Space-Based Edge Computing

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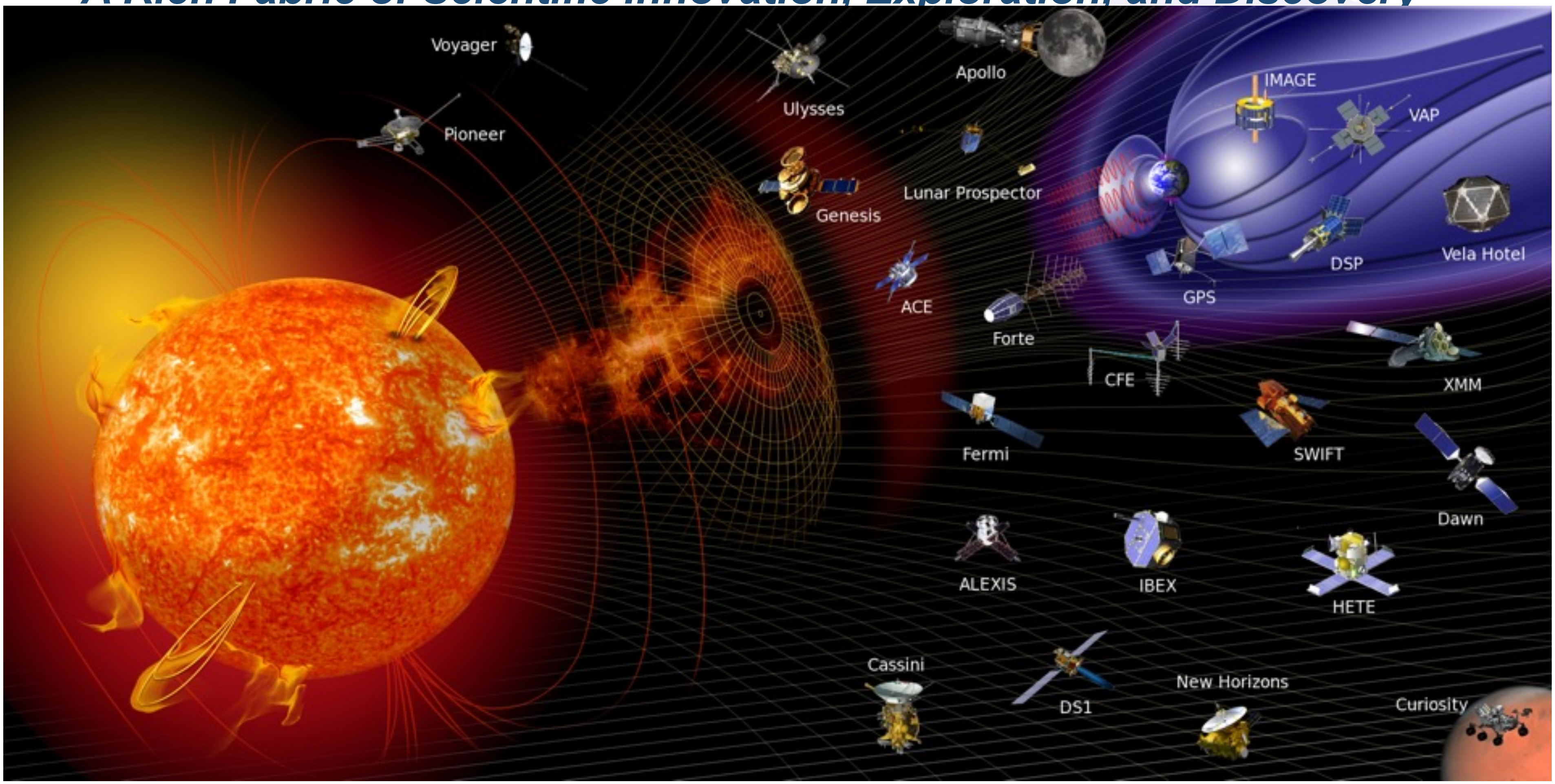
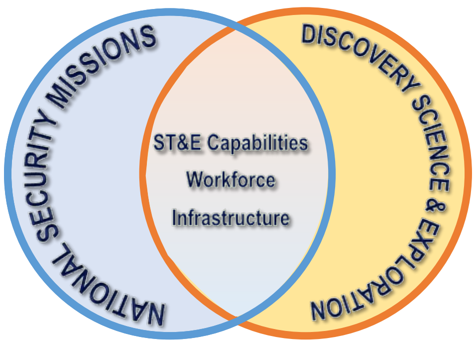
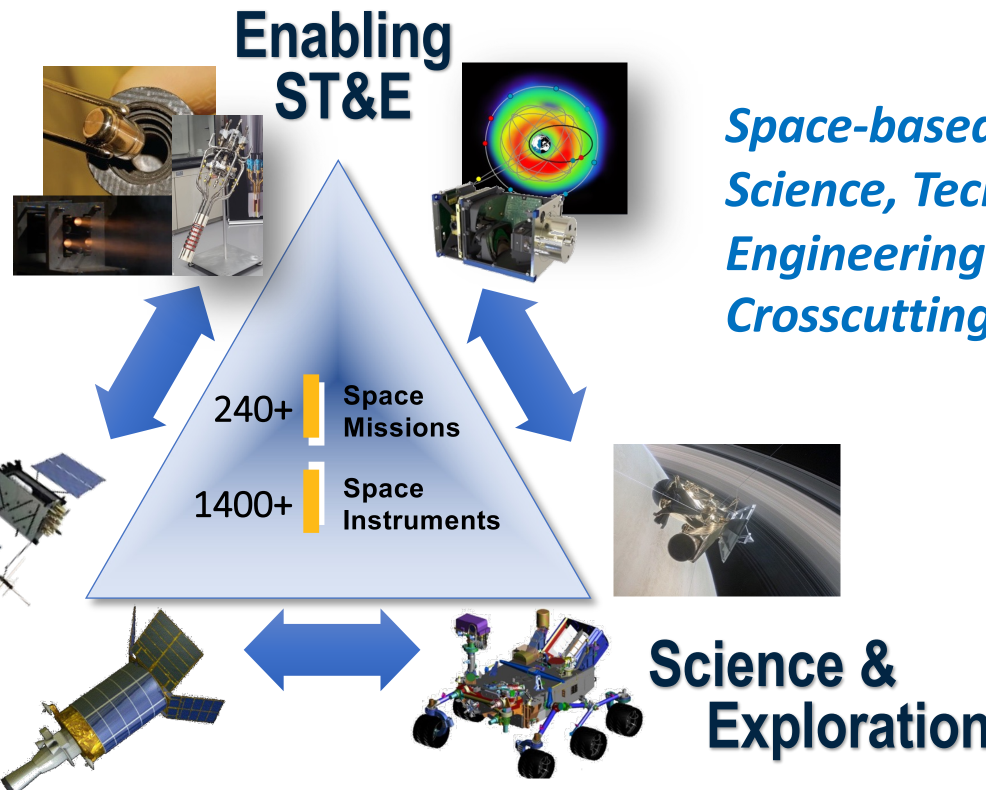
Los Alamos Space: *1400+ Instruments, 240+ Missions*
A Rich Fabric of Scientific Innovation, Exploration, and Discovery



Los Alamos Space Capabilities

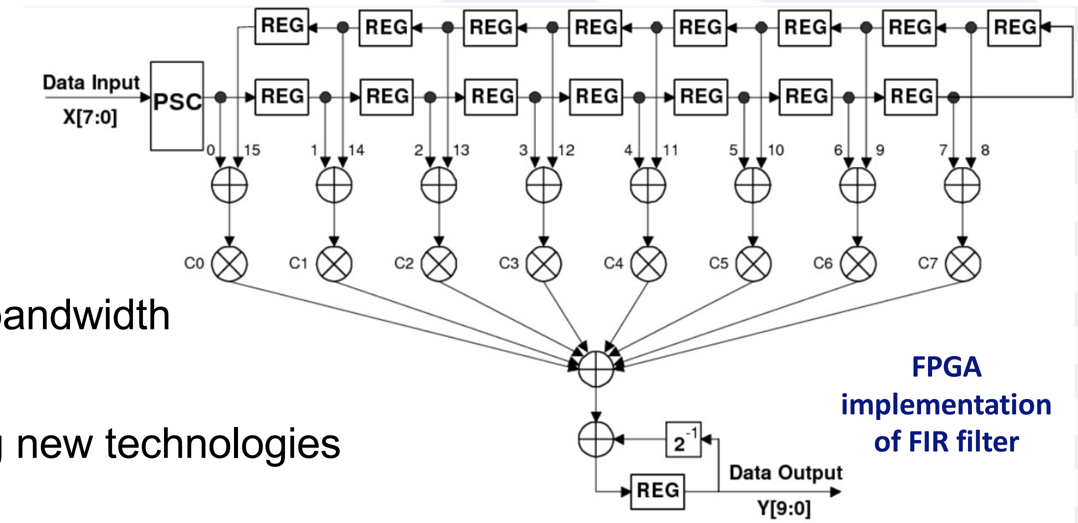
2023: Celebrating 60 Years in Space





Space-based Processing Science, Technology, and Engineering is a Key Crosscutting Capability

