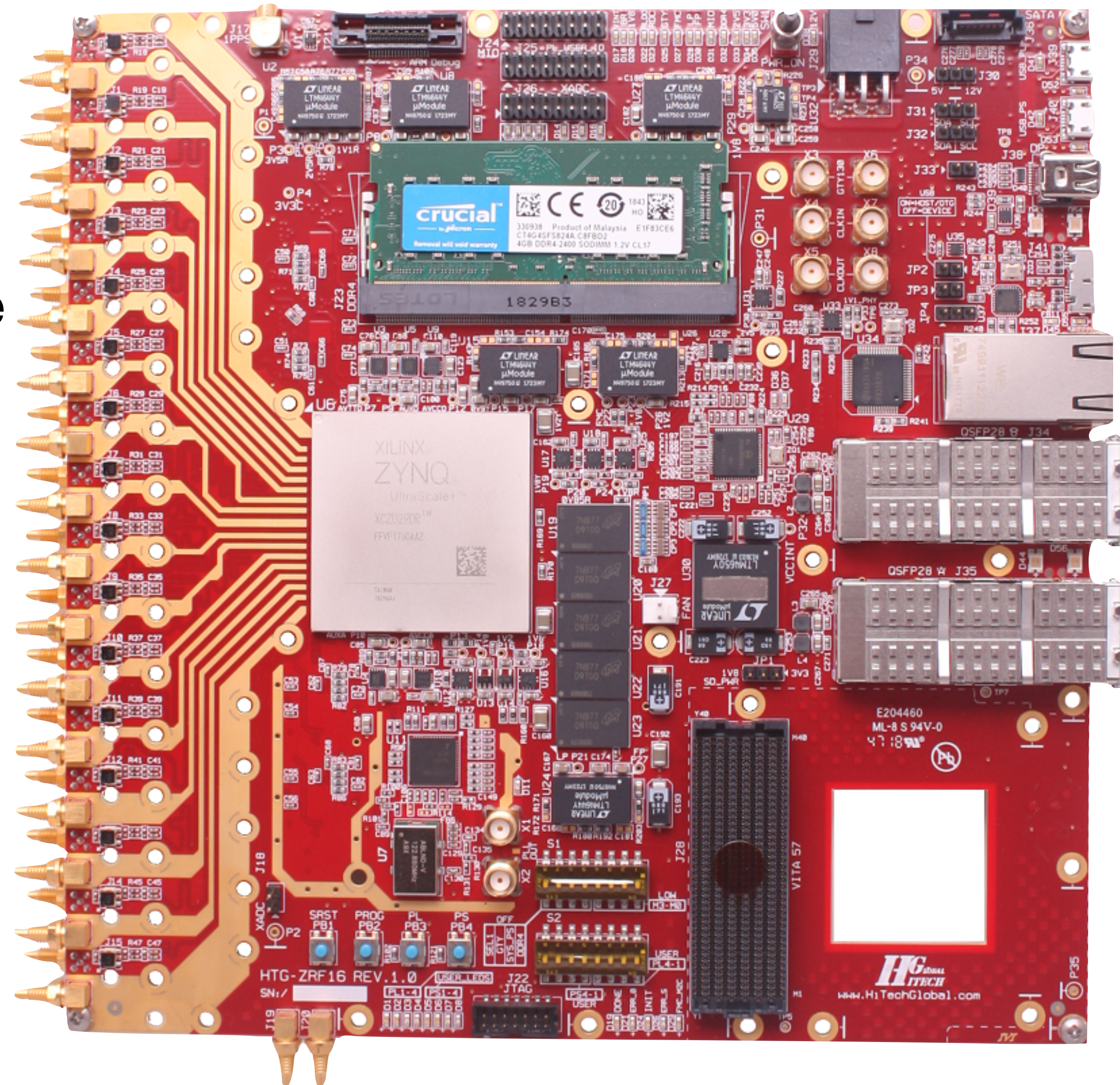
- 5 V 1-2
- 5 V 2-2
- CLK
- DATA
- LE

- V
- C
- POWER

# FPGA RFSoc Board

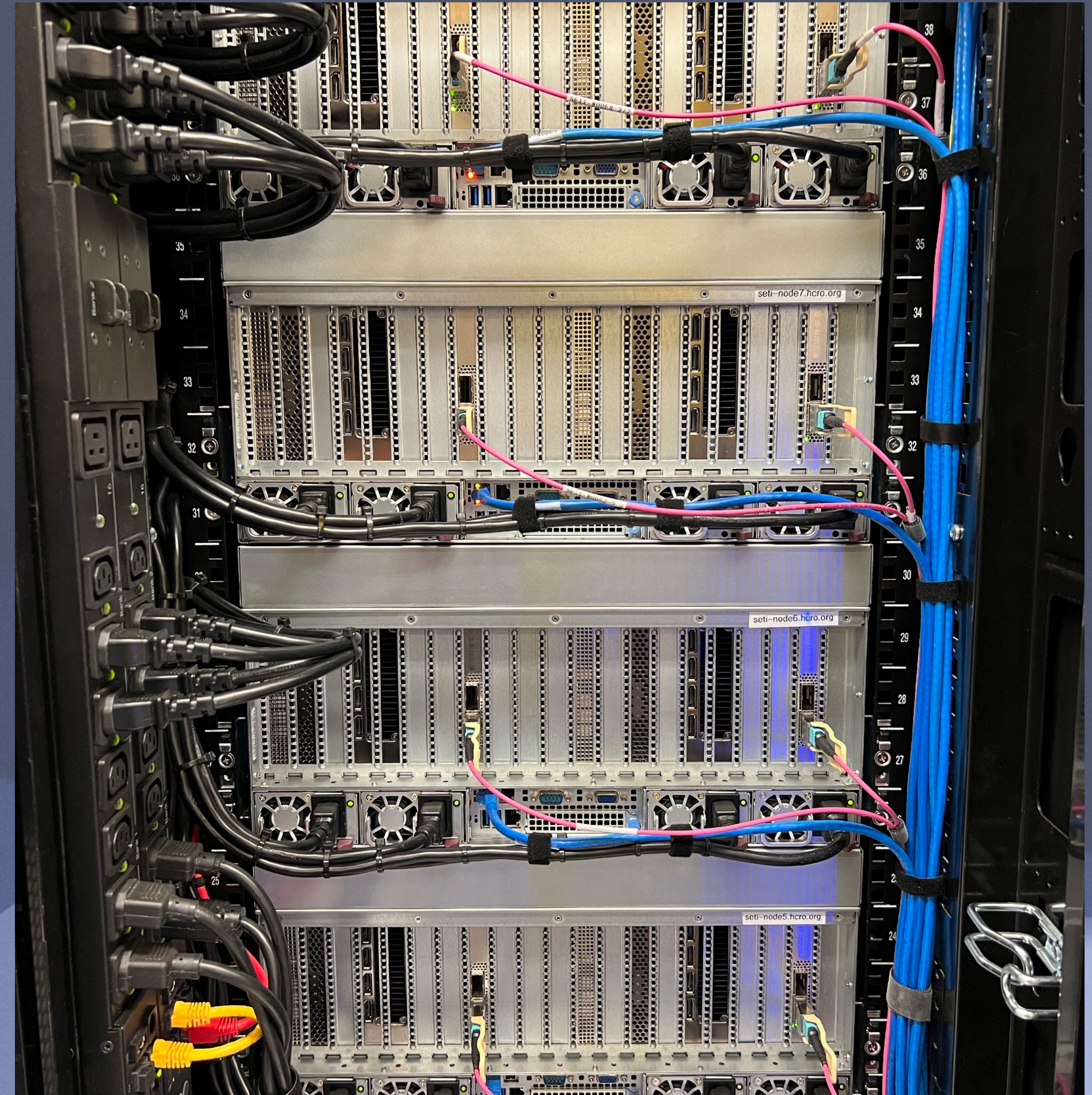
## Data Acquisition

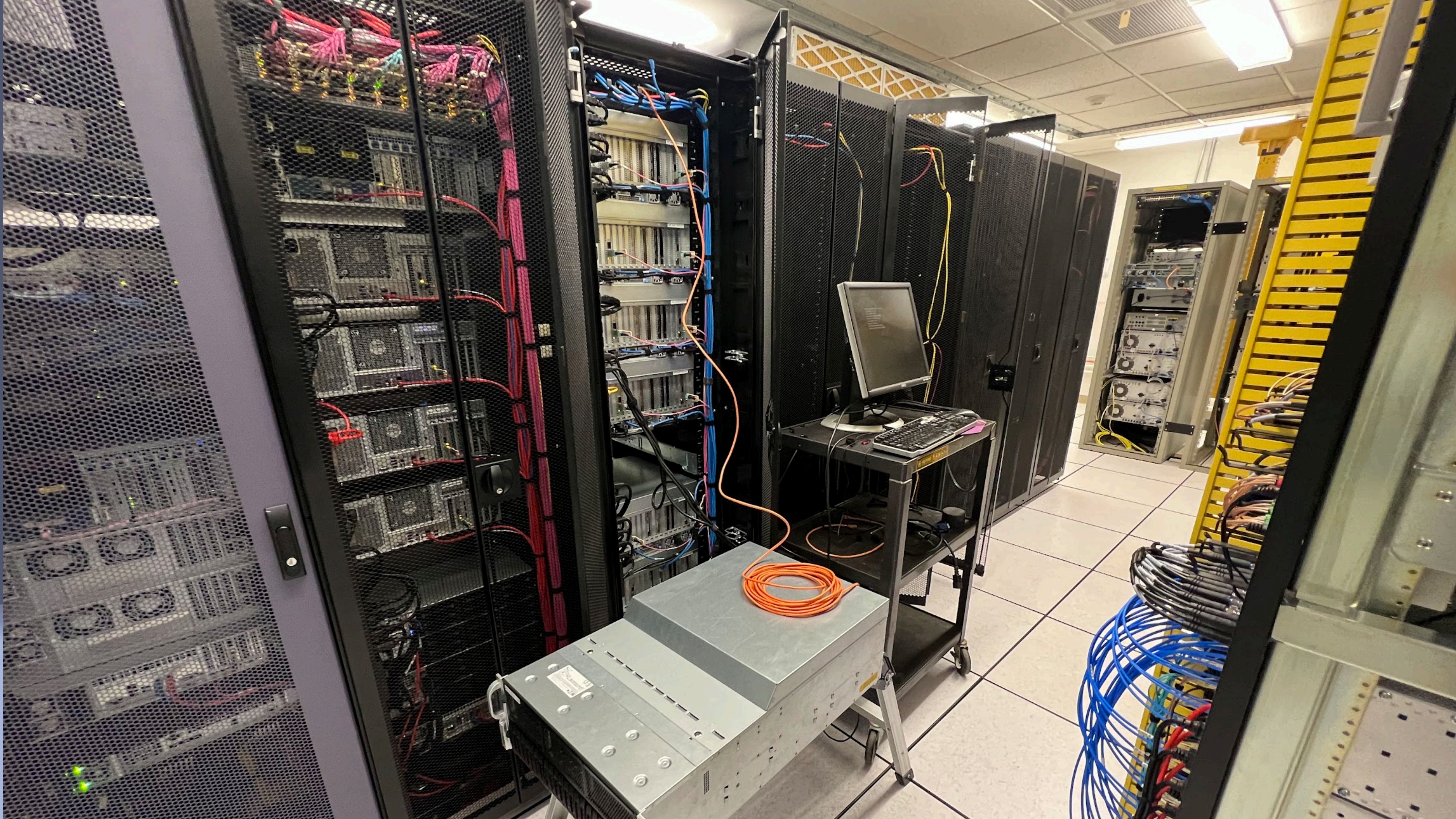
- Received radio signal is transmitted to the DSP room via RF over fiber.
- Signal is converted back to copper, pre-amplified, mixed, and distributed to the data-acquisition boards.
- Signal is digitized using RFSoc FPGA boards where it is pre-channelized, packetized, and sent over the network via 100G fiber.
- Data is received in the processing nodes.



# Allen Telescope Array Compute Cluster

- Compute cluster composed of 8 dual-socket EPYC servers with two NVIDIA RTX 3090 class graphics cards.
- Most of the computing is performed by the GPU.
- Two Mellanox Connect-X 5 dual 100G.
- Two PCIe x16 cards for NVMe cache.

