Flash LIDAR Emulator for HIL Simulation

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Autonomous Landing and Hazard Avoidance Technology

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- Problem
- Emulator Development
- Application
- Results
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Introduction

- Autonomous Landing and Hazard Avoiding Technology (ALHAT/ETDPO)

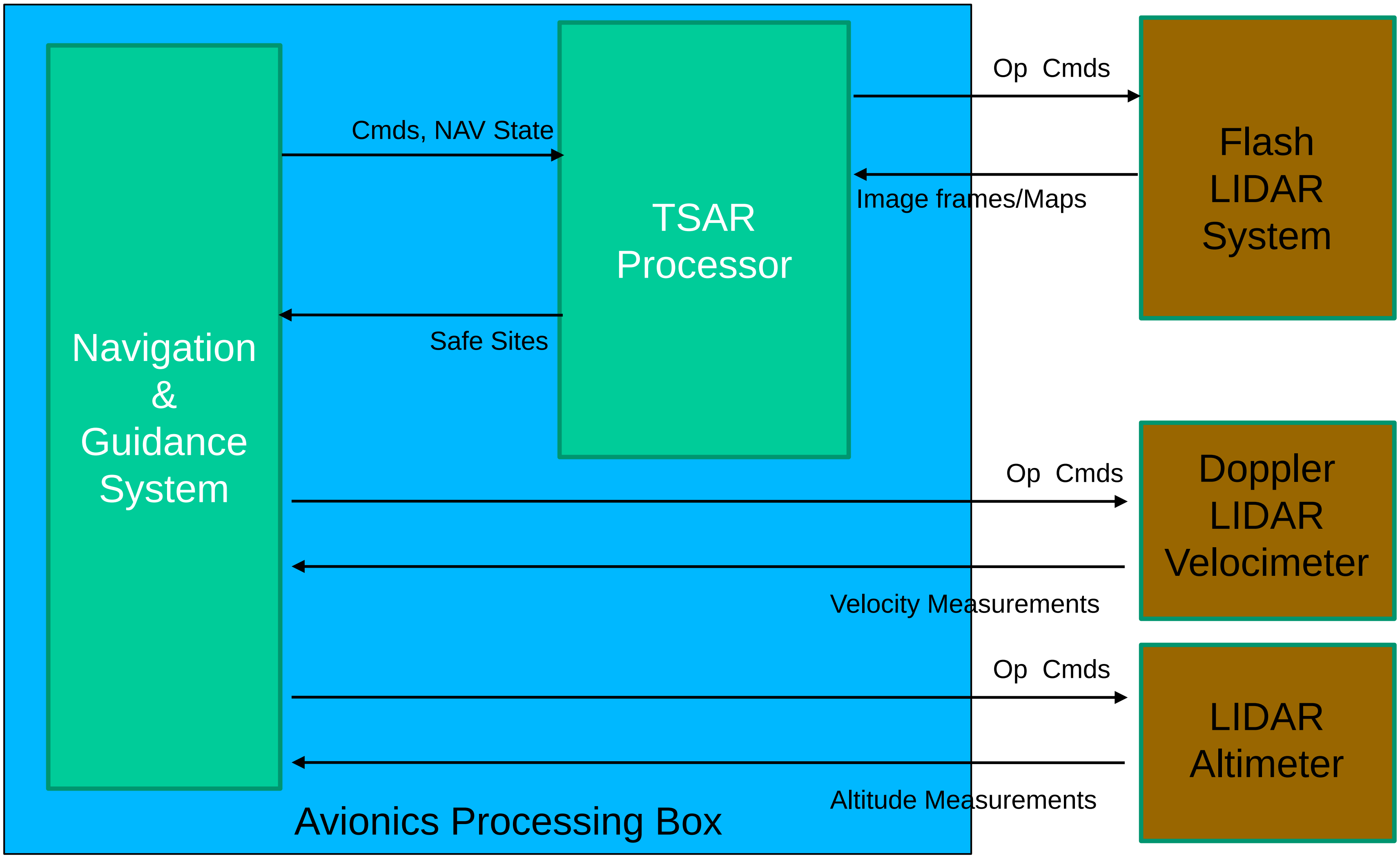
- **Goal:** Develop and deliver a TRL 6 lunar GNC descent and **landing subsystem to place humans and cargo safely, precisely, repeatedly and autonomously anywhere on the lunar surface** under any lighting conditions within 10's of meters of certified landing sites