High-Performance Solutions for Satellite-Based Remote Sensing



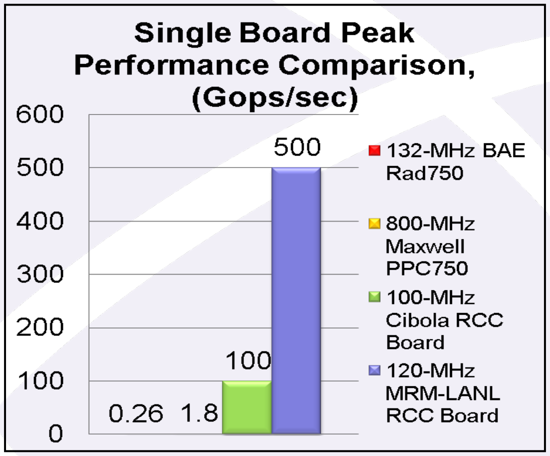
FPGA implementation of FIR filter

- Edge computing at the sensor
  - Data to information
  - Optimize limited data downlink bandwidth
- Goals
  - Developing and space qualifying new technologies
    - Payload and satellite systems
  - Through strategic risk acceptance
    - Can deliver cutting edge solutions
    - Drastically reduce timeline for delivery of new, proven technologies
  - Raising technology readiness level of new technologies / capabilities

FPGAs Enable Processing Throughput and Flexibility

- Why do high speed processing in space with FPGAs?
- Digital Signal Processing

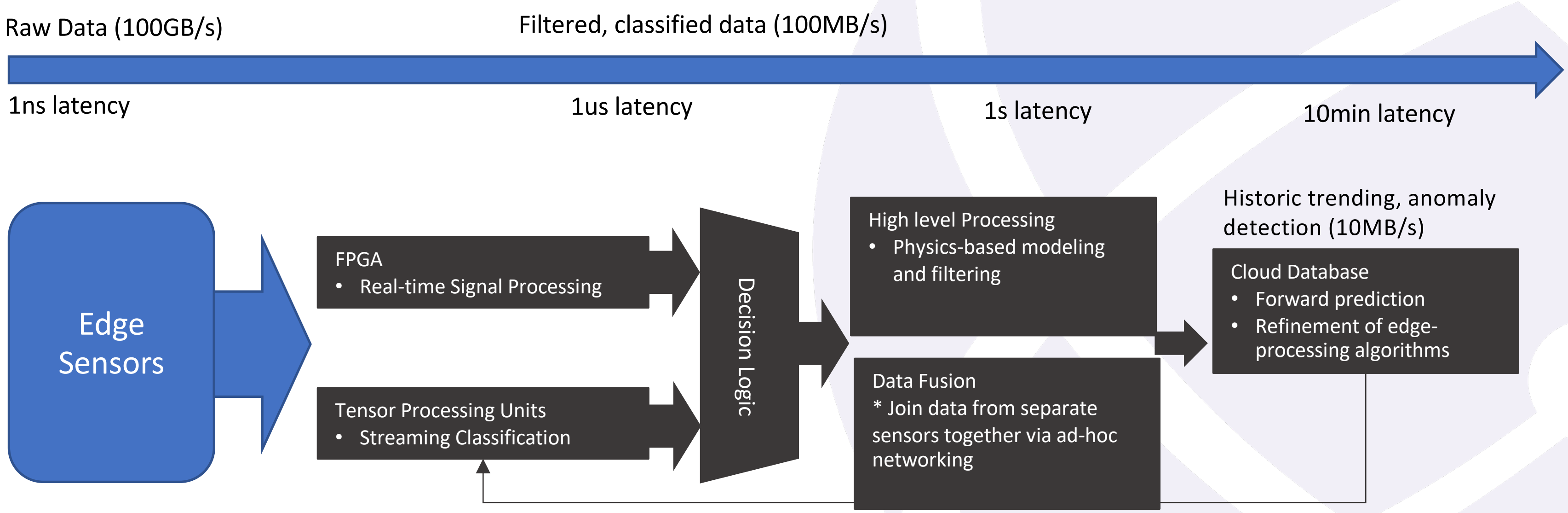
	Processing Throughput	Flexibility	Development Time
General Purpose Processor (GPP)	LOW	HIGH	LOW
Application Specific Integrated Circuit (ASIC)	HIGH	NONE	HIGH
Field Programmable Gate Array (FPGA)	HIGH	HIGH	MEDIUM



FPGAs offer the best of both worlds

Theme: Data to Useful Information

- Edge processing and on-board computing for reducing data to knowledge



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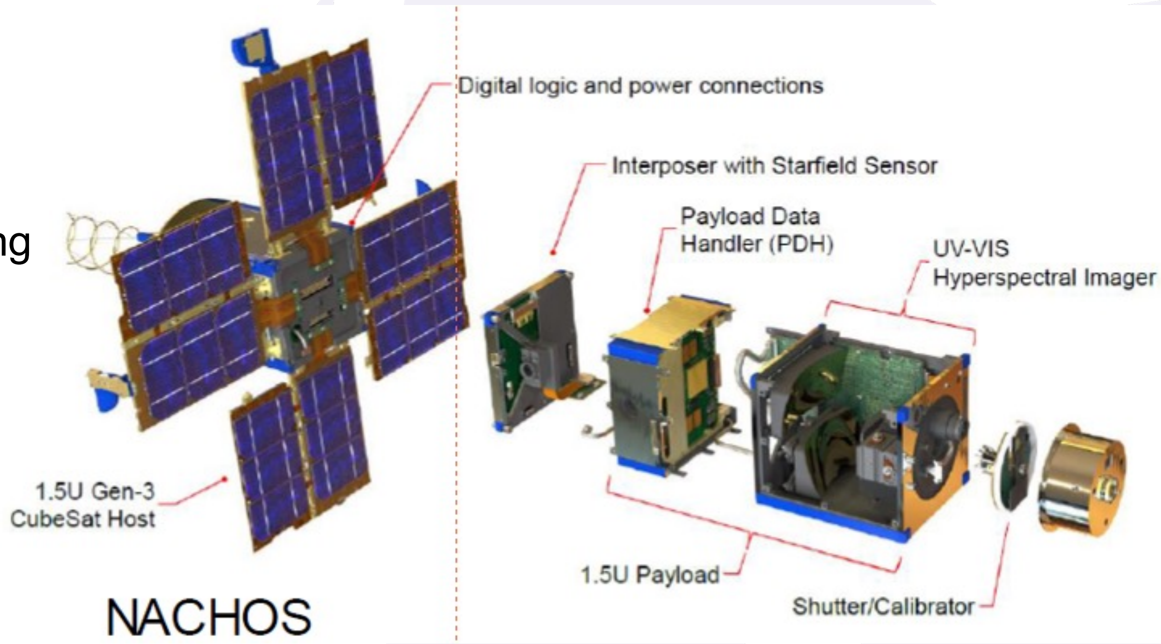
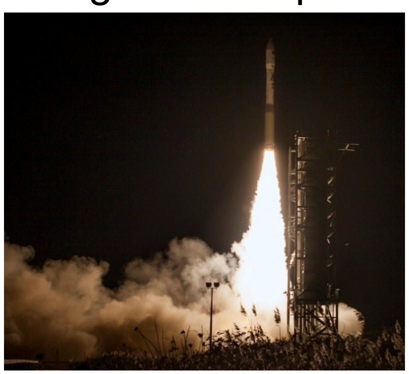
Contents

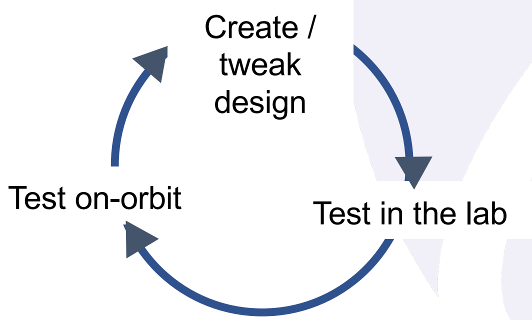
- Design and qualification of edge computing on satellites
  - Strategic risk acceptance
  - Hardware solutions
  - Firmware solutions
- Application 1:
  - High reliability edge computing
  - Wideband Software Defined Radio for Lightning Detection from space
- Application 2:
  - Risk tolerant data fusion and networking