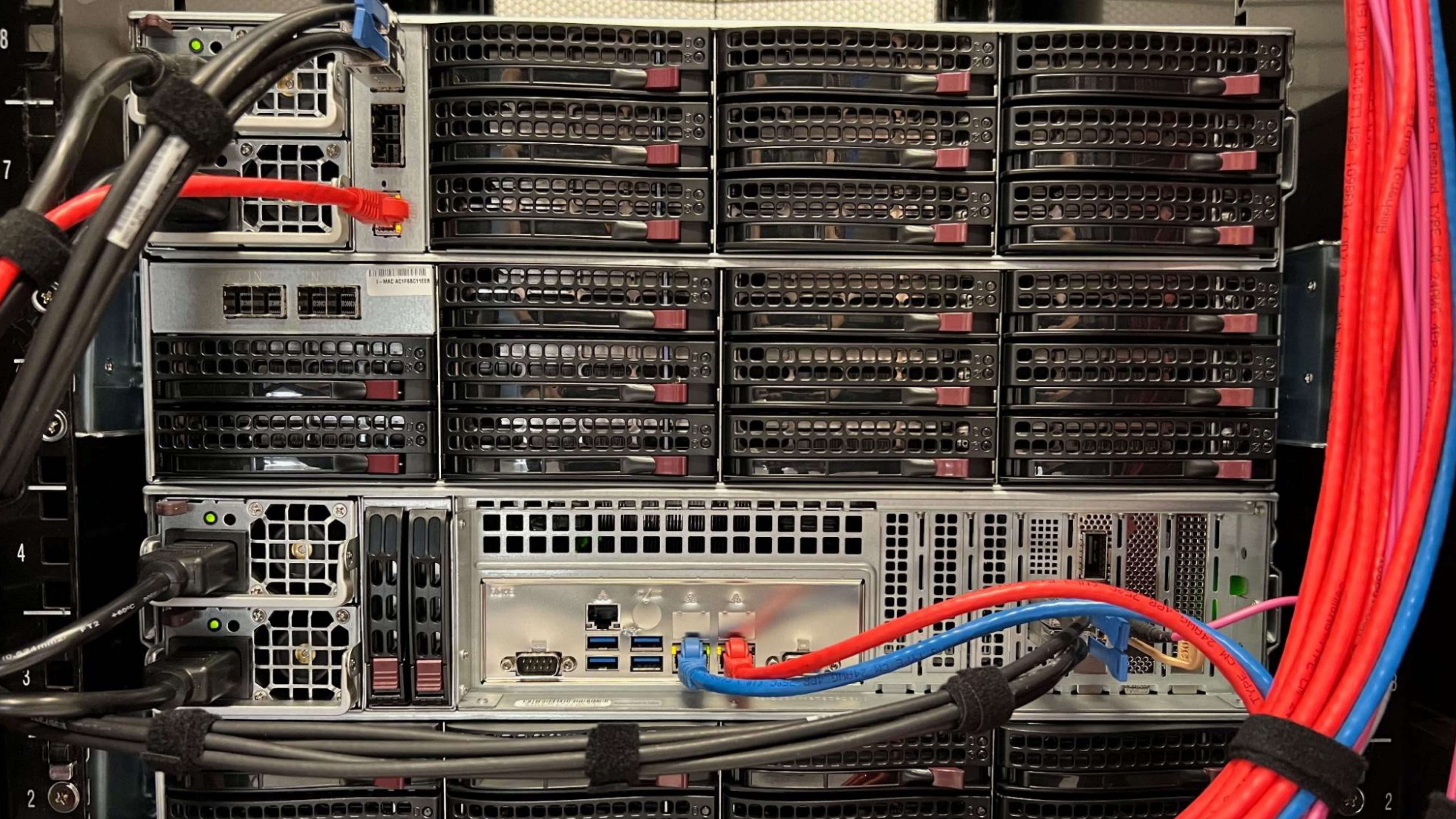






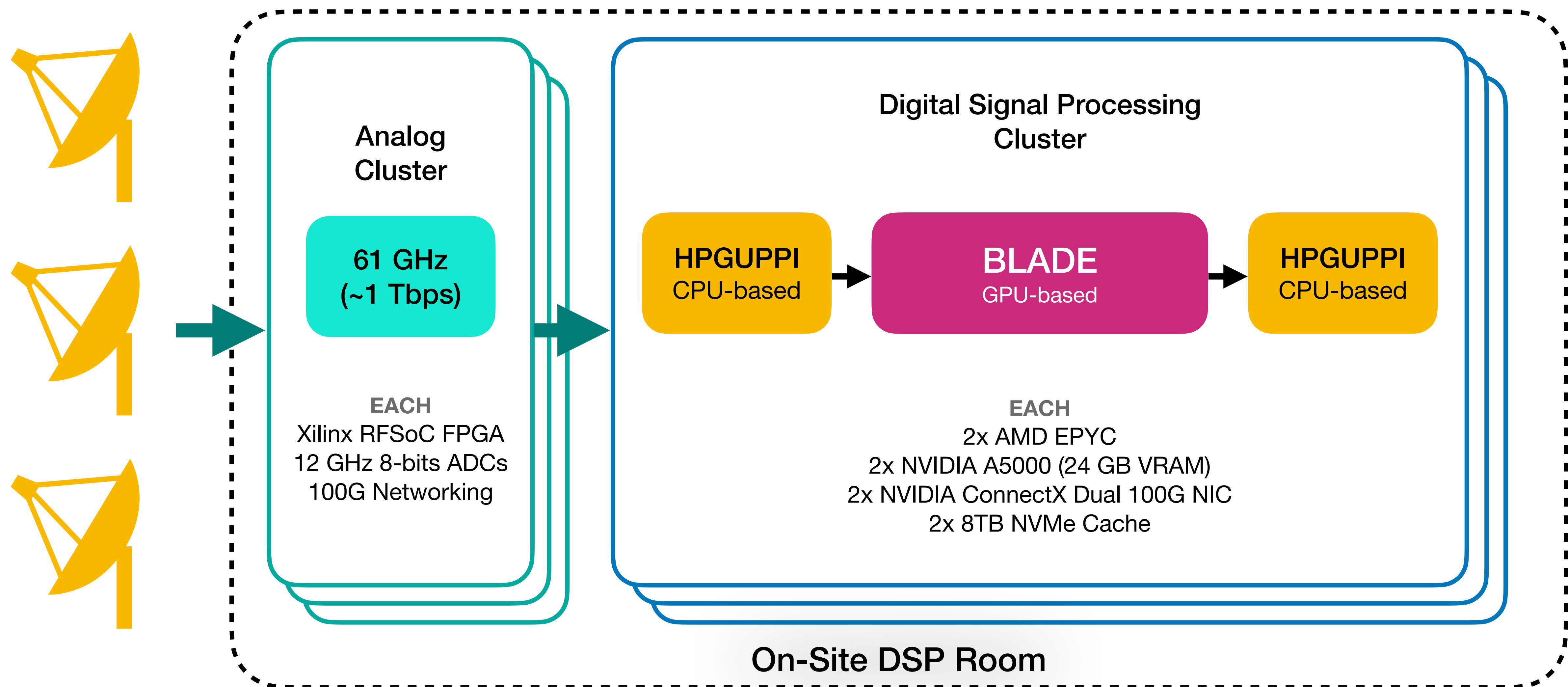
seti-node7.hcro.org

seti-node6.hcro.org



# Data Processing

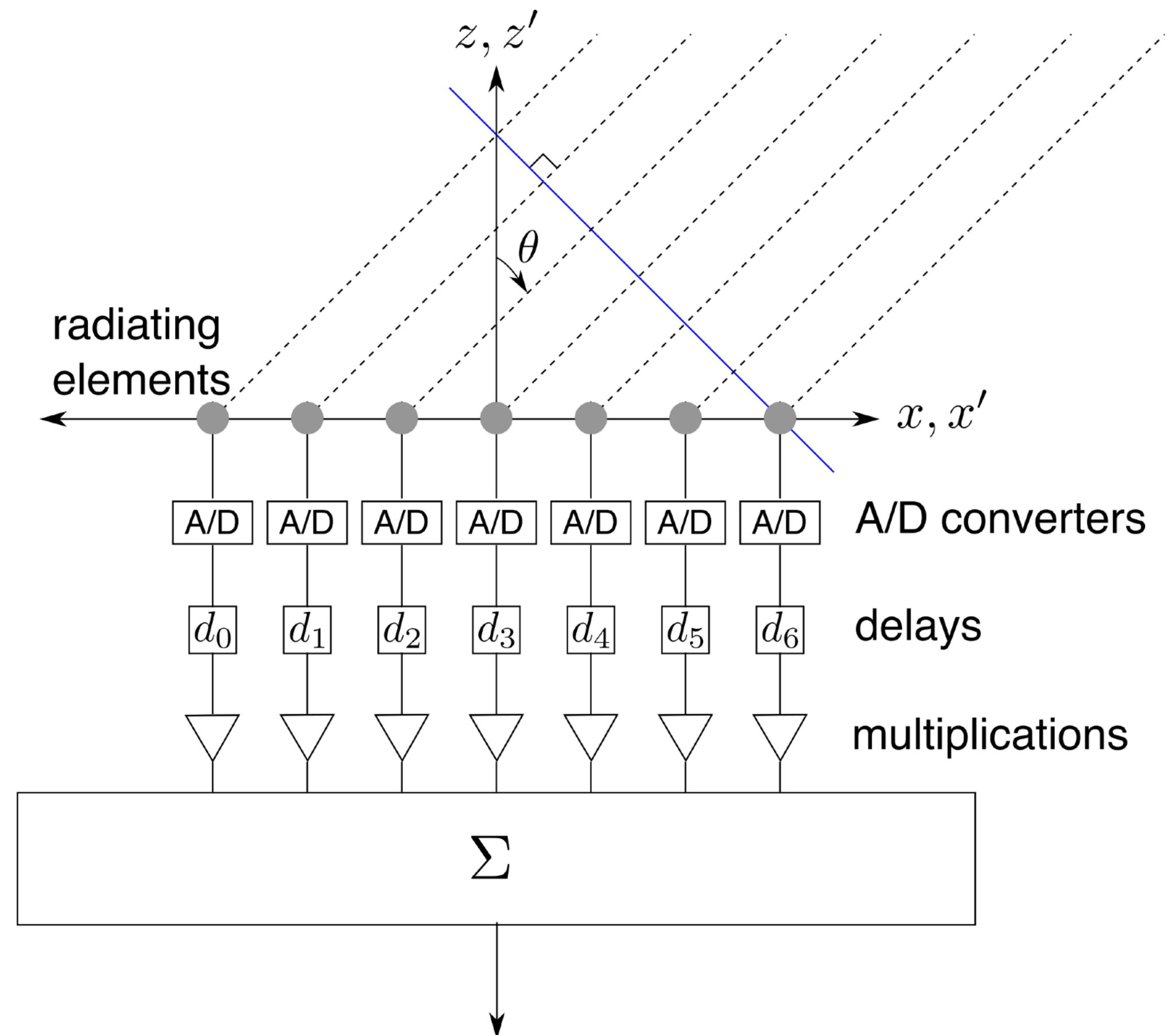
## Current Pipeline



# Allen Telescope Array

## Beamforming

- Signal processing technique used in sensor arrays (e.g., antennas or microphones) to focus on signals from a specific direction.
- Involves applying different weights and phases to the signals received by each element in the array.
- The weighted signals are then summed together to create a single output signal.
- The weights and phases are chosen to enhance signals from the desired direction (main lobe) and suppress signals from other directions (side lobes).
- Beamforming is used in applications such as wireless communication, radar, sonar, and audio processing to improve signal quality and spatial selectivity.



$$y(t) = \sum_{n=1}^N w_n \cdot x_n(t)$$

# BLADE

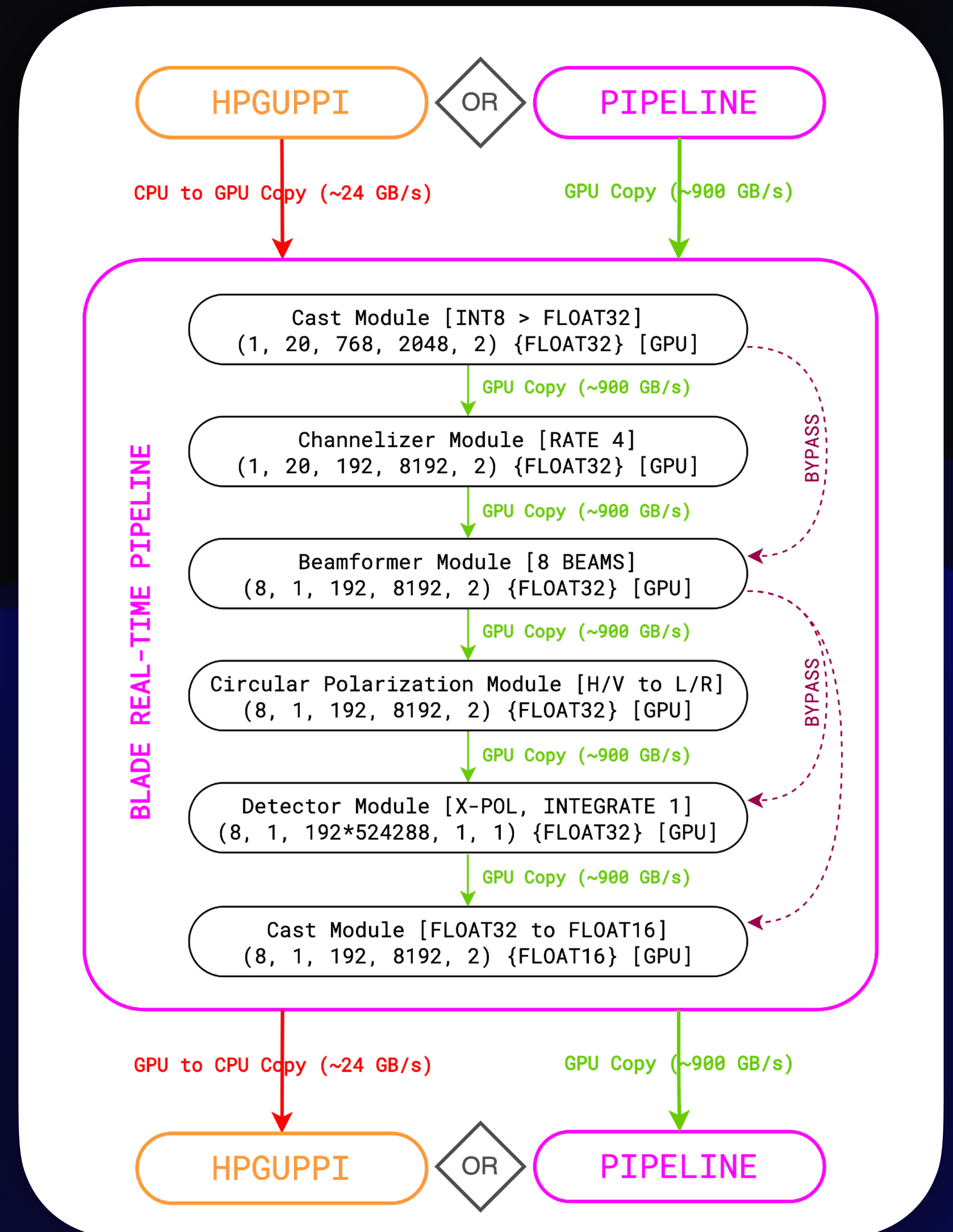
## Breakthrough Listen Accelerated DSP Engine

- Responsible for most of the Digital Signal Processing of the ATA.
- Currently processing data incoming from 20 antennas with more soon!
- Each antenna represents ~3.0 GHz of bandwidth in 8 bits samples.
- Equates to an aggregated ~960 Gbps in 16 instances (~60 Gbps/instance).
- Currently implements 8 processing modules (beamforming, channelization, etc).
- Design rules followed:
  - Performant while hackable.
  - Not afraid to use new tech (C++20, JIT Kernels, etc).
  - Low number of dependencies.

# BLADE

## Overall Architecture

- Each module represents a compute operation (cast, beamforming, channelization, polarization, etc).
- A sequence of modules is contained inside a pipeline. It's also responsible to interface with the host device and hold staging buffers.
- Runner will hold one or more (ideally two) pipelines described as workers. The runner will asynchronously schedule the execution optimizing for maximum parallelization.