- **Approach:** During the Approach phase, use three LIDAR systems to automatically scan the landing site, detect safe landing areas, and navigate to a determined safe area

Organization

- NASA Johnson Space Center
  - Program Management
  - Hardware-in-the-Loop Testing (HAST)
  - Avionics (APB)
- NASA Langley Research Center
  - LIDAR Sensors
  - 6DOF Simulation (POST2)
- NASA Jet Propulsion Laboratory
  - Hazard Detection Algorithms (TSAR)
  - System Integration
- Draper Labs
  - GNC algorithms
  - Navigation Filter
- Applied Physics Laboratory
  - Lunar Science
  - Lunar Terrain Models

System Block Diagram



- Flash LIDAR
  - Fires a laser pulse, measuring the time for the pulse to return back to the camera, calculating the distance
  - Uses an array of sensors to create an image of distances, rather than a single point
- Doppler LIDAR Velocimeter
  - Fires three lasers in orthogonal directions
  - Determines velocity by measuring the doppler shift of the return beam
- LIDAR Altimeter
  - Fires a single laser pulse, measuring the time of return
  - Calculates the distance using a single point

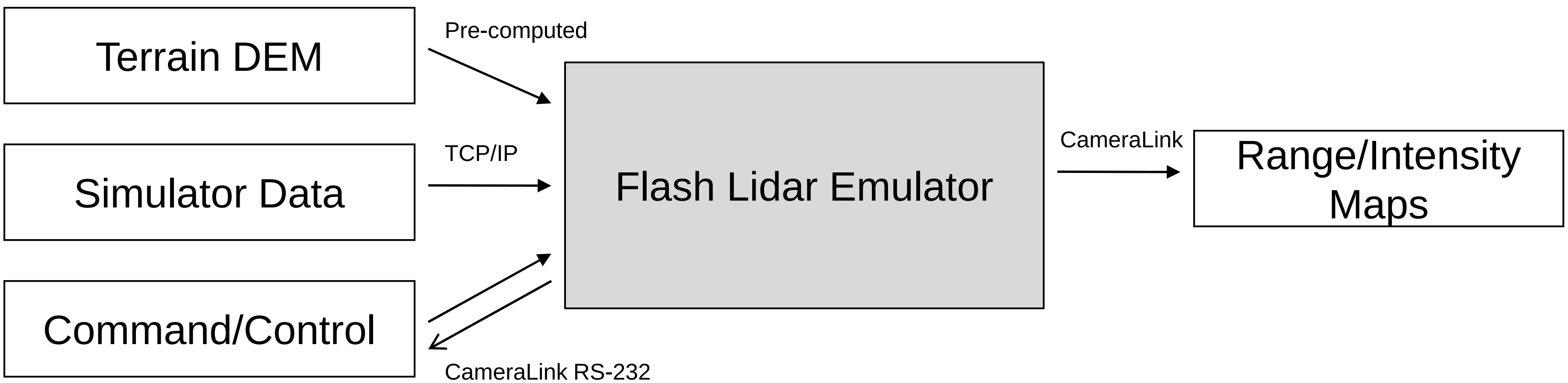
Problem

- **Problem:** How do we develop, test, and evaluate the ALHAT system in a lab environment?
  - System components are being developed in four independent organizations
  - Impractical to use real LIDAR in a closed loop, hardware-in-the-loop, real-time lab environment
    - Physical constraints
    - Schedule constraints
    - Cost constraints
- **Solution:** Use a functionally equivalent **software emulator** to replace the LIDAR systems