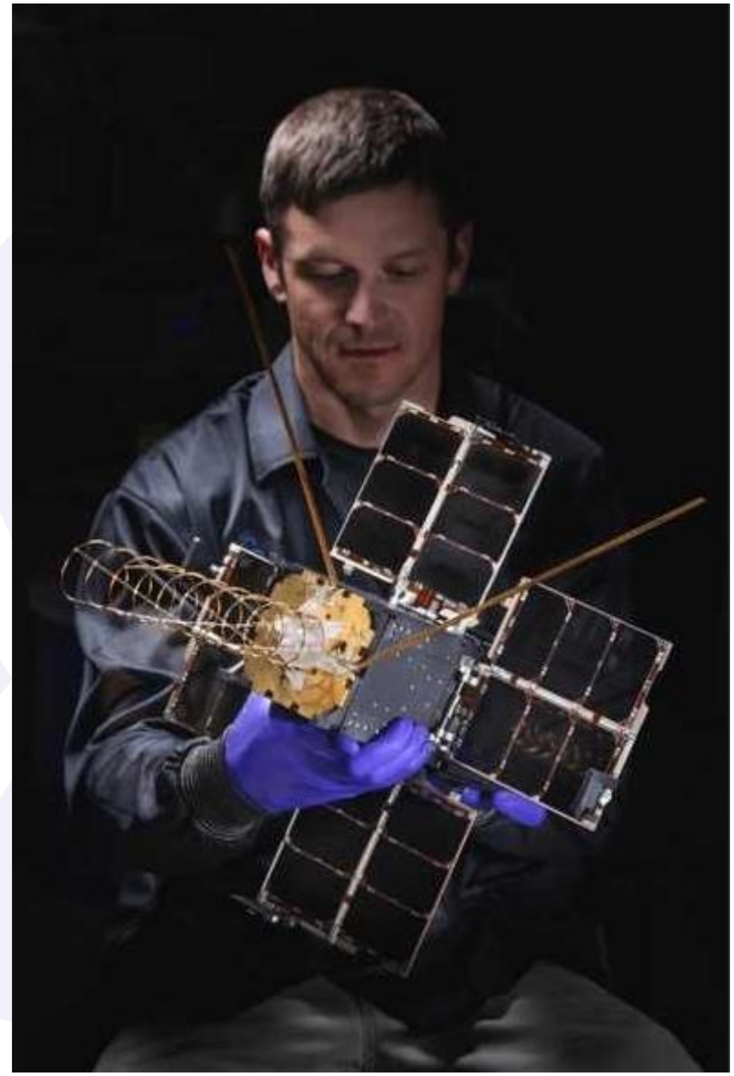


Design and Qualification of High-Performance Solutions for Space Systems

- Hardware survivability – fly, fix, fly
  - LANL 1.5U CubeSat bus
  - 15 CubeSats on 11 launches over 6-year span
- Firmware employing algorithms needs to function in true, complex space environment
  - Radio Frequency background
  - Algorithmic optimization continues after launch

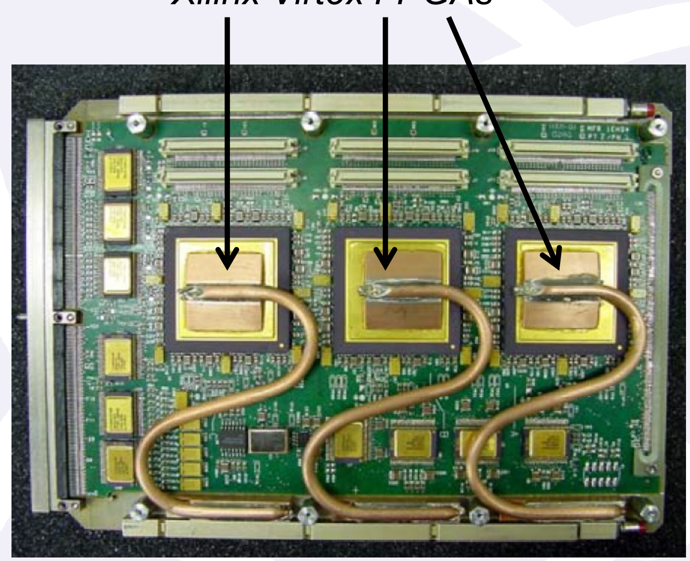






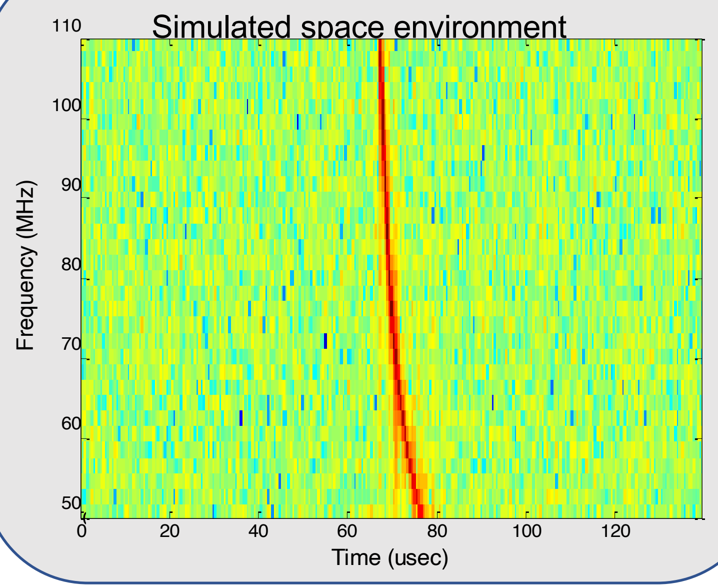
Using Radiation Tolerant Parts in Space

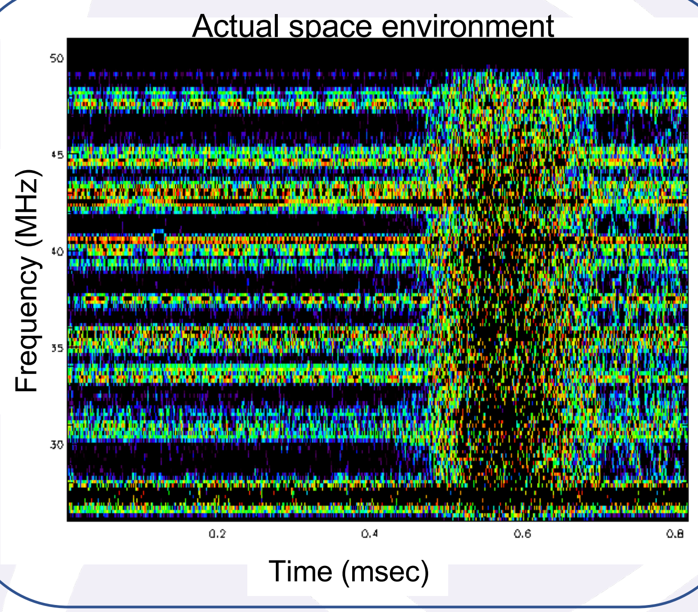
- Cost savings and capability gains through use of radiation tolerant parts
  - Radiation tolerant Kintex 7 FPGA $2k
  - Radiation hardened equivalent $80k
- Use commercial versions of flight parts
  - Understand the vulnerabilities
  - For the LANL 1.5U CubeSat bus, the Kintex-7 FPGA was selected
    - Symptom, engineered solutions
- Utilization of radiation tolerant FPGAs in space made possible by LANL research
  - Configuration readback, partial reconfiguration
  - Triple Modular Redundancy (TMR)



Cibola ReConfigurable Computer

Algorithm Qualification in the Complex Space Environment





Algorithmic excellence can be achieved by testing in the real-world environment, tweaking, and iterating

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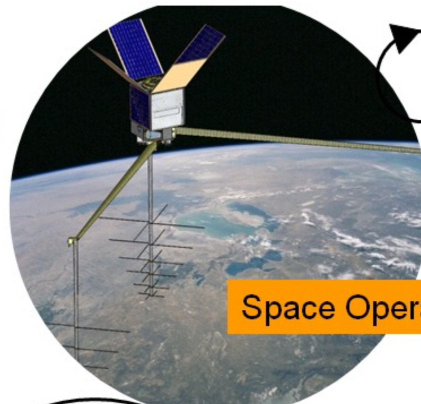
CFE, a Remote Sensing Lab in Space



Space Operations

On Orbit
Reconfiguration
< 1 minute

Application
Modification
1-2 weeks

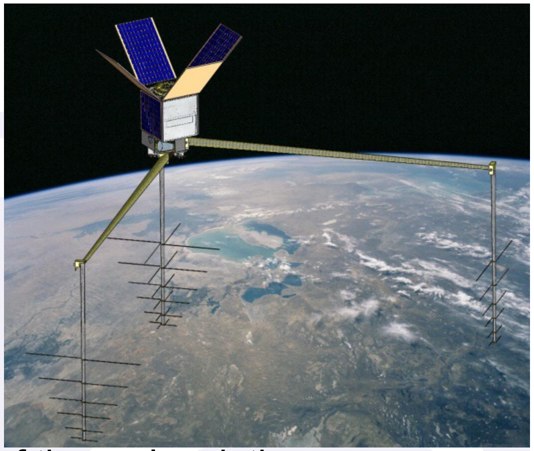
Minor
Adjustment
1 day

Application
Development
2-3 months

Application Development

Data Analysis

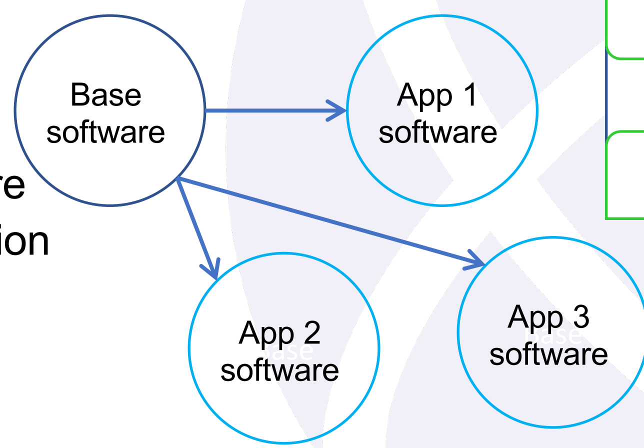
Cibola Flight Experiment (CFE) Accomplishments