Polarizer

Correlator

BFR5

Guppi

**And many more...**

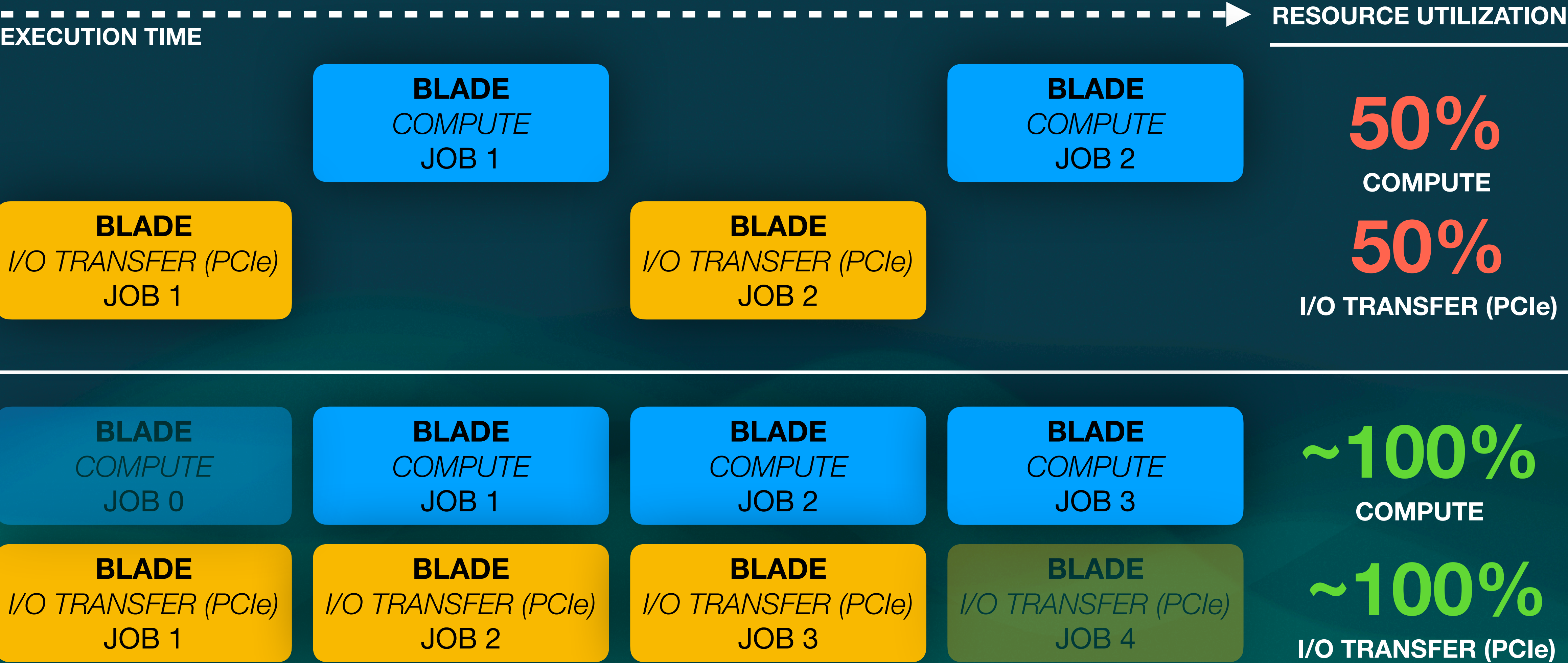
Detector

Cast

Phasor

# Concurrent Execution

## Asynchronous Worker Pool



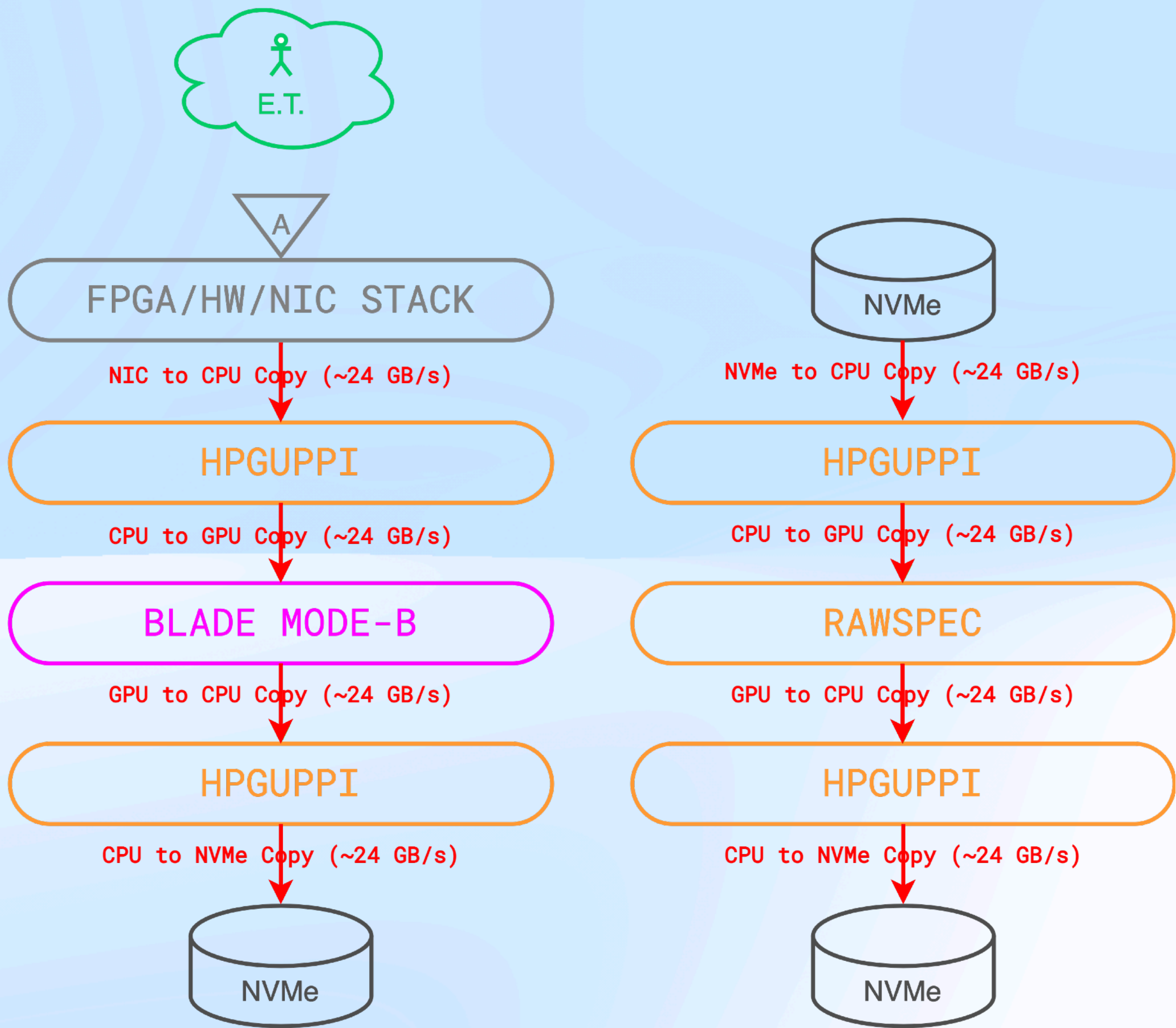
BLADE v0.6.5

PREVIOUS PRODUCTION

- 8x PCIe 4.0 Hops

- 2x NVMe Writes

- 1x NVMe Reads



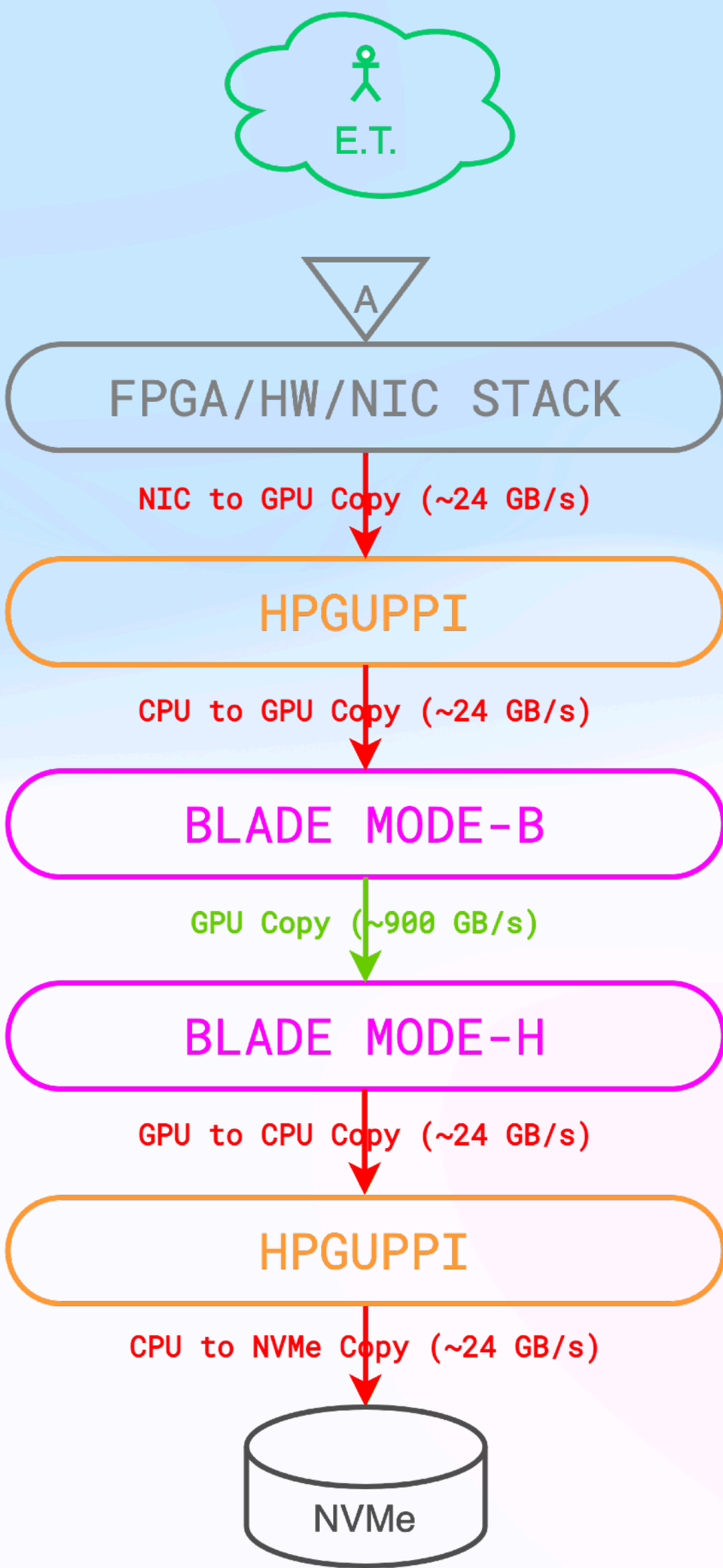
CPU  BLADE  NOT COMPUTER

BLADE v0.7.0

CURRENT PRODUCTION

- 4x PCIe 4.0 Hops

- 1x NVMe Writes

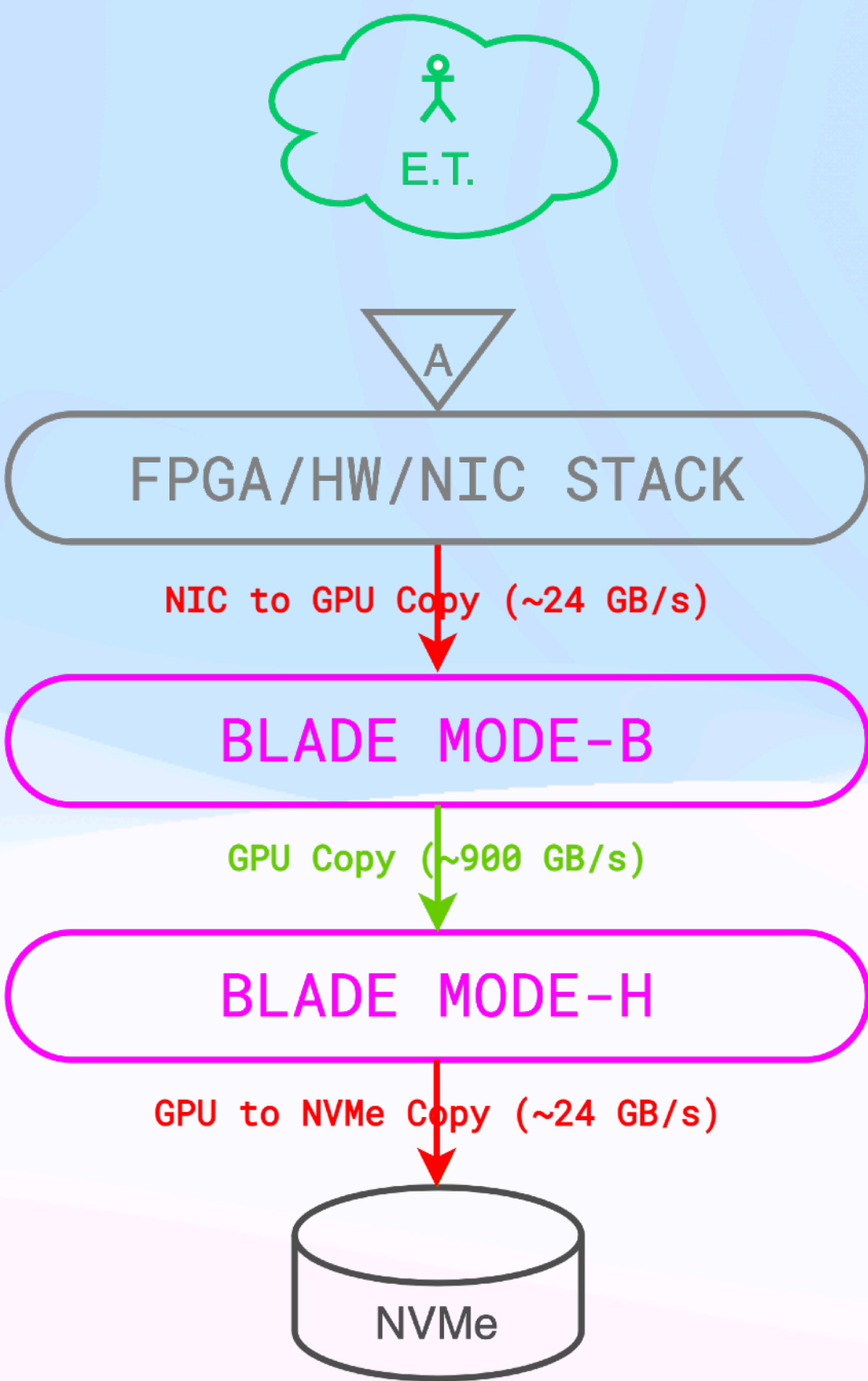


BLADE

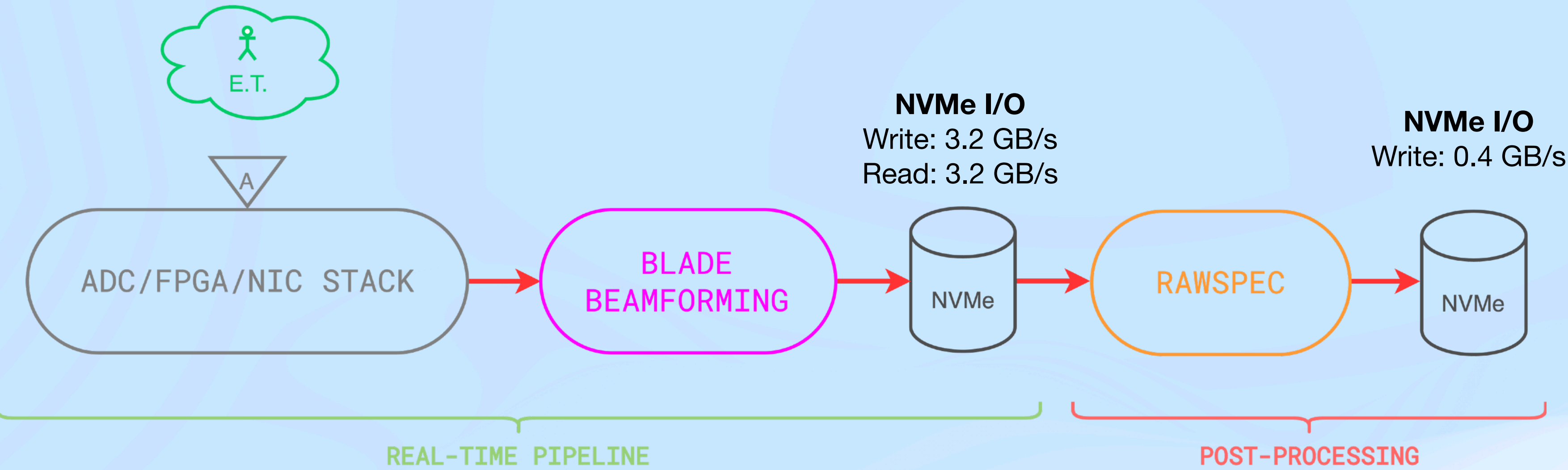
NEXT

- 2x PCIe 4.0 Hops

- 1x NVMe Writes