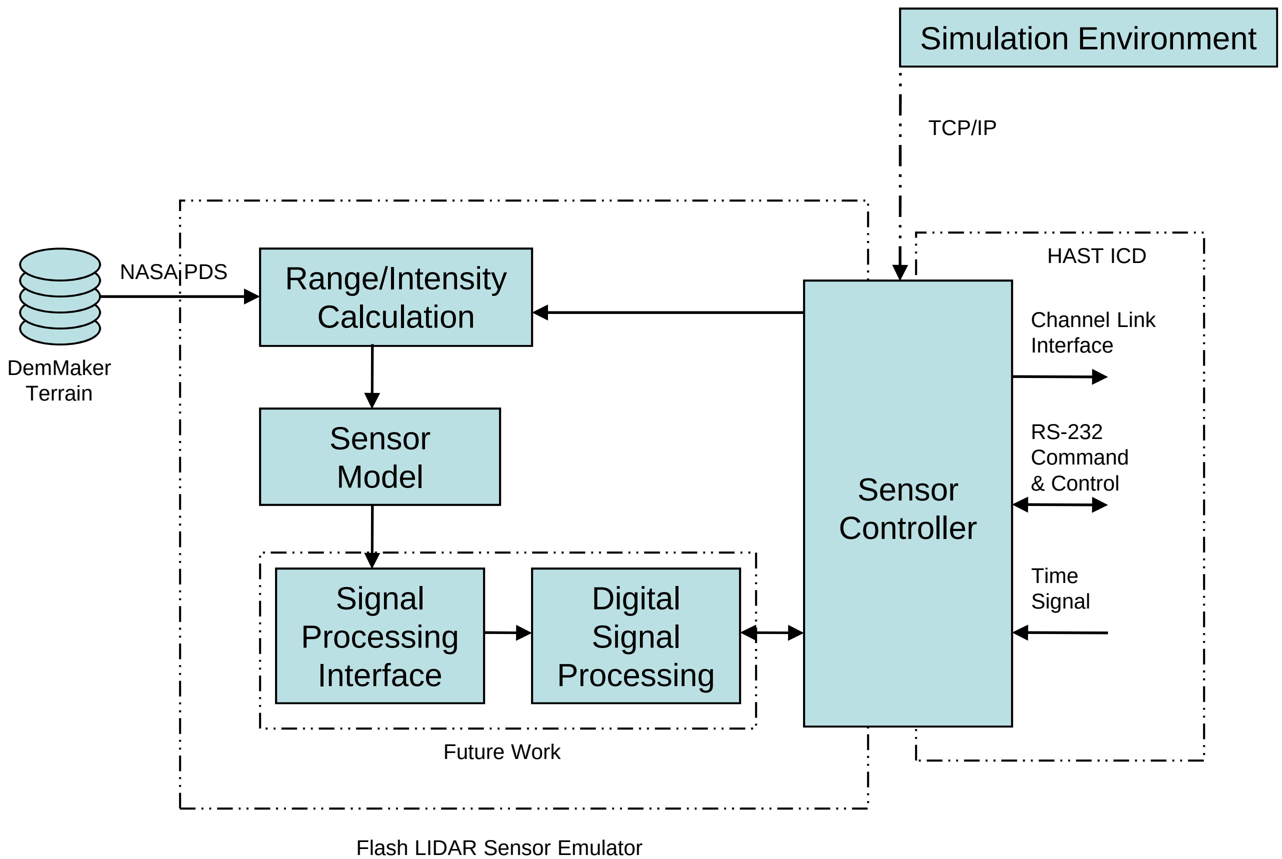
Emulator Requirements

- Complies with Flash LIDAR Interface
  - Input
    - Command & Control
  - Output
    - 256 x 256 Range Image
    - 256 x 256 Intensity Image
    - 30 Images/Second
- Identical Hardware Interfaces
  - CameraLink (Images)
  - RS-232 (Command & Control)
- Similar Image Quality
  - Noise/Signal Ratio
  - Dead Pixels
  - Precision
- Integrates into HAST framework
  - Input
    - Sensor position & orientation (Ethernet)
    - Lunar Terrain Data (Pre-computed) (5000 x 5000 DEM)