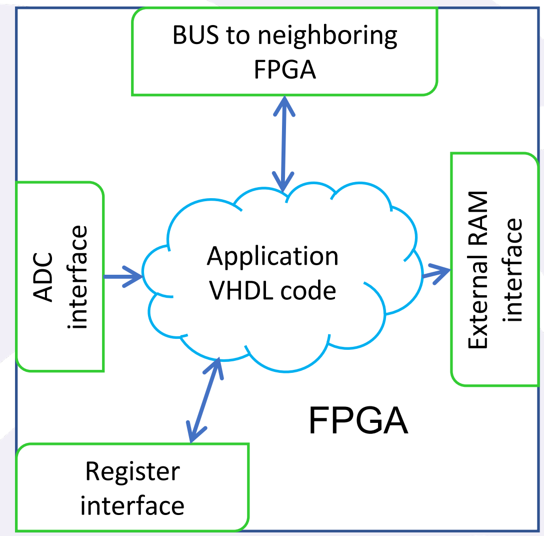


- Primary mission planned: interferometric geolocation
- Challenges faced after launch
  - One of three antenna masts deployed correctly
  - Designed for oscillator matching, not frequency stability in the presence of thermal variations
- ReConfigurable Computer enabled mitigation of CFE hardware failures
  - RCC enabled hardware failures to be overcome, something that would not have been possible if ASICs had been used instead
- New mission achieved after launch, Doppler geolocation
  - Narrow Band Recorder developed, uploaded and tweaked after launch
    - Multiple Narrow Band Recorders in parallel
    - Using known source (ground emitter) to remove thermal frequency drift from unknown source (ground emitter)
    - Using Electro Magnetic Interference to remove thermal frequency drift from unknown source (ground emitter)
- Uploaded new FPGA configuration files > 65 times after launch

Enabling Cost Savings for Developing New Applications

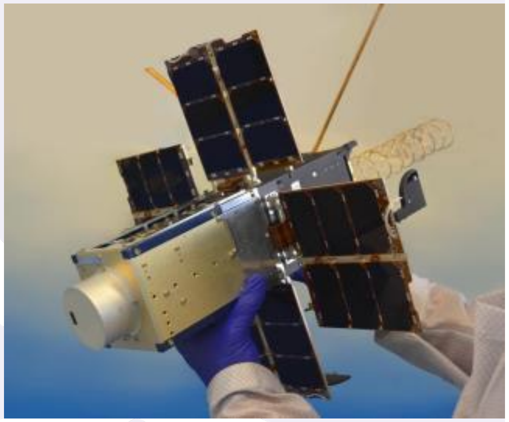
- Plan for new applications during initial payload design
  - Base software, application software
  - Reusable firmware for FPGA external interfaces
  - Power allocation
  - Configuration memory
  - Data container
- Engineering Design Unit
  - Verify no damage to hardware
  - First-level algorithmic validation





Los Alamos CubeSat Bus Accomplishments

- Developed communications radios from scratch
  - Implemented all algorithms in Kintex-7 FPGA
    - Transmitter: data encoding, modulation, Forward Error Correction encoding
    - Receiver: synchronization, demodulation, decoding
- Continued to develop and update code after launch
- Developed mission manager to enable automated decision making on-orbit
  - Know what time it is
  - Propagate orbit to determine orbital location
  - Know where ground stations and science targets reside
  - Satellites autonomously develop schedules for
    - Science collection,
    - Ground station passes,
    - Maintenance of bus health priorities (solar charging, detumbling, etc)



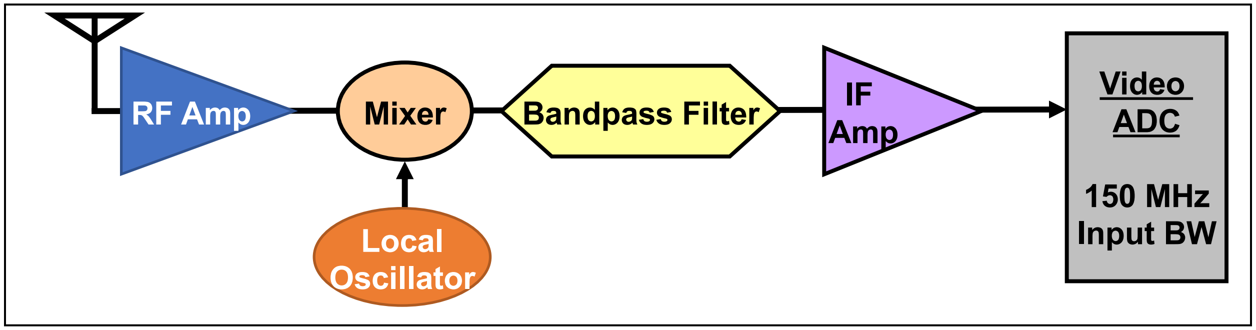
Transition from Research and Development to Operational Systems

- Cibola Flight Experiment (CFE) blazed the path for current operational systems

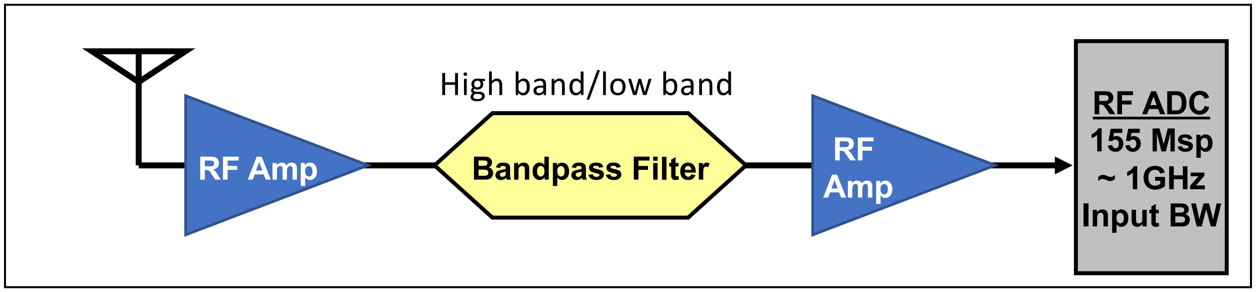
Application 1 – Lightning Detection

- High reliability edge computing
- Wideband Software Defined Radio hosts detection algorithms
- Heterodyne tuners
- Wideband ADC accepts swath of RF bandwidth
- FPGA firmware performs computations that replace analog functions
  - Polarization selection/synthesis
  - Filtering
  - Channelization