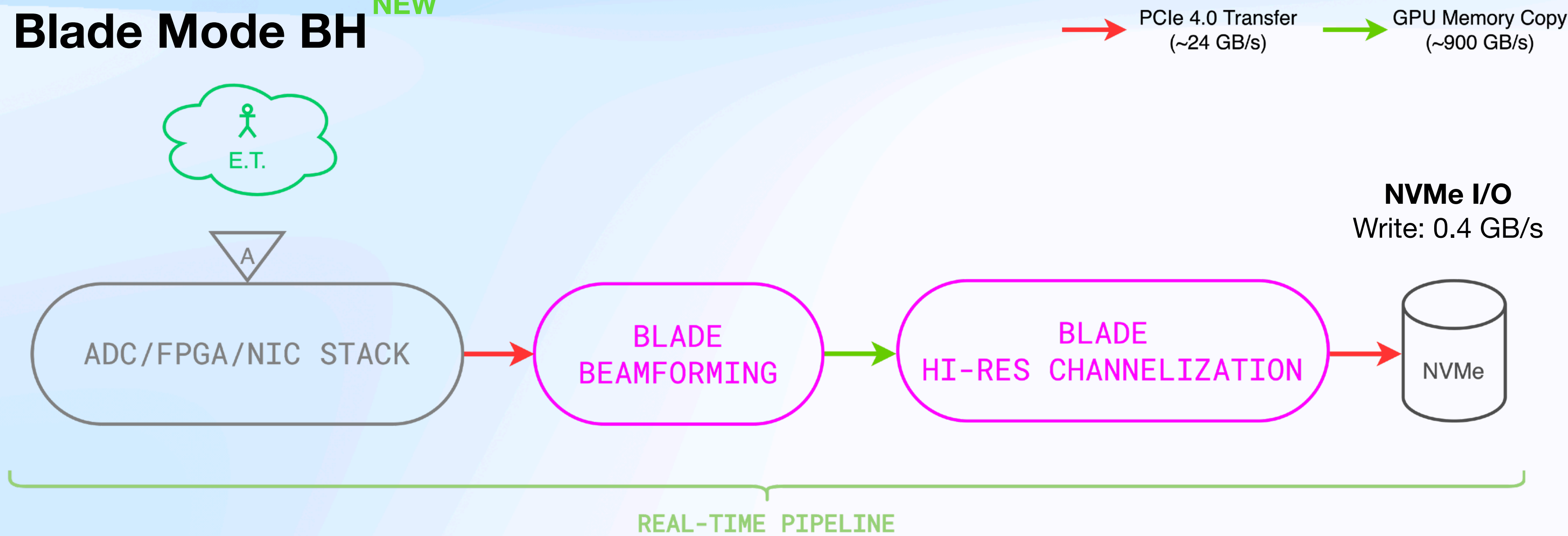
# Blade Mode B + RAWSPEC



**Mode B + RAWSPEC**  
**Total NVMe I/O**  
Write: 3.6 GB/s  
Read: 3.2 GB/s

**Sample Observation**  
Array Tensor: [A: 20, F: 192, T: 8192, P: 2]  
Integration: 4 samples  
Detection: Stokes-I (F32)

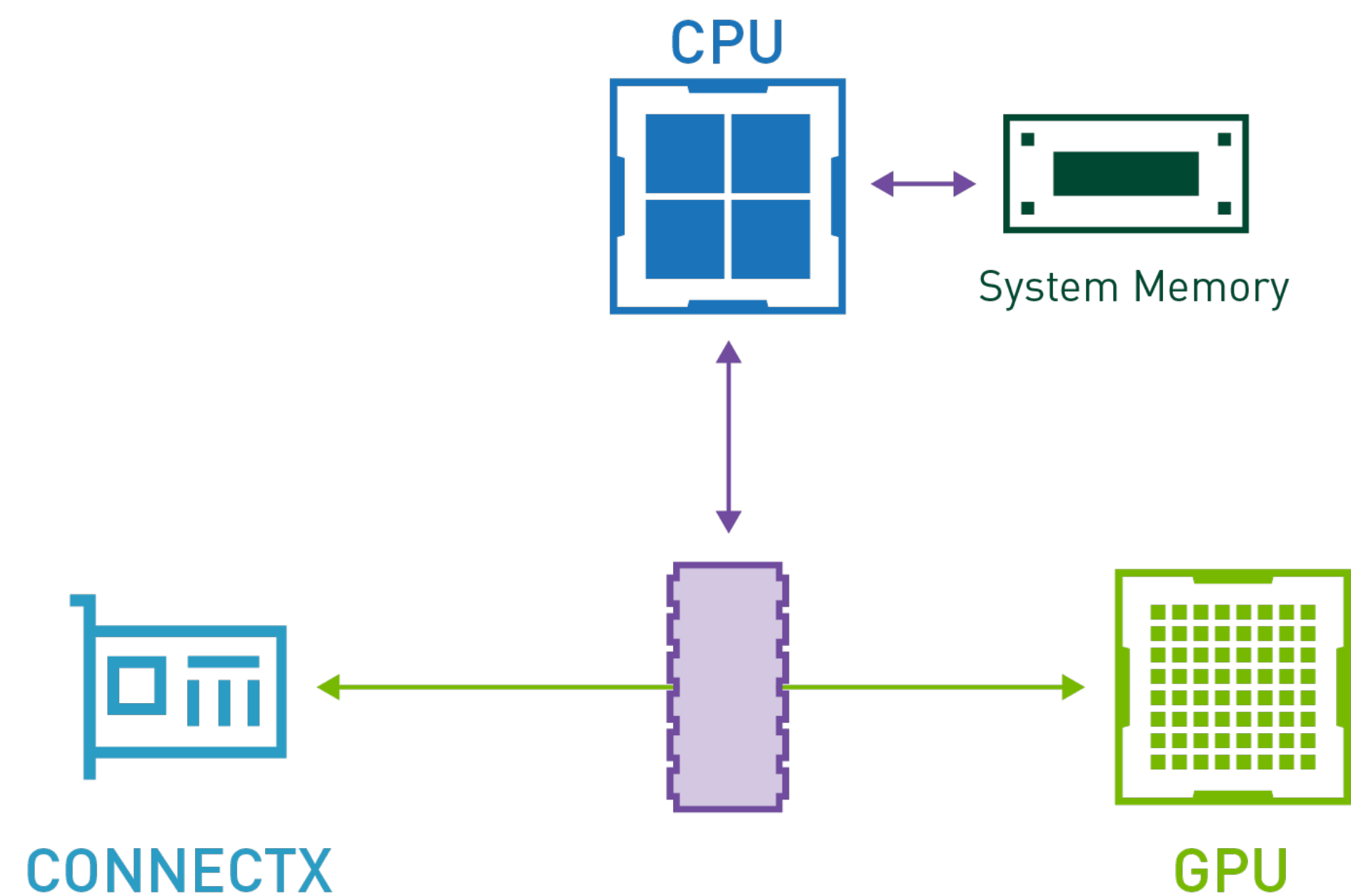
# Blade Mode BH<sup>NEW</sup>



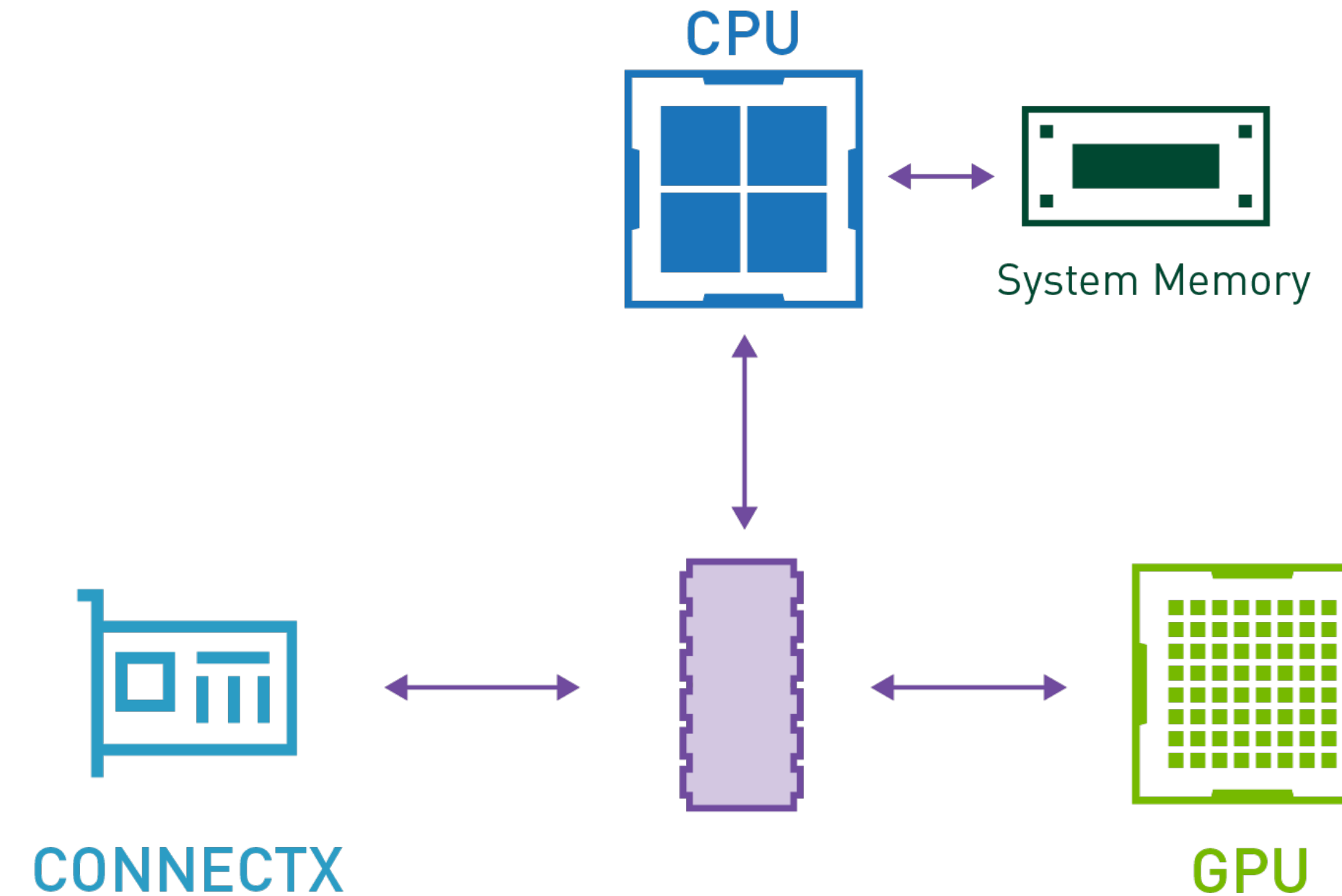
**Mode BH**  
**Total NVMe I/O**  
Write: 0.4 GB/s  
Read: N/A

# NVIDIA Holoscan

## Advanced Network Operator (ANO)



Single RDMA Transfer  
(NIC -> GPU)



Two Transfers  
(NIC -> CPU -> GPU)