Emulator Interfaces

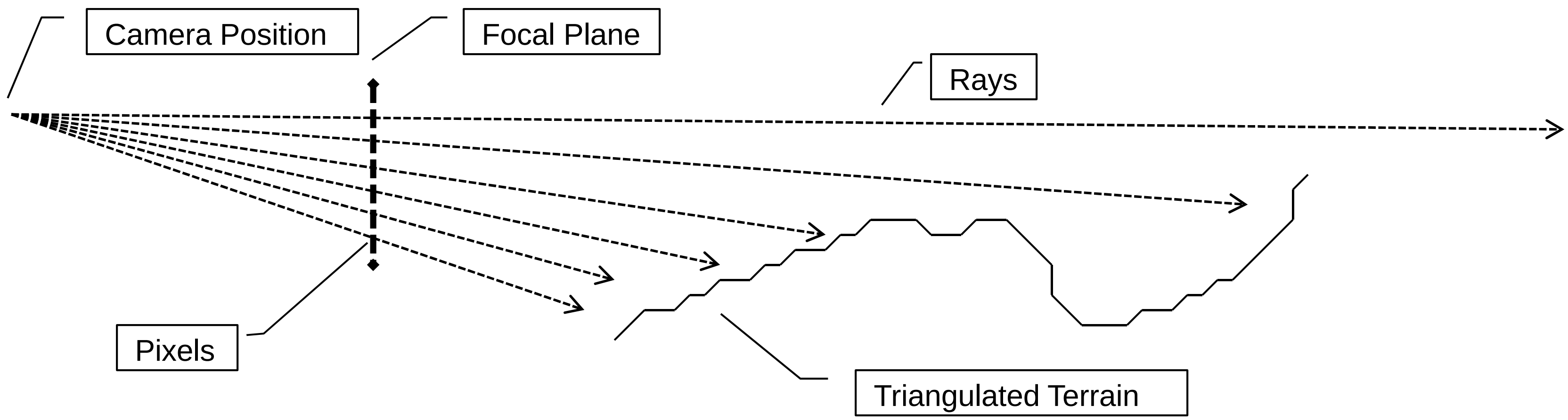


Emulator Block Diagram



Range/Intensity Calculation

- Create a triangle mesh from the DEM data (5000*5000*4 triangles)
- For each pixel on the focal image plane, create a ray from the camera position through the pixel (256*256 rays)
- Range is the distance from the camera position to the point where the ray intersects the triangulated terrain
- Intensity is `reflection*cos(incidence_angle)` at that pixel



Range/Intensity Optimizations

Problem: The non-real-time implementation of the Flash LIDAR takes several seconds per frame. **How do I implement the emulator for real time?**

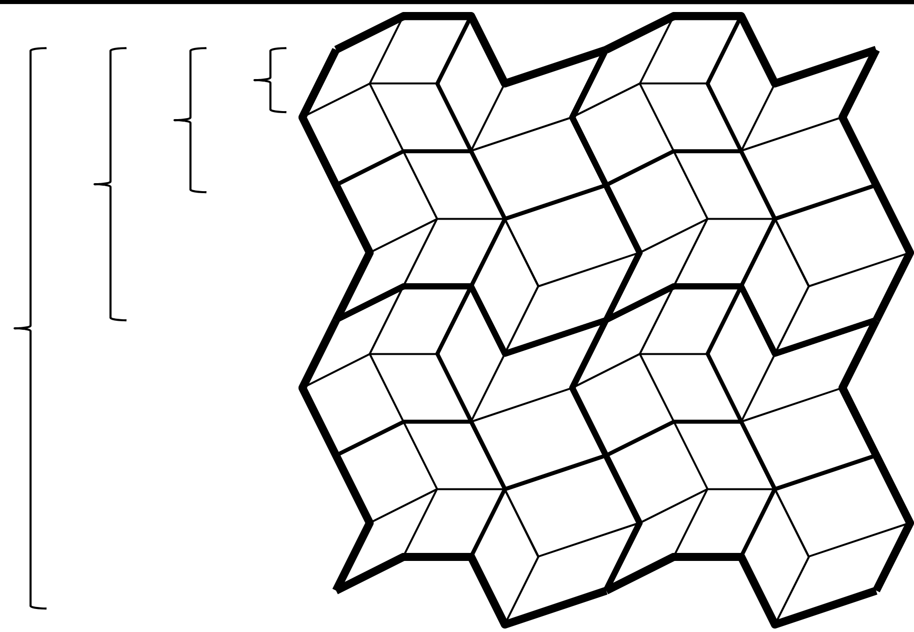
- Test intersection of 65,536 rays with 100,000,000 triangles, 30 times a second