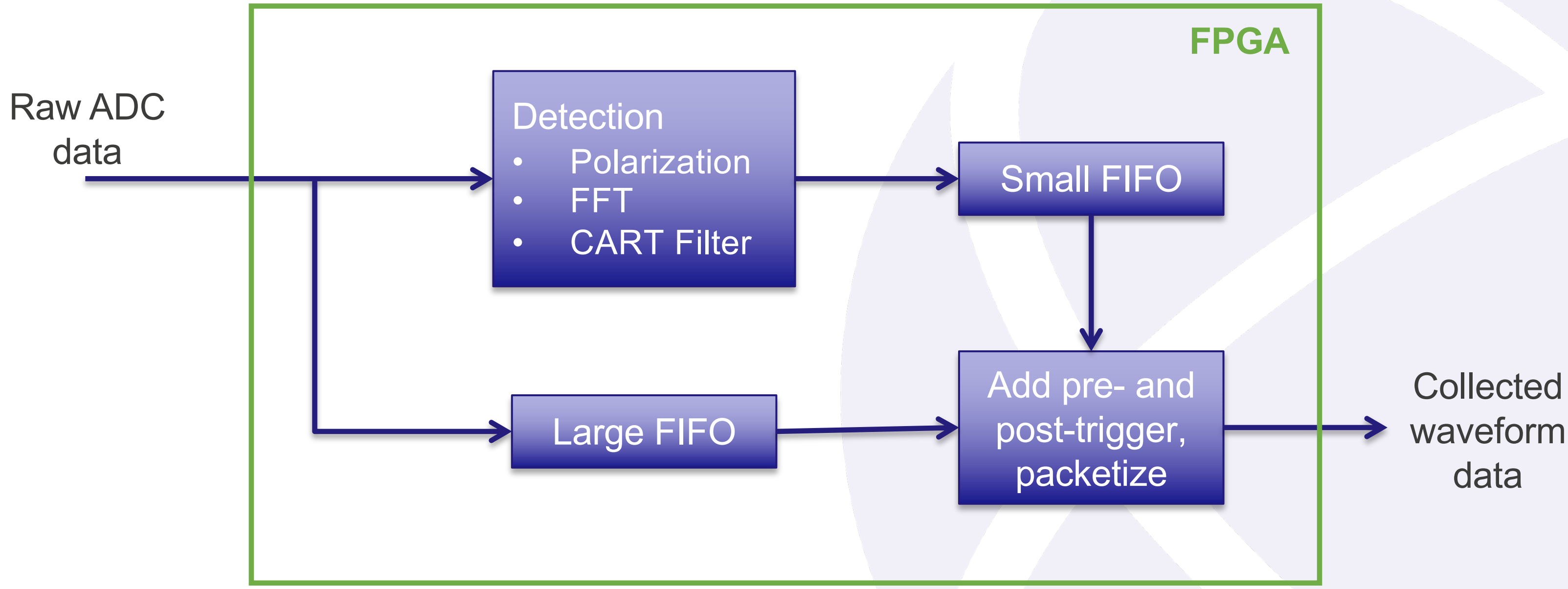
Classic Superheterodyne Receiver



New Direct Digitization Receiver



Detection and Collection Algorithms in FPGA



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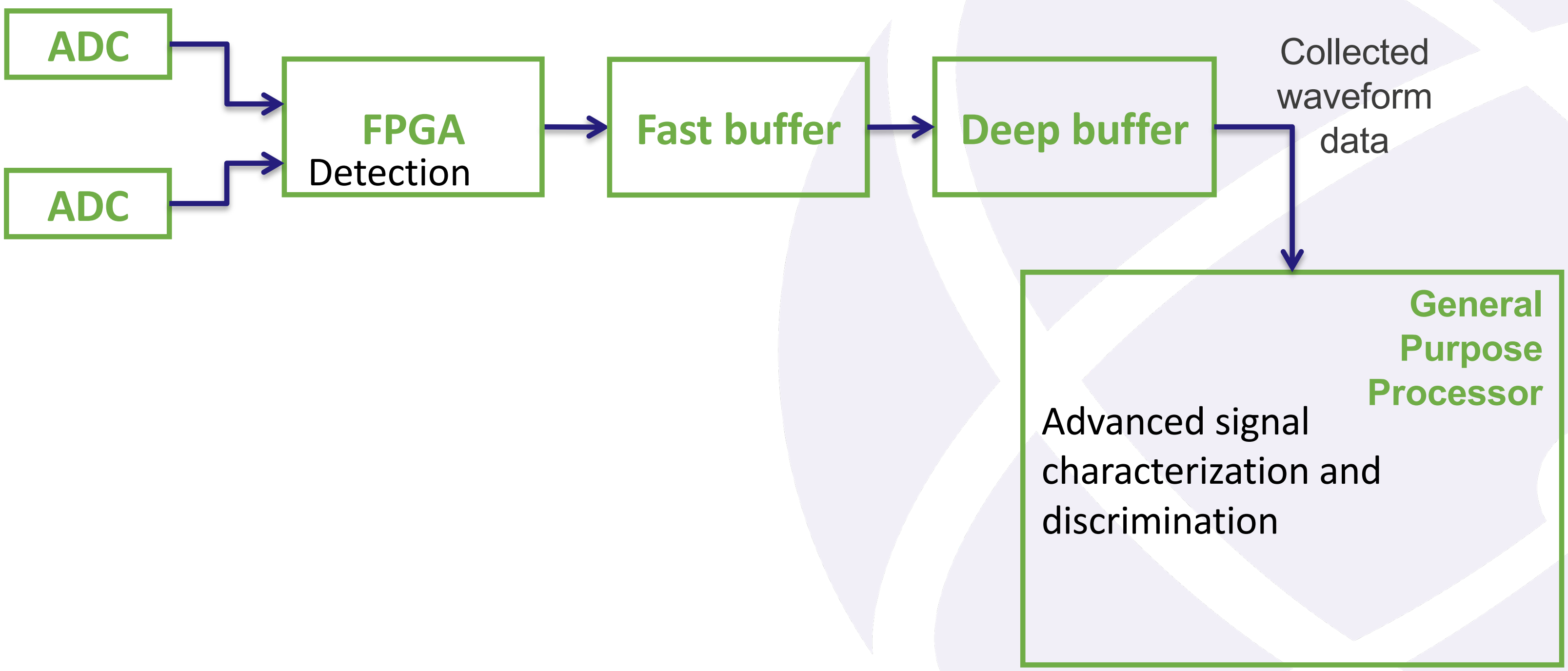
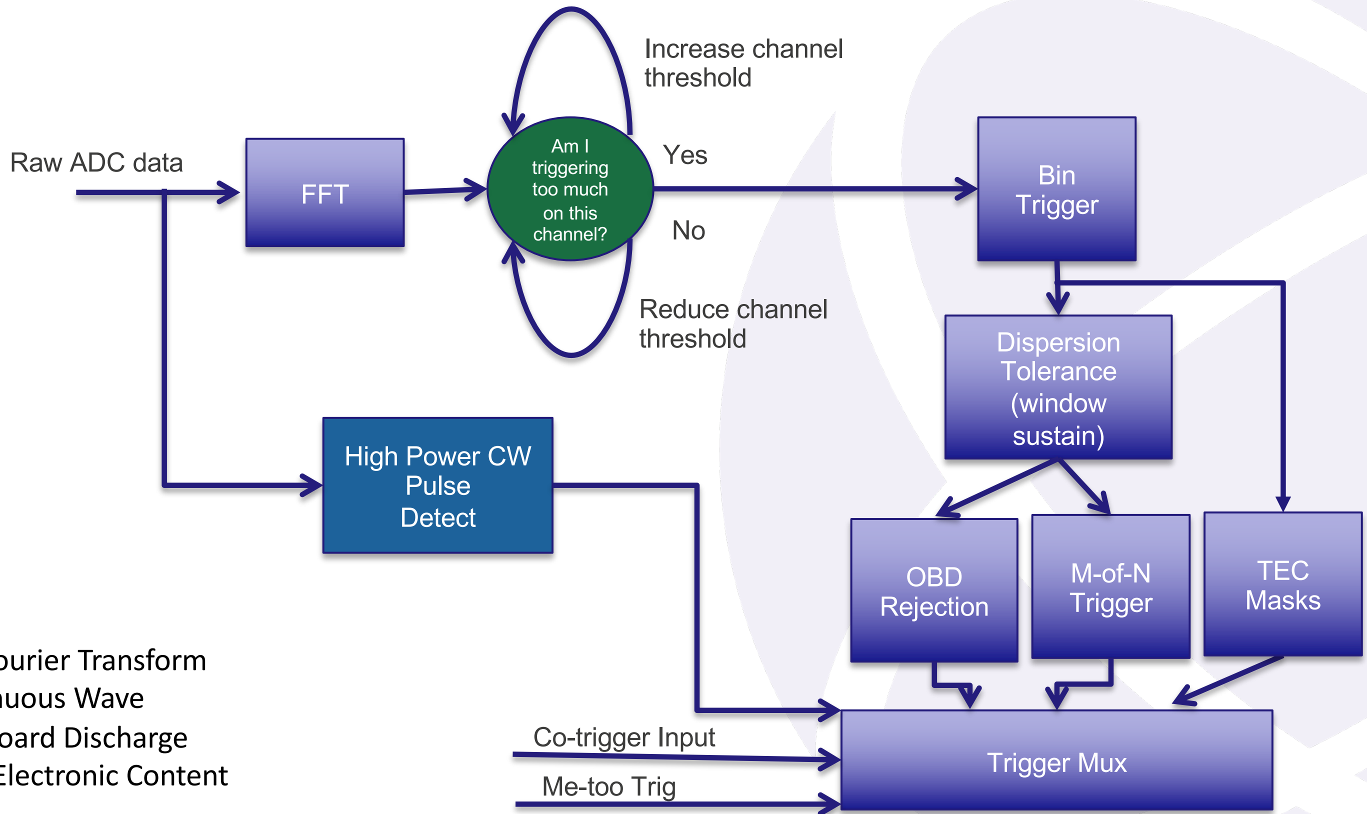
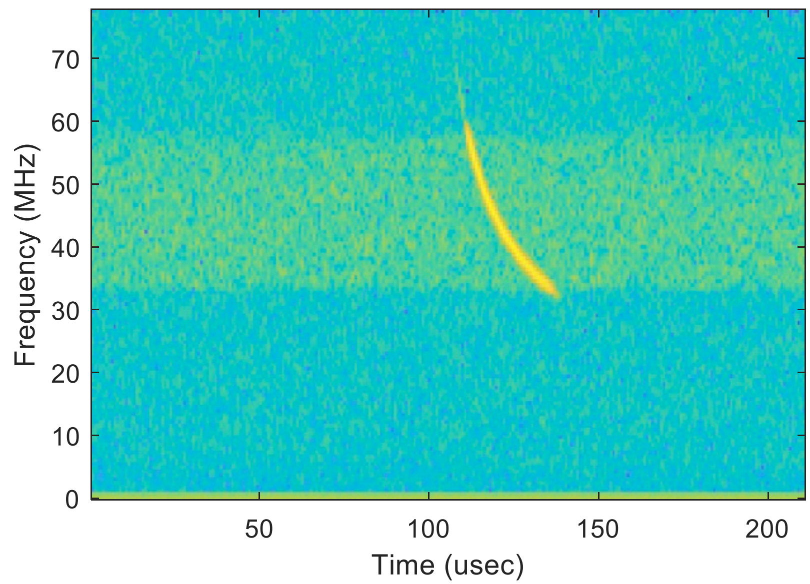
Data Flow through System Architecture