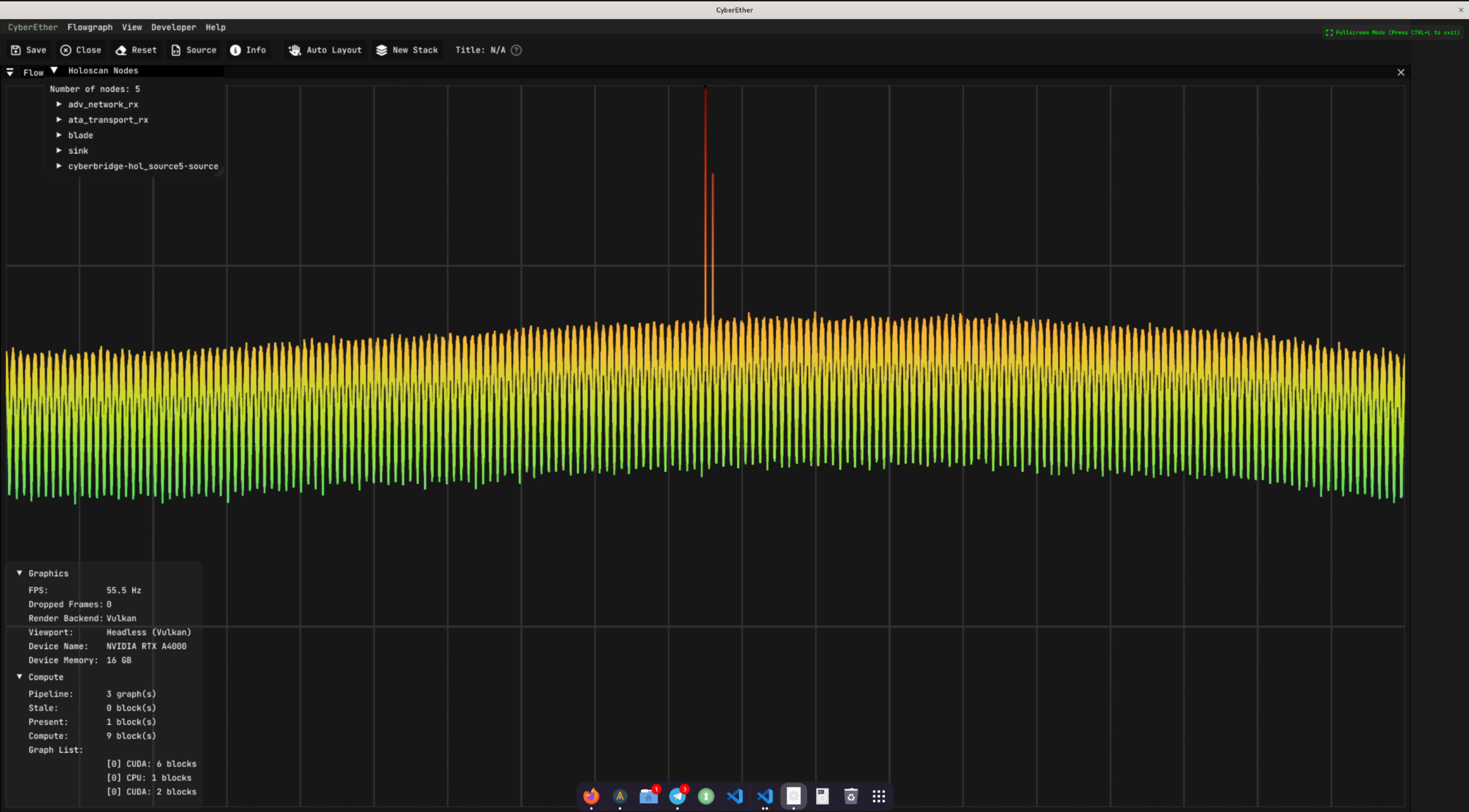
PCIe Switch



GPUDirect RDMA

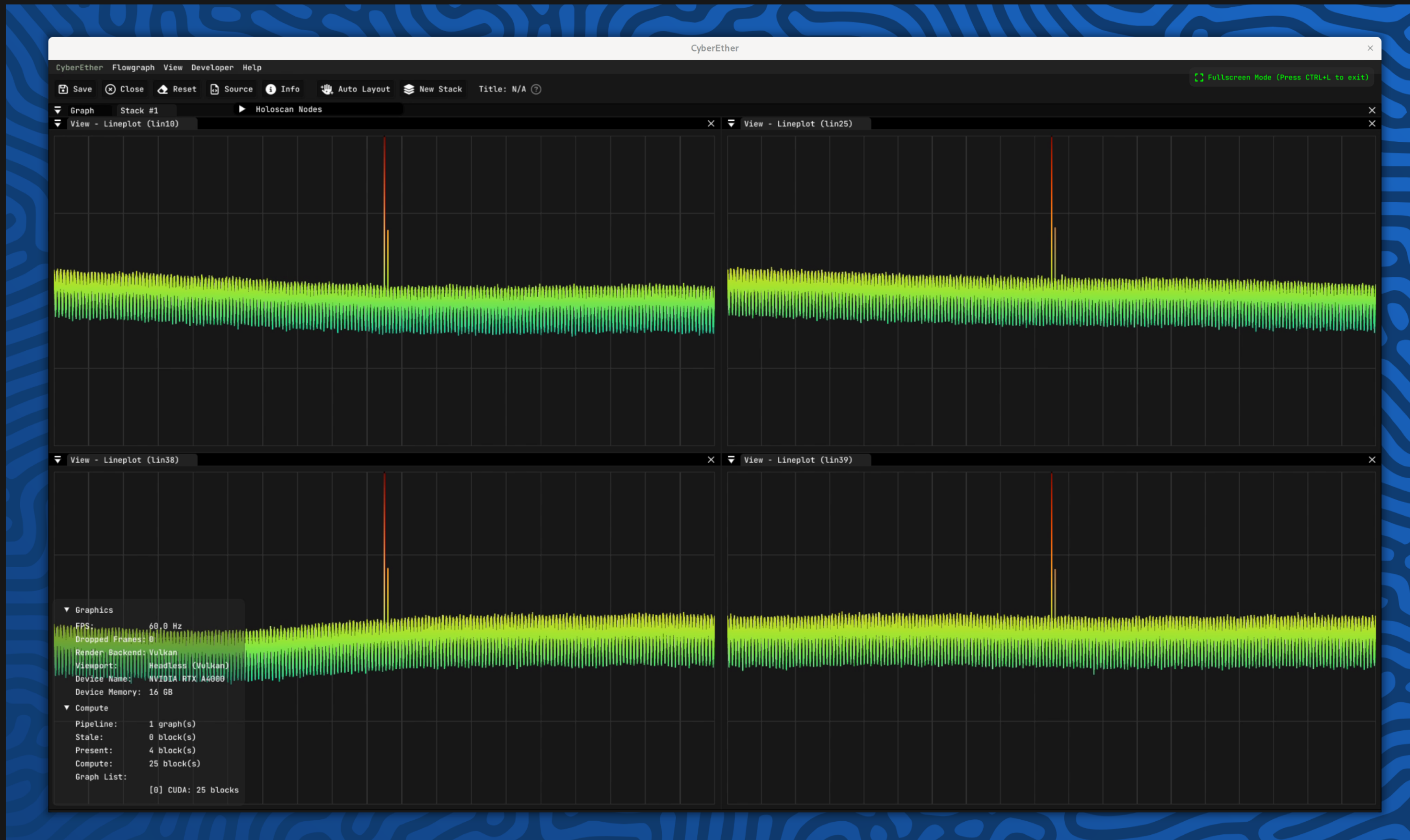
# Data Processing

## Holoscan + CyberEther Pipeline



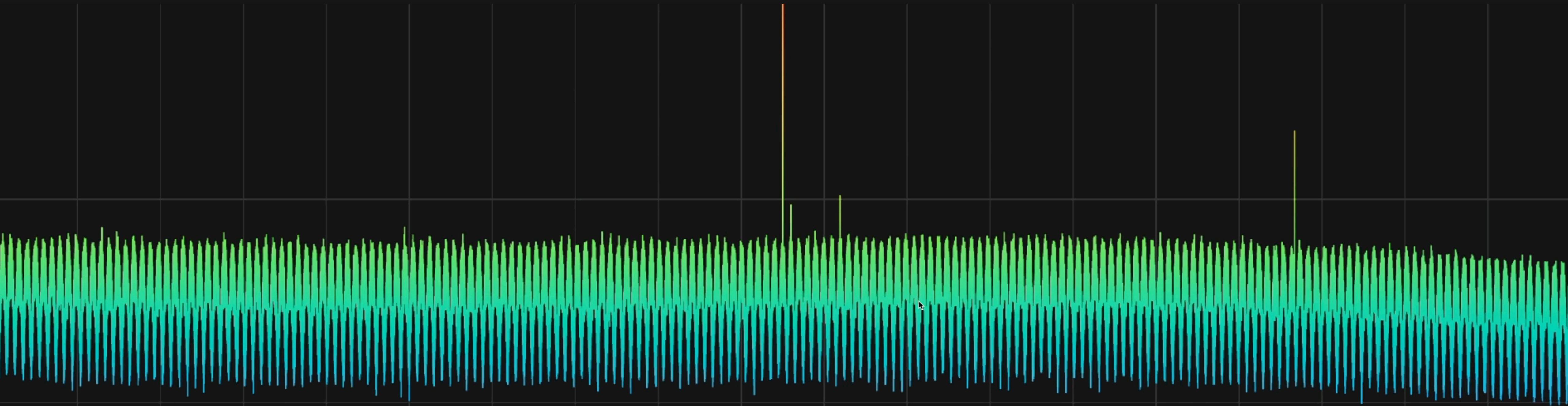
# Data Processing

## Holoscan + CyberEther Pipeline



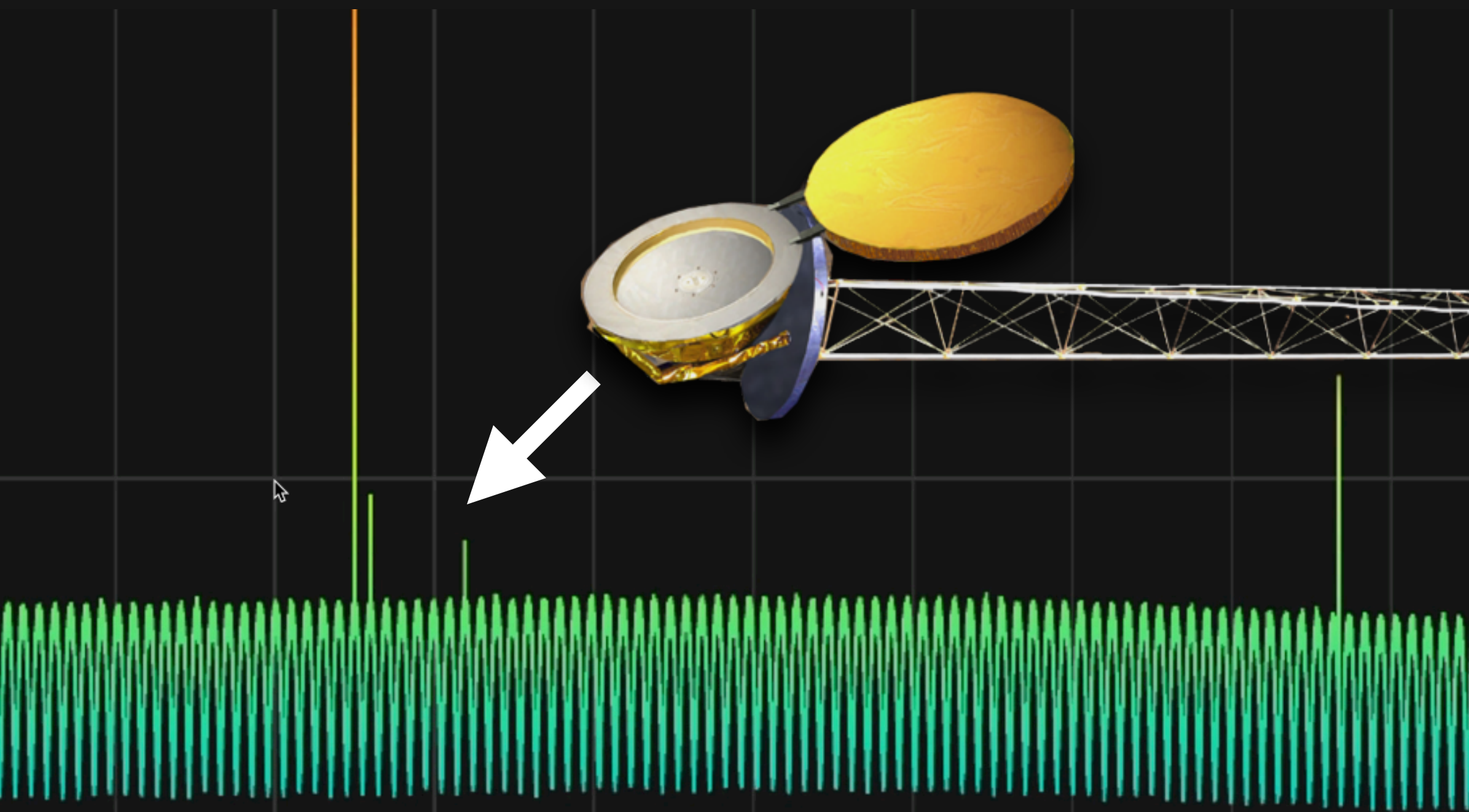