Solution: Use optimization techniques from several computer fields:

- Computational Geometry
- Ray-Tracing
- Parallel Processing
- Vector CPU processing
- General-Purpose computation on Graphics Processing Units

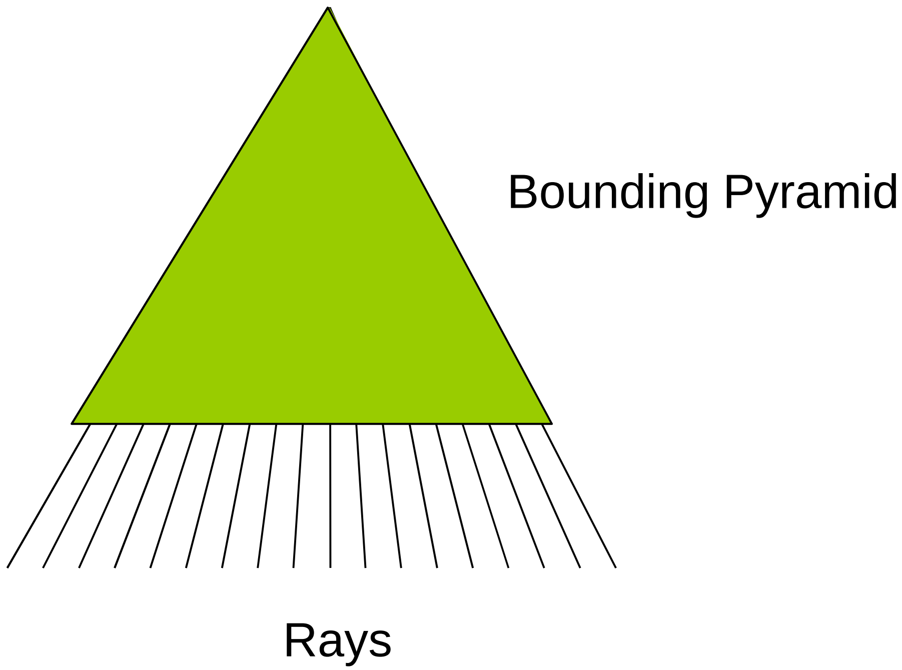
Computational Geometry

Un-partitioned	Quad Tree
List of triangles	Terrain recursively subdivided into 4 partitions forming a 4-way hierarchical tree
Each ray is tested against each triangle	Each ray is tested against the parent partition If intersected, the ray is tested against the child partitions
O(n) per ray, n is number of triangles	O(log n) per ray, n is number of triangles