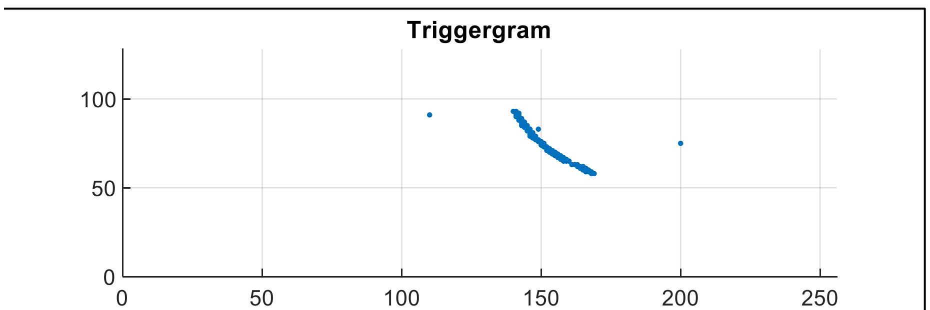


Constant Alarm Rate Trigger (CART)



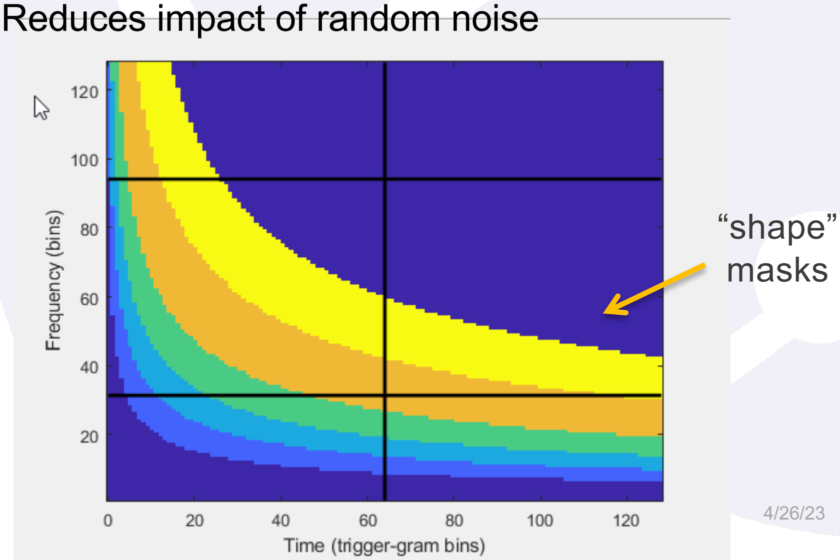
Acronyms -
FFT = Fast Fourier Transform
CW = Continuous Wave
OBD = On-Board Discharge
TEC = Total Electronic Content





Ionospheric Effects

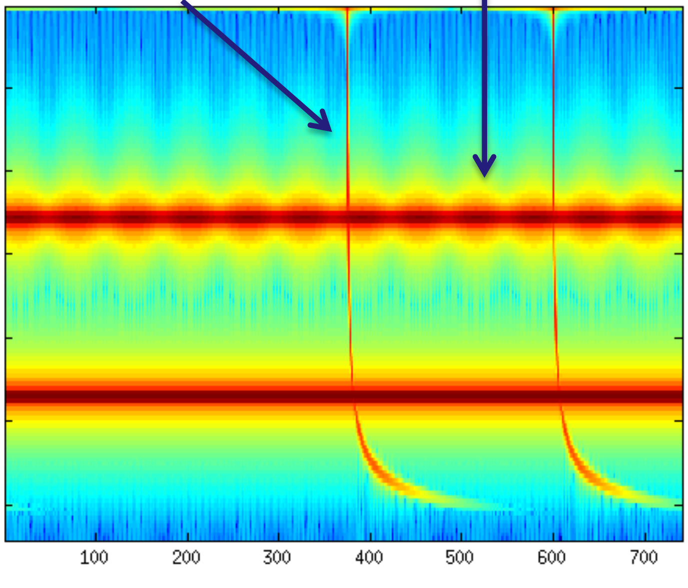
- Lower frequency radio waves are delayed with respect to higher frequency due to ionosphere
- Convolutional "shape" engine compensates for these effects in the real-time detection algorithms
  - Focuses detection on signals of interest
  - Reduces impact of random noise

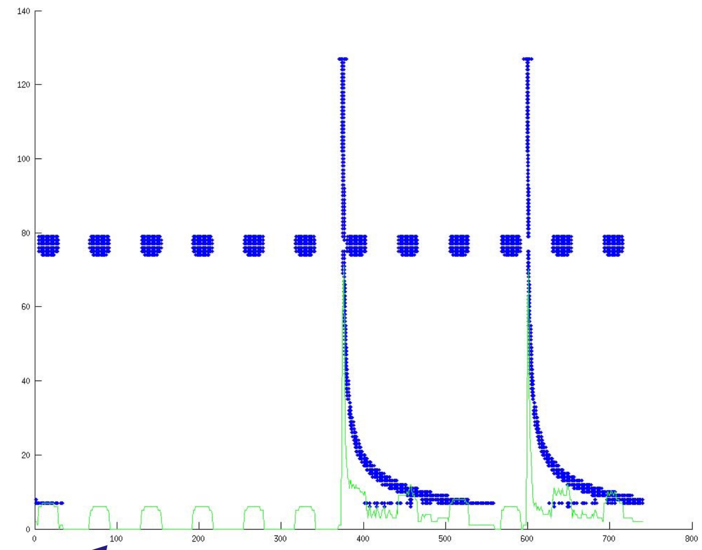


CART Filter Operating on Representative Data

Distinctive curved shape implies ionospheric propagation

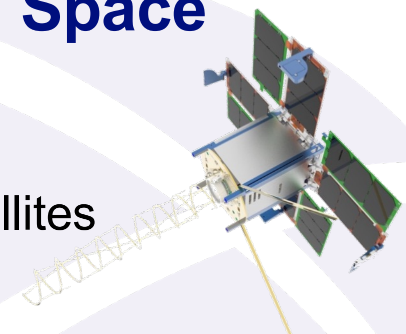
AM carriers





Column sum of frequency bin triggers

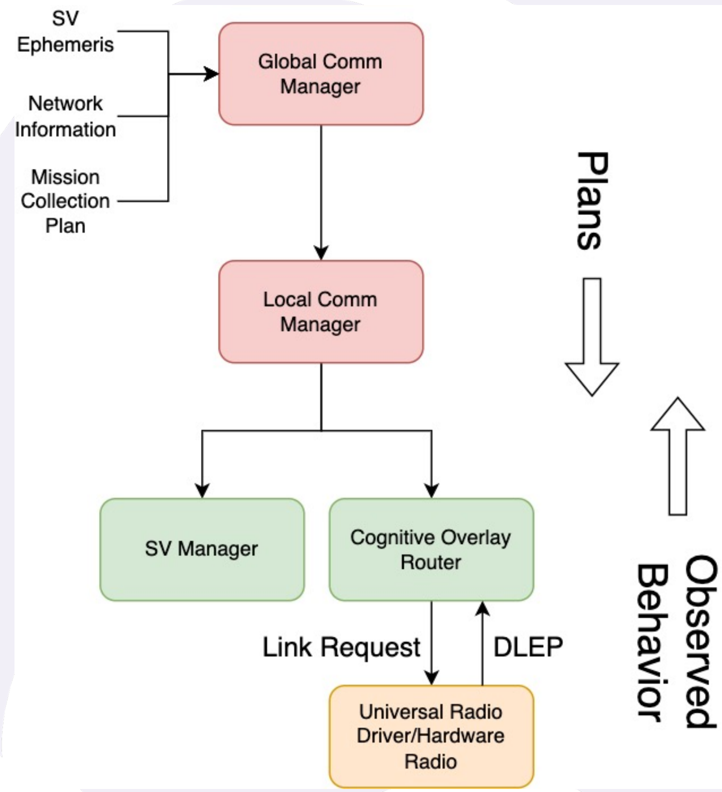
Application 2 – Data Fusion and Networking in Space