# Deep Space Demonstration

Allen Telescope Array Holoscan Pipeline



# Deep Space Demonstration

Allen Telescope Array Holoscan Pipeline

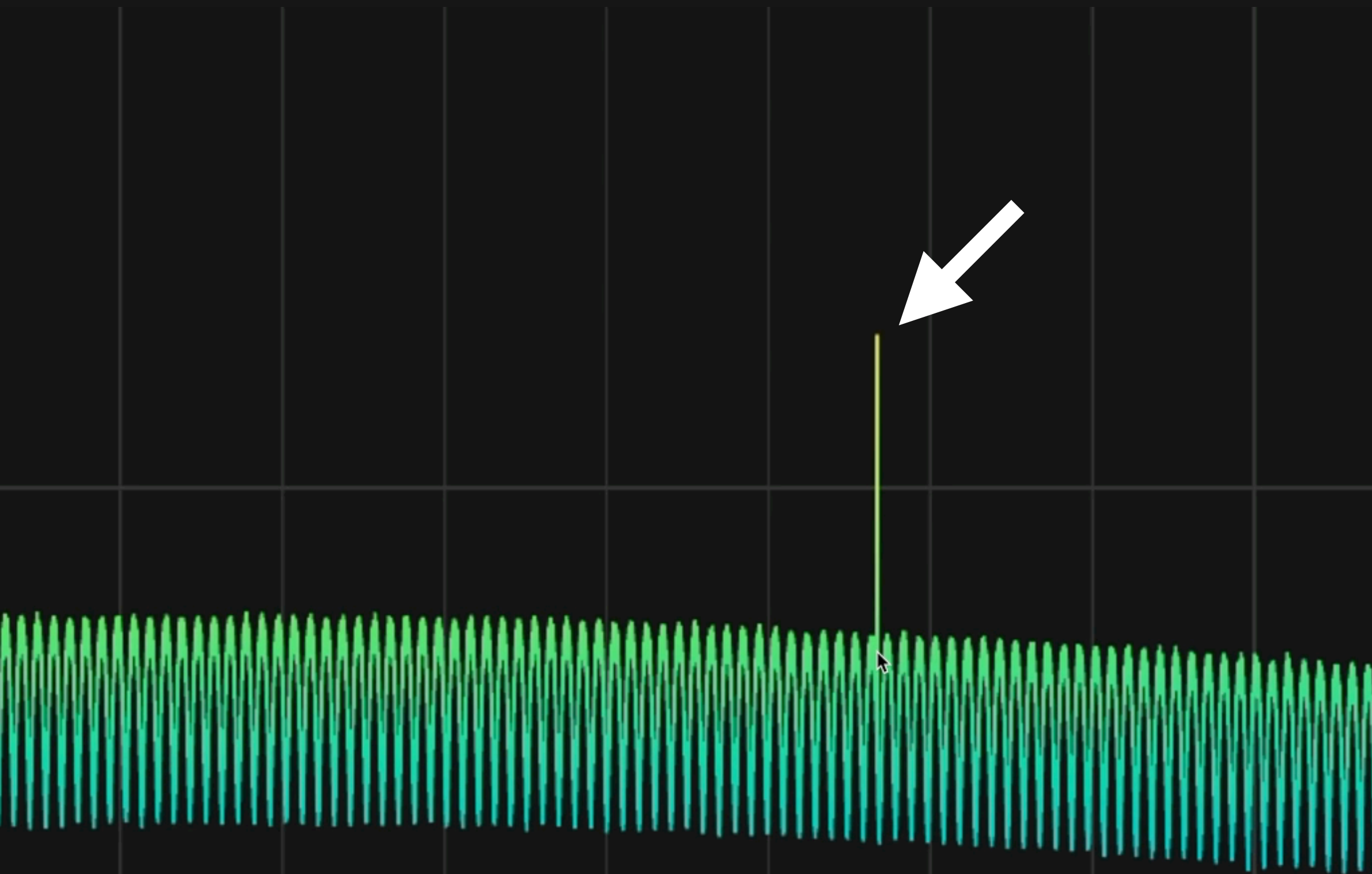


~8406 MHz

# Mars Odyssey

# Deep Space Demonstration

Allen Telescope Array Holoscan Pipeline



~8430 MHz

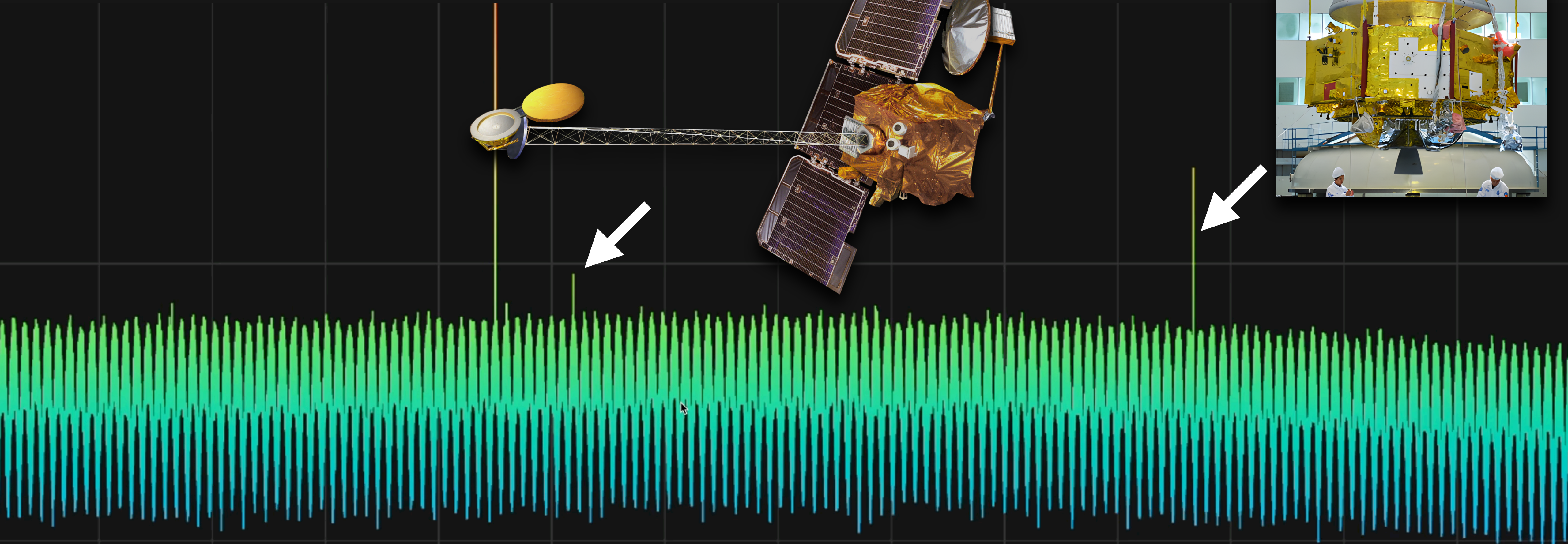
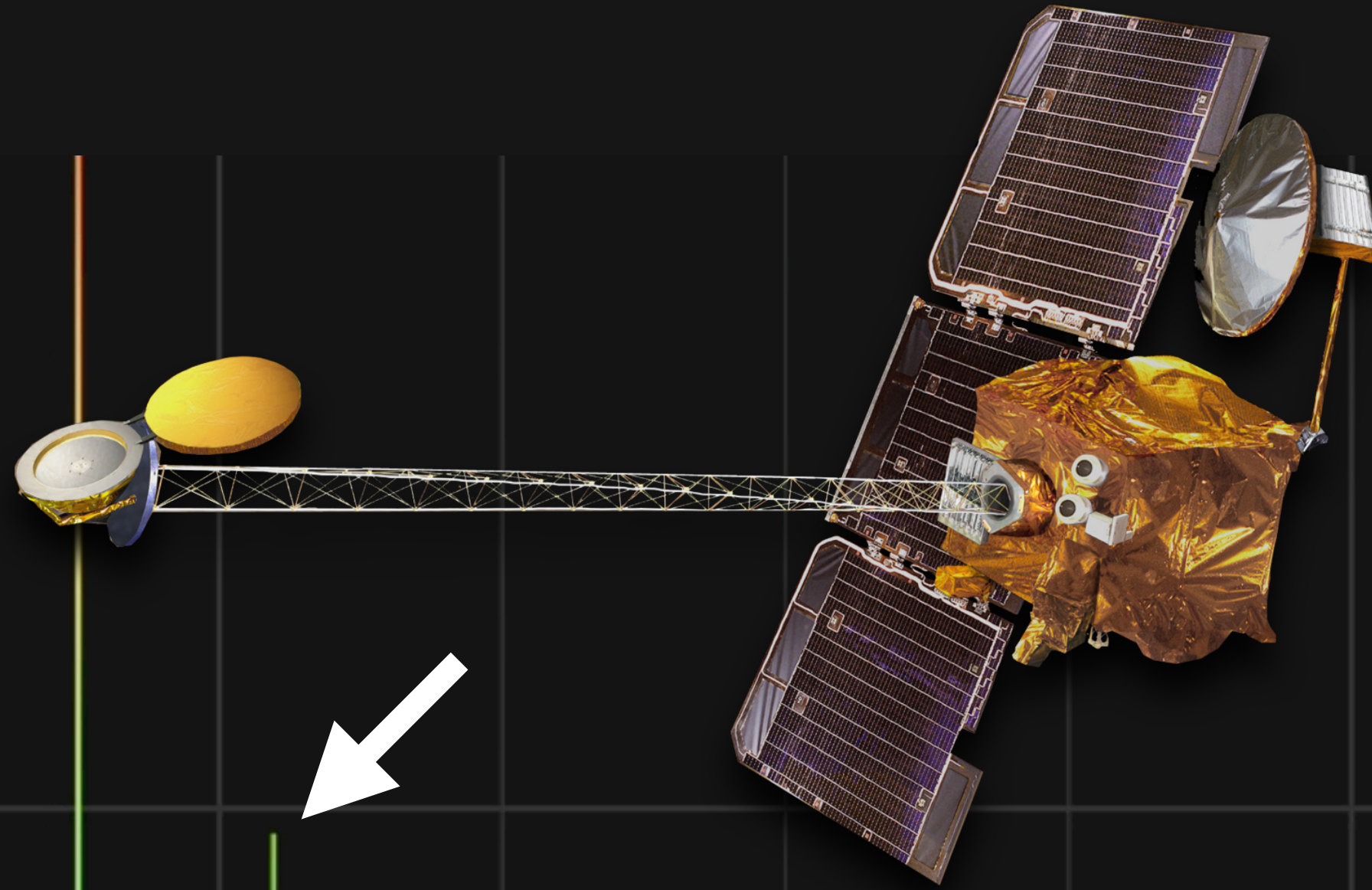