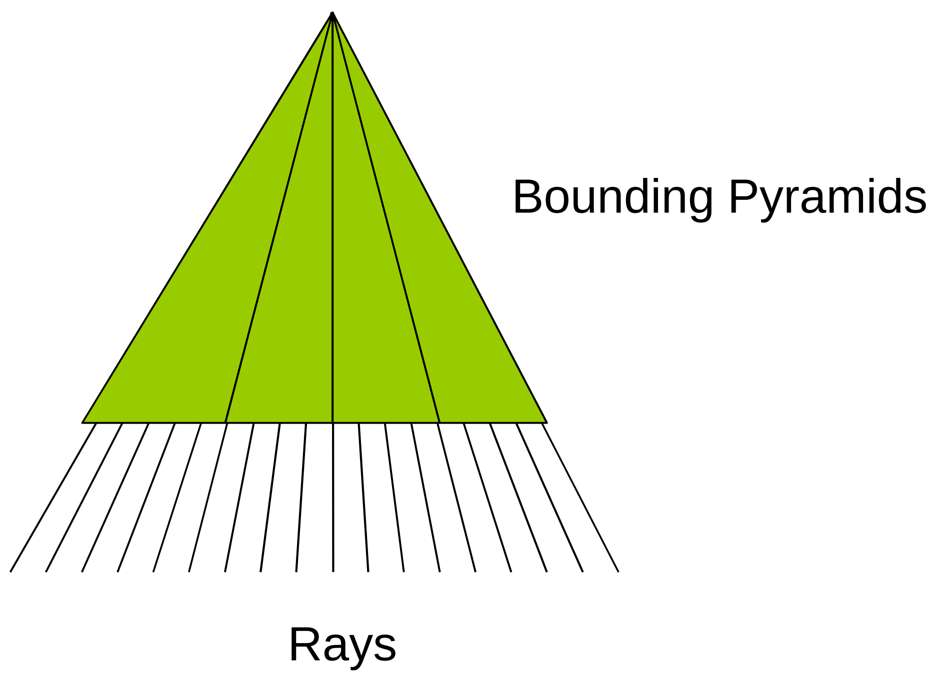
Ray Tracing

Un-Bundled Rays	Bundled Rays
256 x 256 array of rays	1 bounding pyramid around the rays
Each ray is tested for intersection	Pyramid is recursively tested against each partition At the leaf partitions, intersect the 256 x 256 rays against the triangles
O(n), n is number of rays	O(1) partitions, O(n) leaf triangles



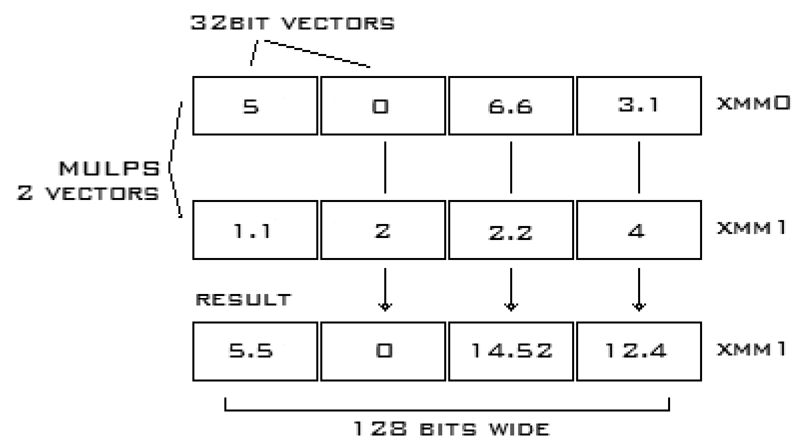
Parallel Processing

Single Bundle	Parallel Bundles
All the rays in a single bundle	Divide the bundle into sub-bundles, one for each CPU core
Not easy to parallelize	Independent tasks for 100% parallelization