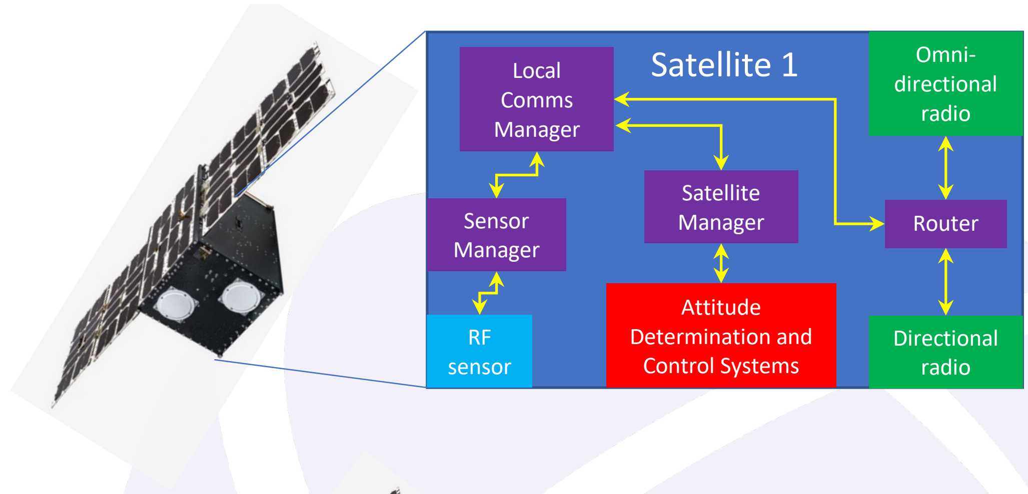
- Risk tolerant
- Fusion of data from multiple phenomenologies and multiple satellites
- Optimization of network of satellites
- Building on the mission manager work employed on LANL CubeSat bus
- Developed a high-fidelity simulation of satellite networking
  - Small cluster of satellites
  - Separation between satellites is about 20 km, but very dynamic
  - Satellites utilize cross-link radios to increase operational awareness and pass and share data

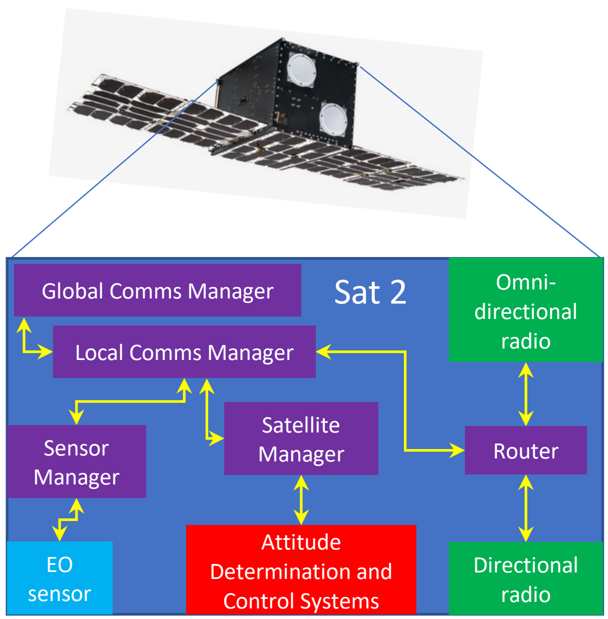
Top-Down Optimization through Bottom-Up Action

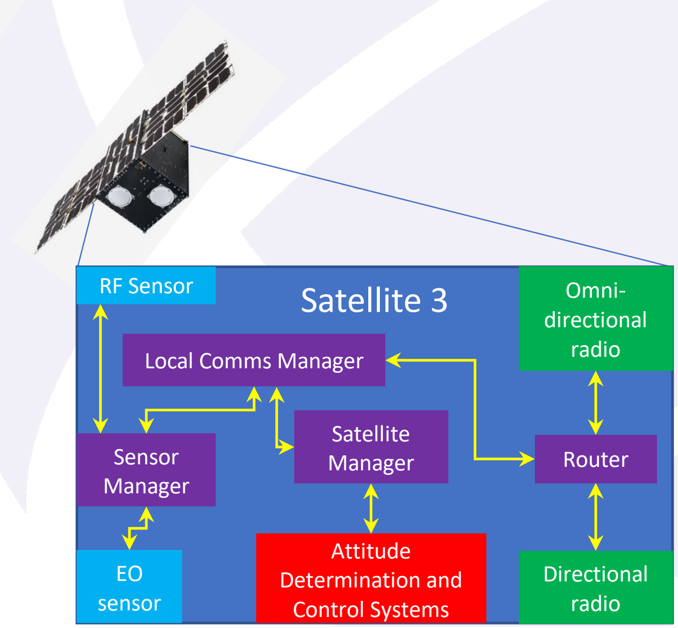
- Assumptions:
  - Satellites are in a cluster and need to perform data fusion by exchanging raw sensor data. Satellites have two cross-link radios:
    1. Low bandwidth omnidirectional radio
    2. High bandwidth directional radio that requires satellite to slew
  - Satellites have mutual exclusive goal:
    1. Sensing (science) antennas should be pointed at ground target
    2. Directional (cross-link) antennas should be pointed at other vehicles to maintain network
  - Comms managers work in real-time to optimize dynamic network



Satellite Cluster

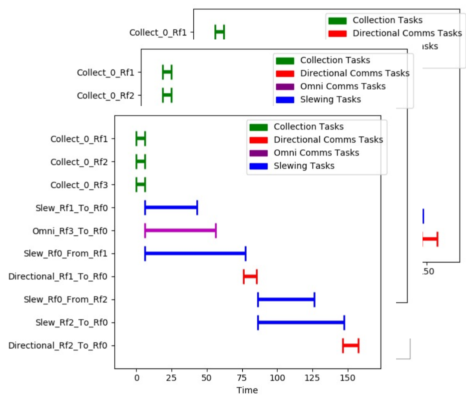


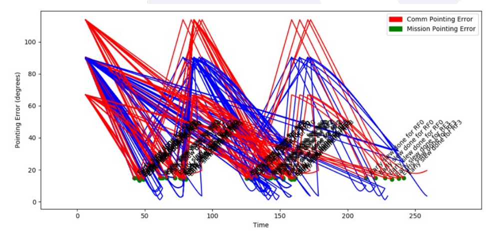


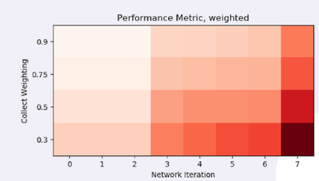


Comm Manager Planning Phase

- Comm manager “dry-runs” network and collect strategies to score them
  - Discrete event simulator framework
    - High level model of slewing, network and collection behavior
    - Parallel “Hypothetical” execution

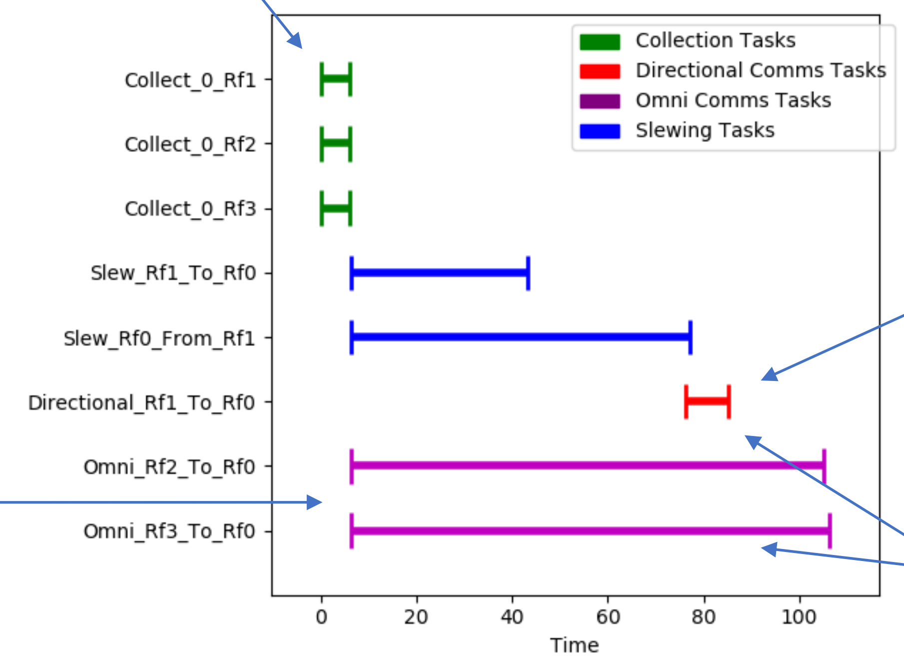






Simulation Run

Sensor collects happen simultaneously



Directional link requires slewing of TX and RX platforms to be within 10 deg before starting

Omni link transmitters share channel bandwidth when active simultaneously

Link send durations calculated from current receive rates or simulated link budget