# Tianwen

天问一号

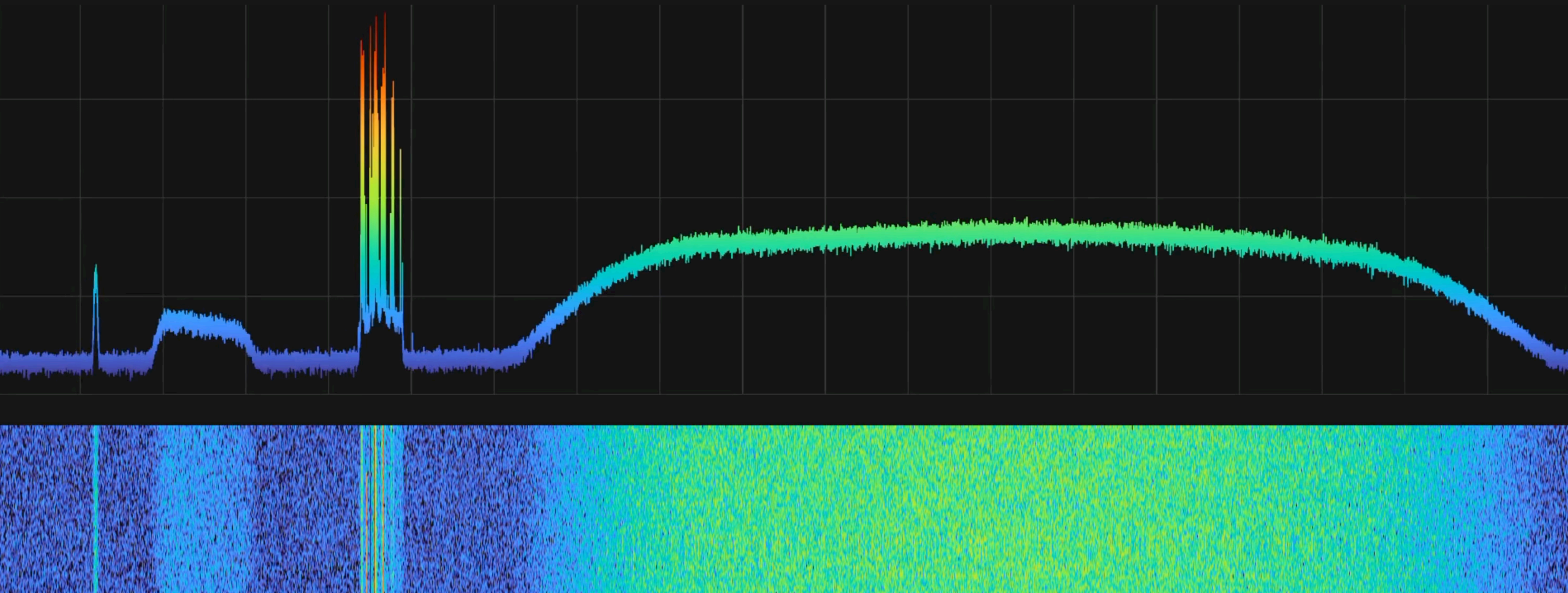
# Deep Space Demonstration

Allen Telescope Array Holoscan Pipeline



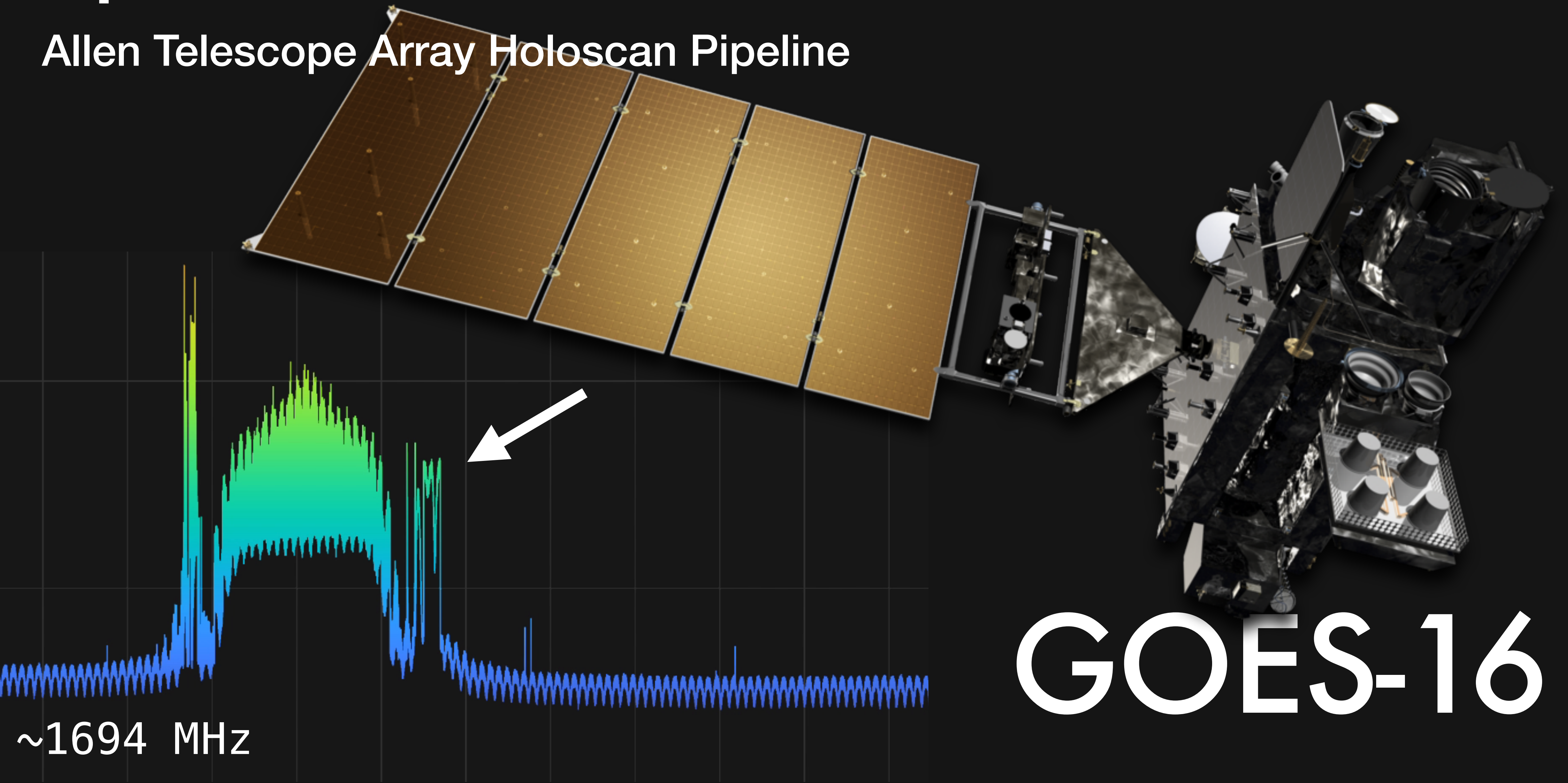
# Space Demonstration

Allen Telescope Array Holoscan Pipeline



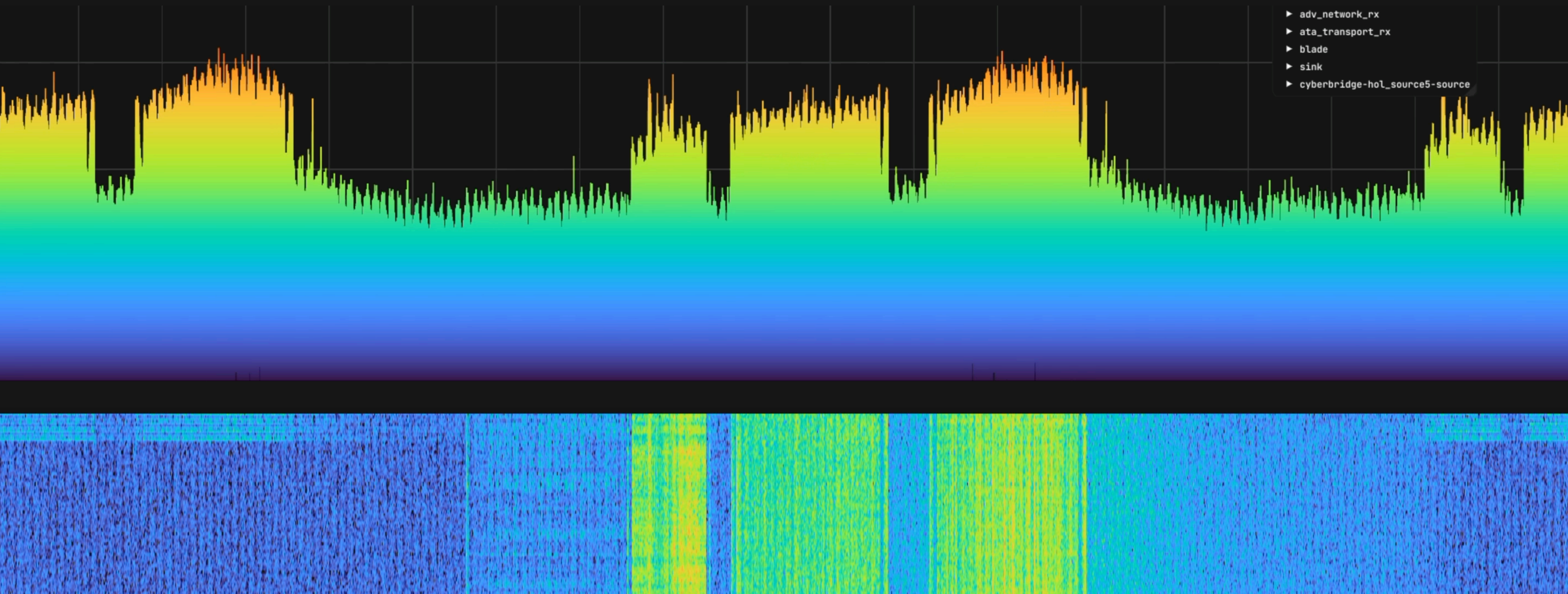
# Space Demonstration

Allen Telescope Array Holoscan Pipeline



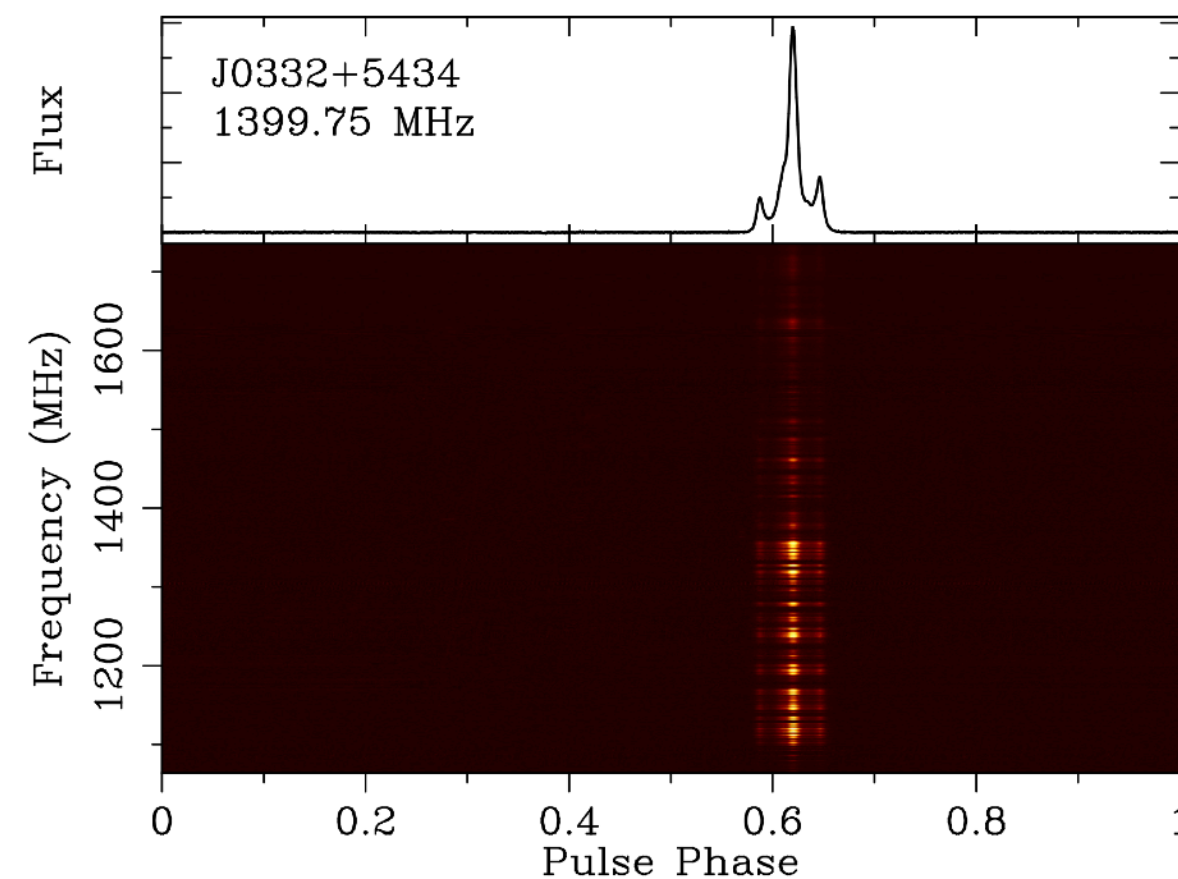
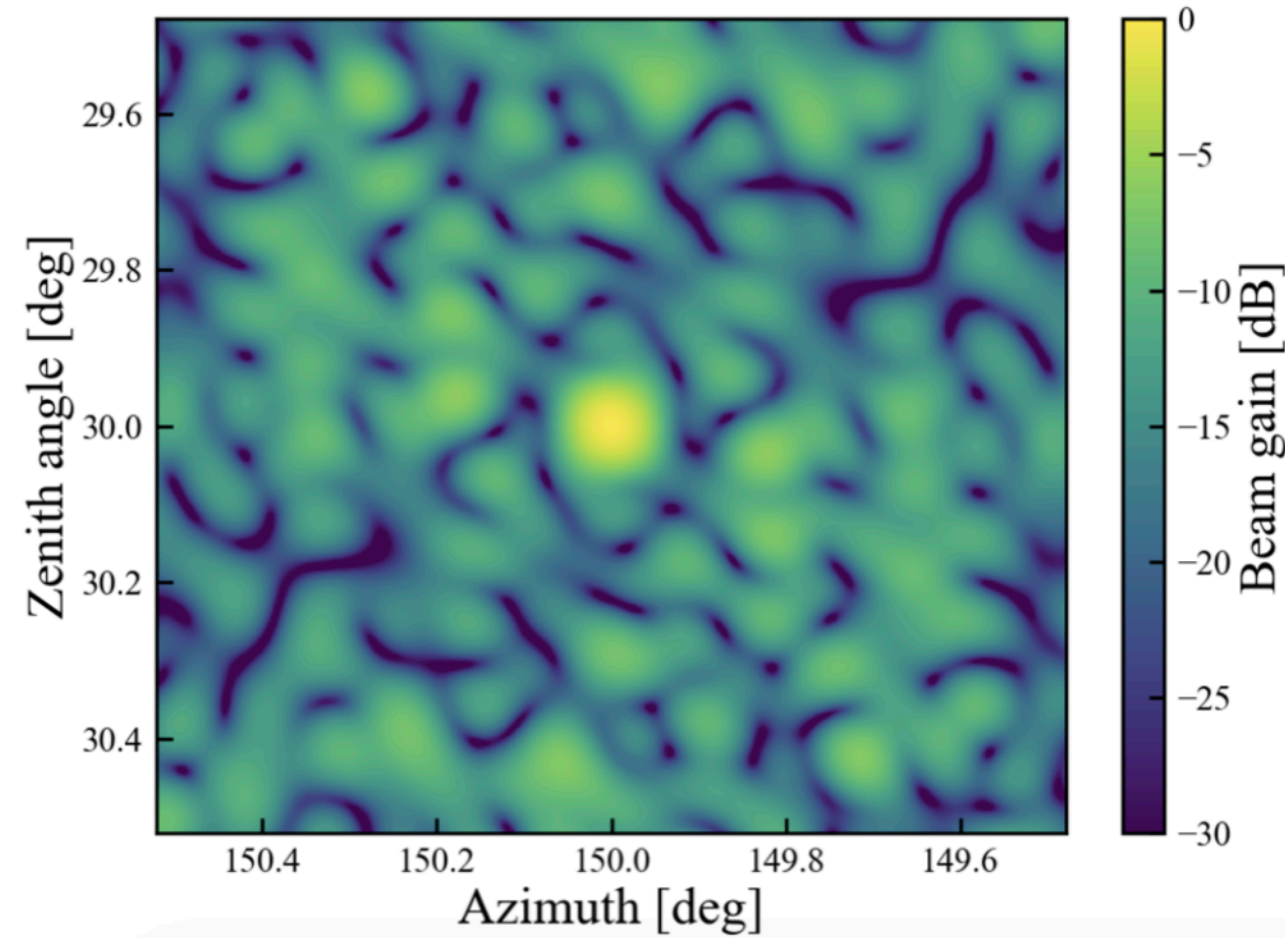
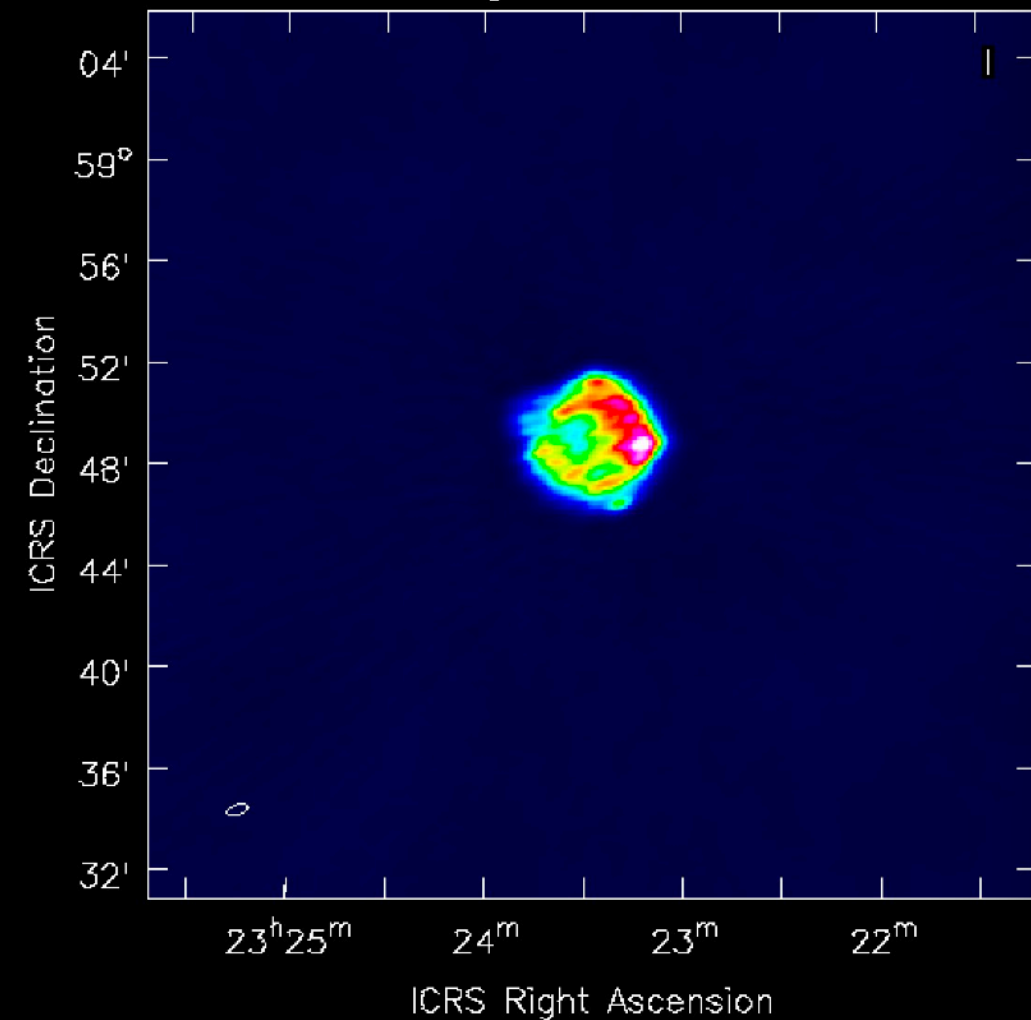
# Space Demonstration