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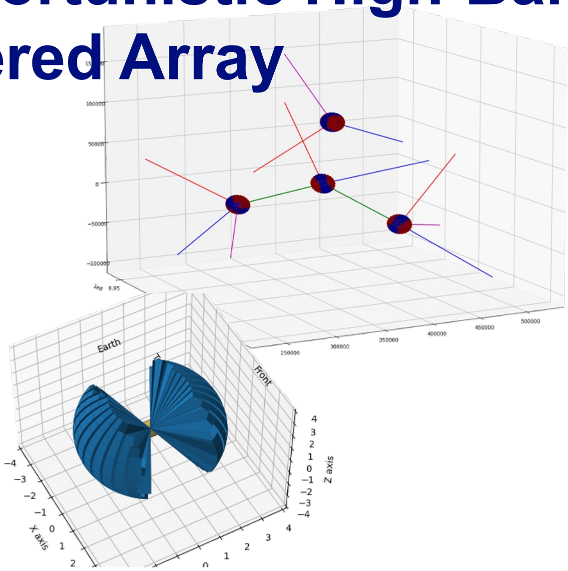
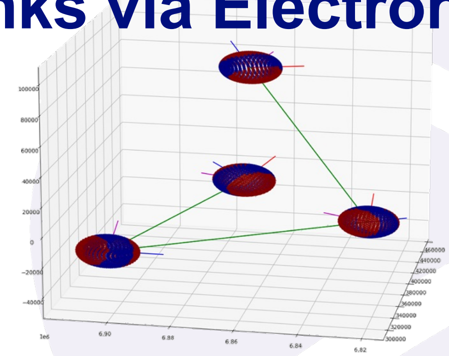
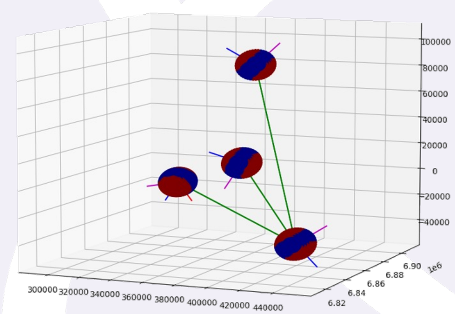
Opportunistic High-Bandwidth Links via Electronically Steered Array







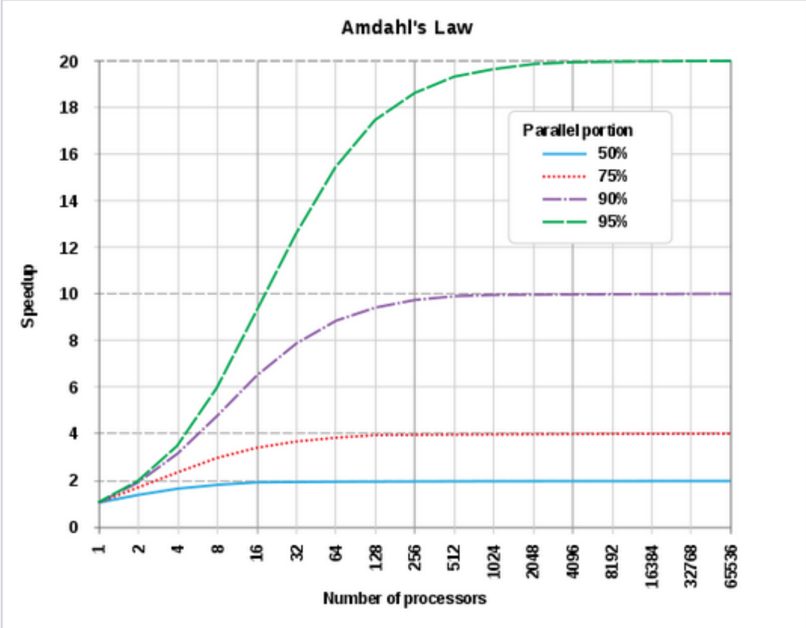
Electronically Steered Array allows flexibility in off-boresight pointing

- Global Comm Manager uses minimum spanning tree and other scoring algorithms to transform network into fully connected directional system

Backups

Computing at the Edge

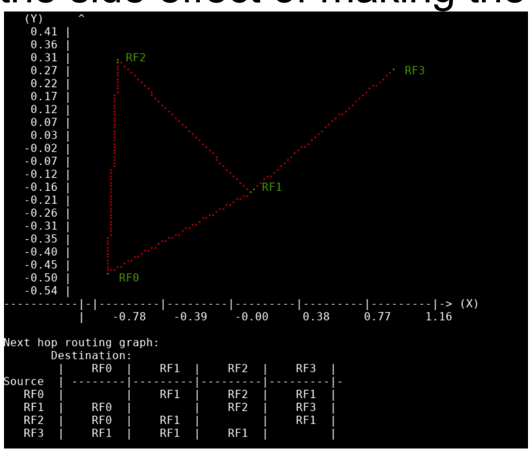
- Field Programmable Gate Arrays (FPGA)
  - Fantastic acceleration for certain kernels
  - Signal processing is a particular strength (highly parallel)
  - 1000x
- Co-Design
  - Design the perfect hardware/software system matched to your problem
  - Accelerate the common case; the high date rate, anything that can process raw data
    - Amdahl's Law is a key limiter



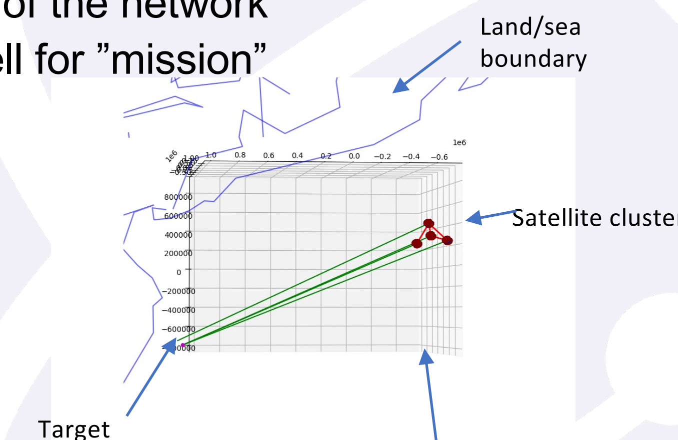
The theoretical speedup of the latency (via a reduction of latency, ie: latency as a metric is elapsed time between an input and output in a system) of the execution of a program as a function of the number of processors executing it, according to Amdahl's law. The speedup is limited by the serial part of the program. For example, if 95% of the program can be parallelized, the theoretical maximum speedup using parallel computing would be 20 times.

Always-in ‘Opportunistic’ Route Optimization

- Actively driving “opportunities” for a better network
- Active analysis to seek out optimized omni patterns and attitude control
  - Instead of trying to directly map the network to “mission” data needs, just try to optimize the connectivity and overall performance of the network
  - Has the side effect of making the network work well for ”mission”



Global comms manager analyzes network connectivity and takes action to improve it

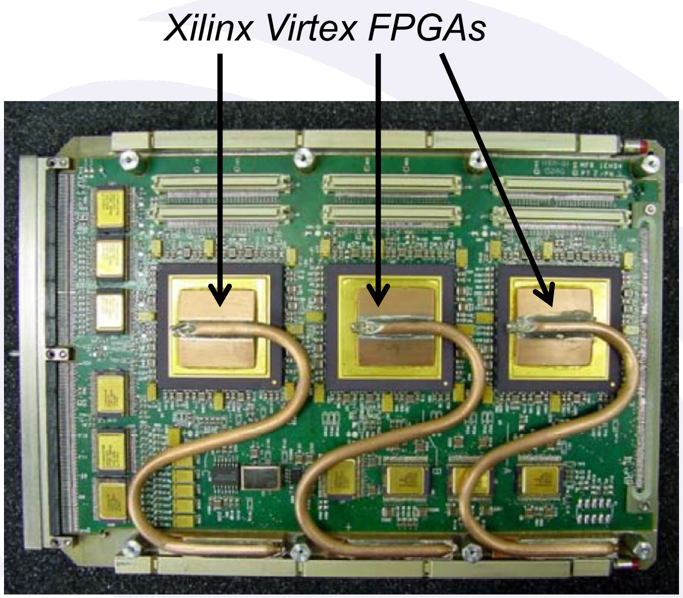


Simultaneous mission pointing and connected network graph with minimal slewing off of nominal “mission pointing”

- Secondary pointing objective is conveyed to SV manager so primary pointing is not damaged – a means of implicit multiple constraint optimization

Cibola Flight Experiment (CFE)

- LANL-developed and operated experimental satellite launched in 2007
- Hosts a ReConfigurable Computer RF payload developed by LANL
- ReConfigurable Computer is made up of nine first generation Xilinx Virtex (FPGAs)
- LANL foundational research and development enabled using radiation tolerant (vs. radiation hardened) FPGAs in space



Cibola ReConfigurable Computer

CFE validated ReConfigurable Computing in space