## Allen Telescope Array Holoscan Pipeline

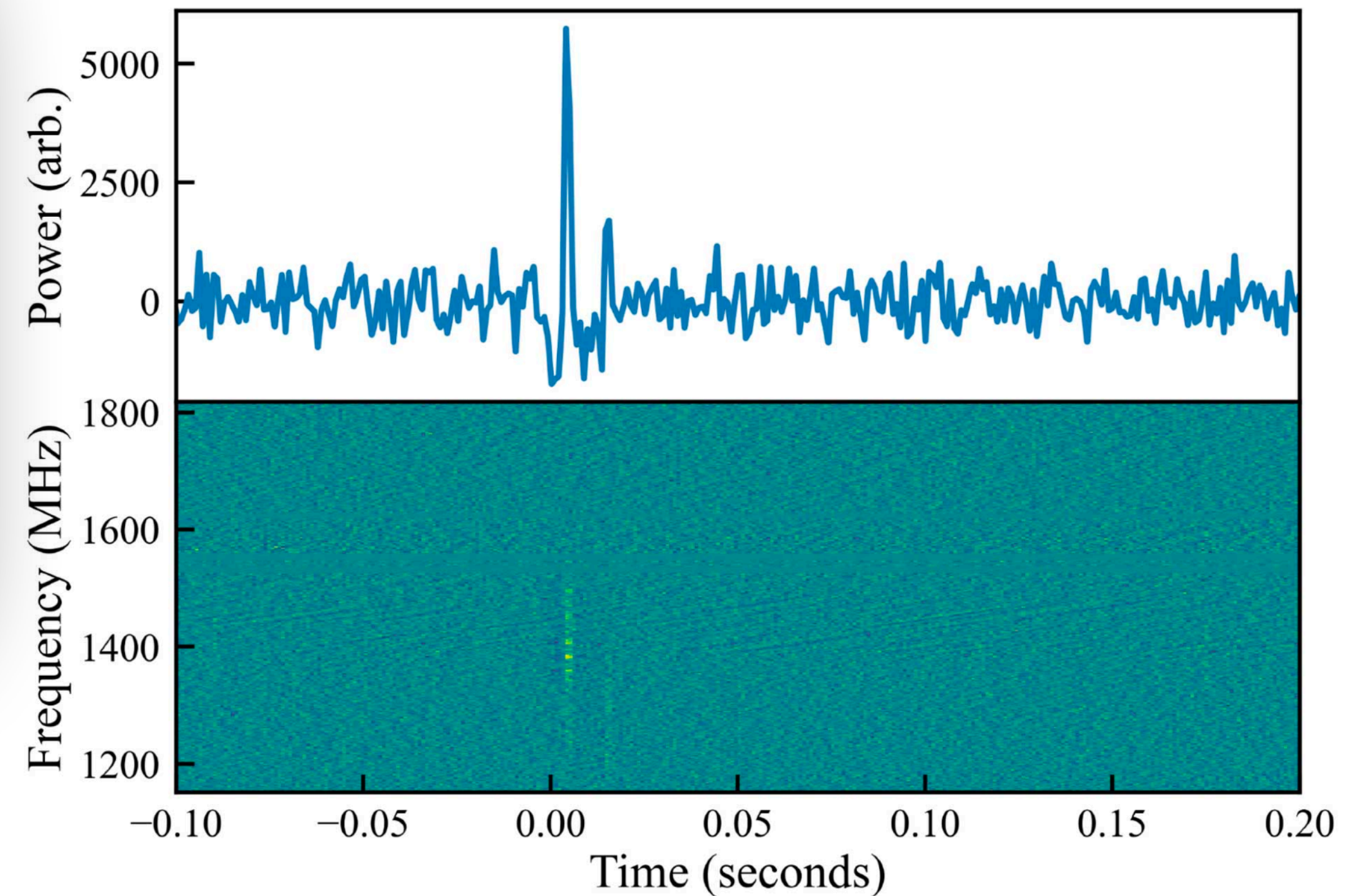


# Allen Telescope Array

## Scientific Contributions



Fast Radio Burst Discovered by SETI  
Institute's Allen Telescope Array  
Jun 3, 2021

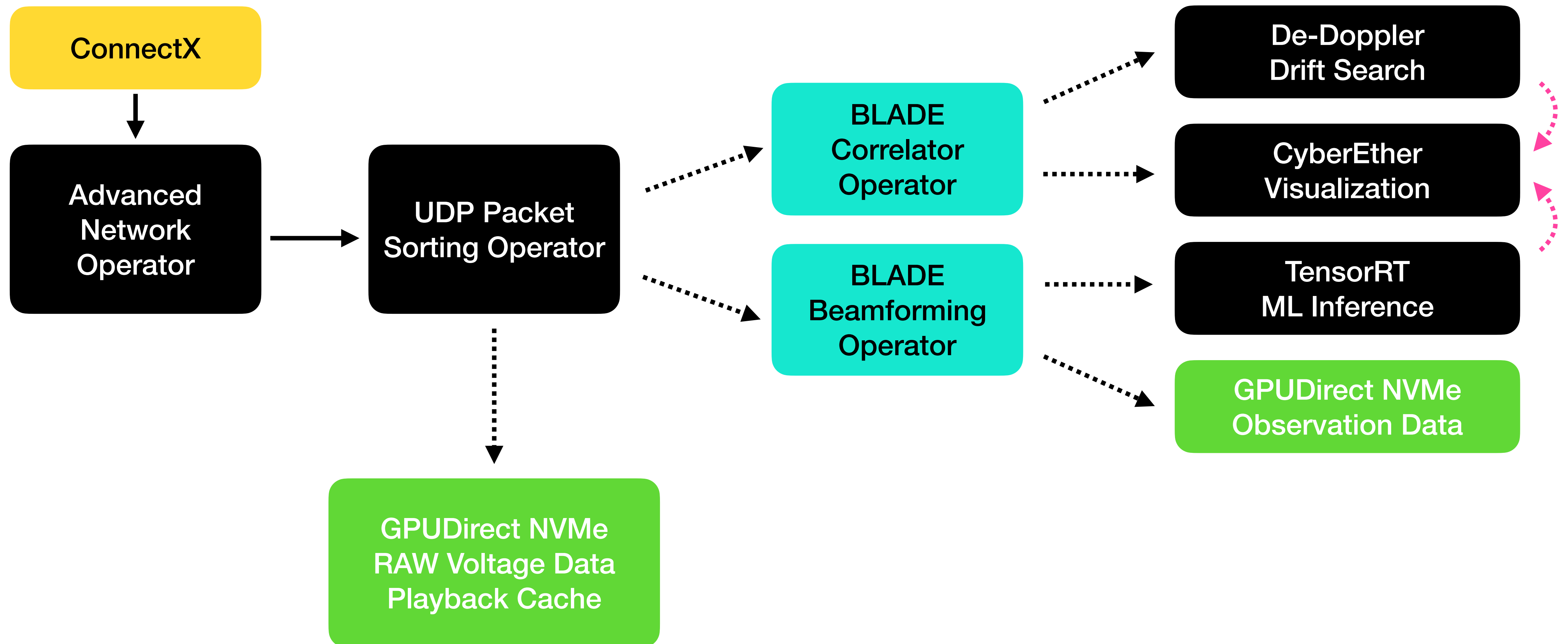


The Astronomer's Telegram  
@astronomerstel

(NEW) ATel 15735: Bright radio bursts from the active FRB 20220912A detected with the Allen Telescope Array... [astronomerstelegram.org/?read=15735](https://astronomerstelegram.org/?read=15735)

# Future

## Extending the ATA's Capabilities with Holoscan



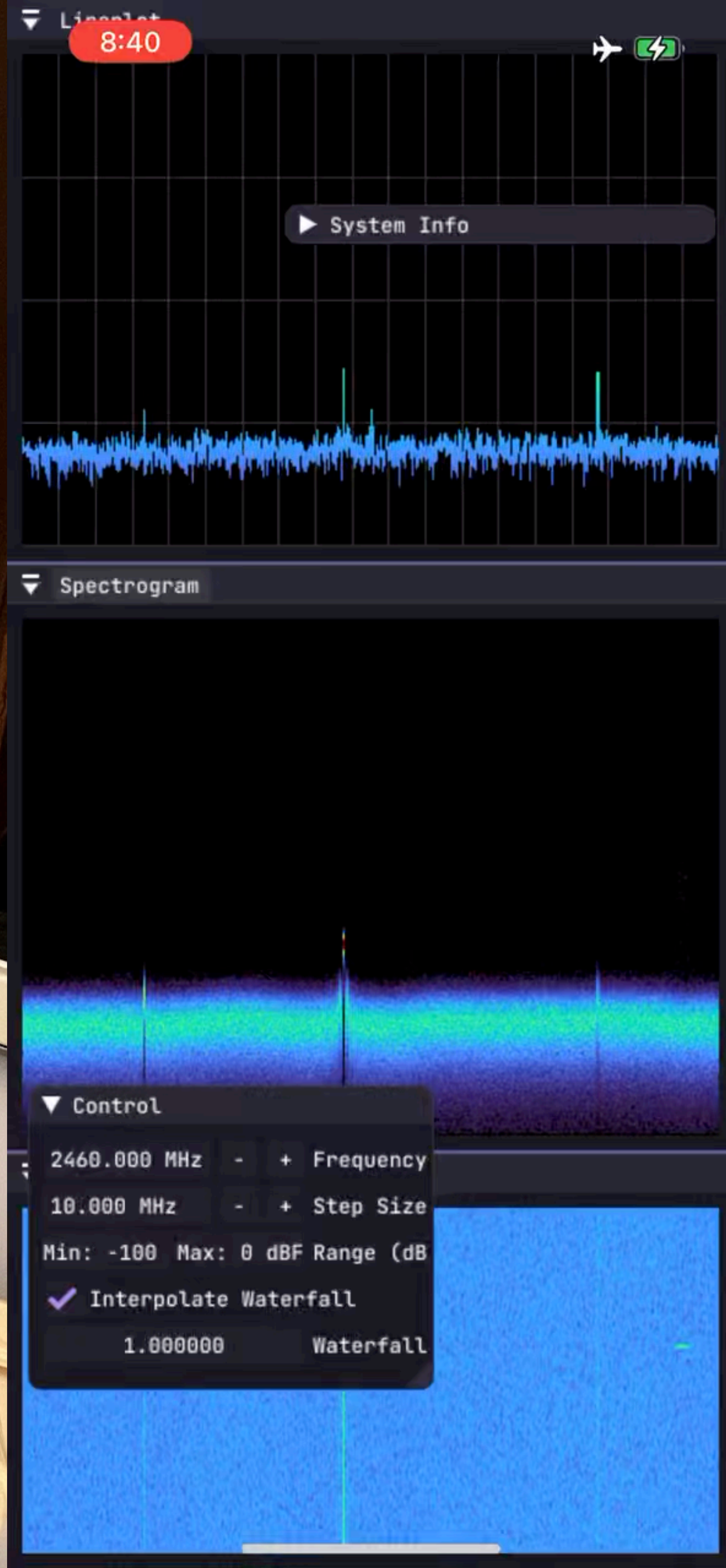


**GREEN BANK OBSERVATORY**



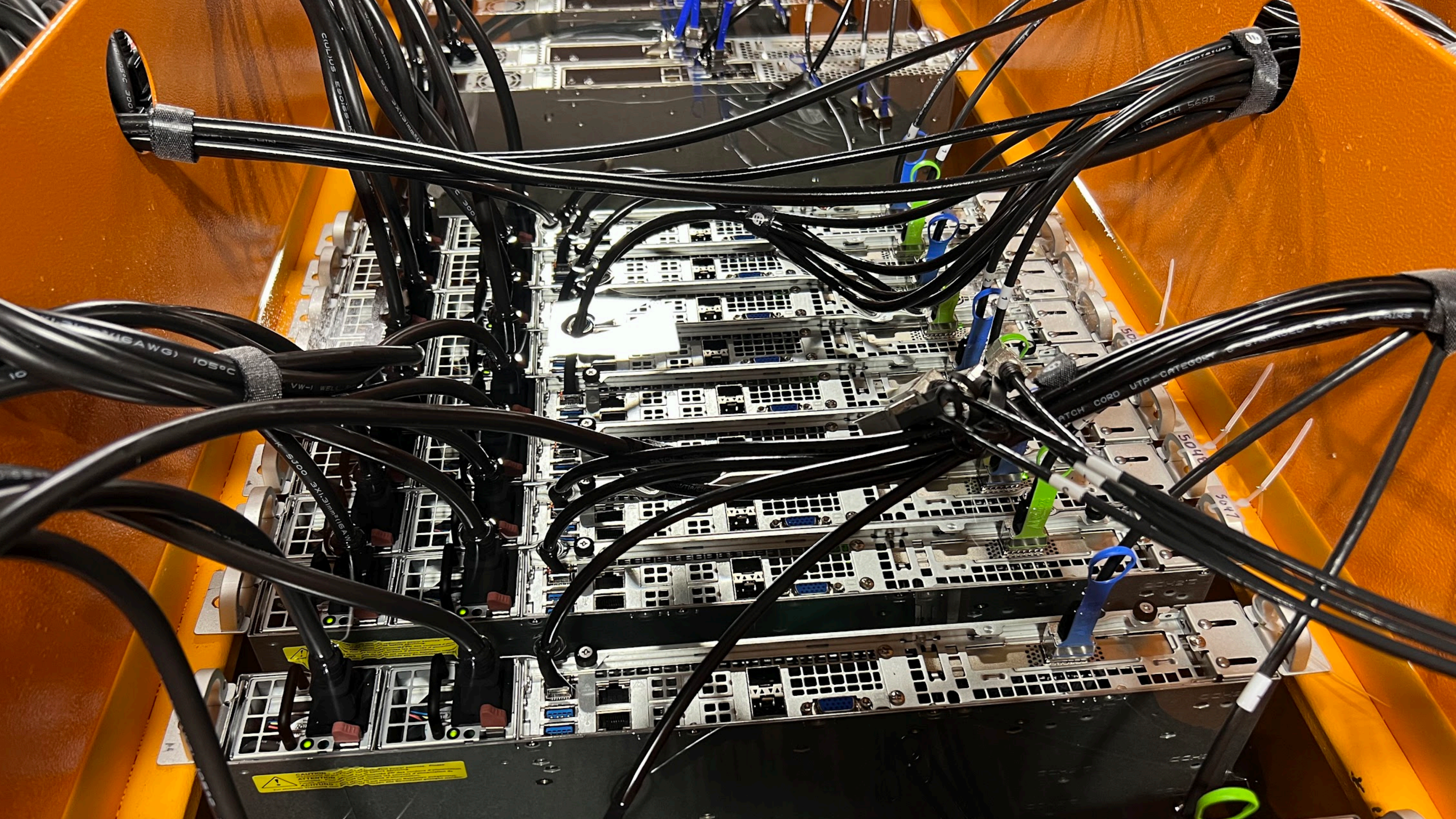














<https://github.com/luigifcruz/blade>

art by jgs

# Comments or questions?

# Contact me!

<https://luigi.ltd/contact/>