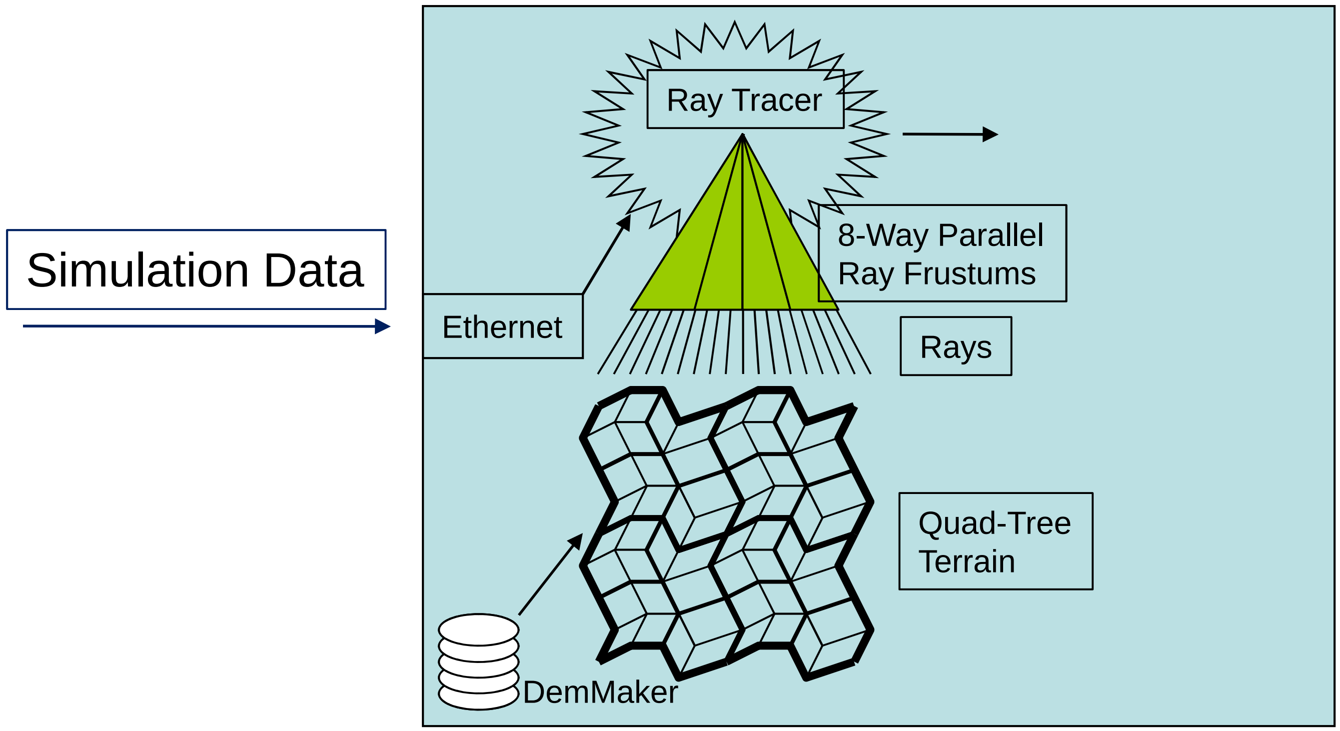
Vector CPU Processing

- Modern CPUs are scalar processors
  - Each instruction operates on one data item at a time
- Streaming SIMD Extensions
  - Intel extend the x86 instruction set (SSE)
  - One instruction can operate on
    - 4 32-bit integers
    - 4 32-bit floats
    - 2 64-bit floats
    - 2 64-bit integers
    - 8 16-bit integers
    - 16 8-bit characters



  - Ideal for Vector/Matrix math
  - Additional instructions that must be explicitly used

Emulator Design

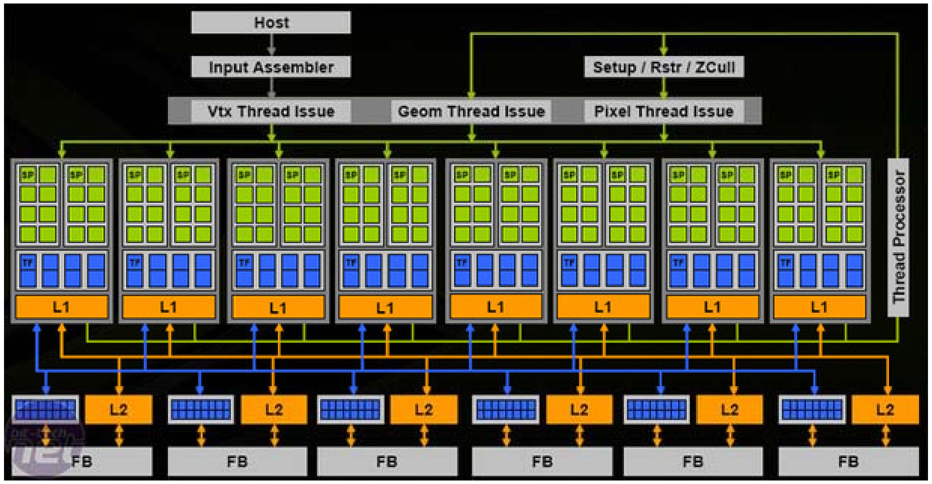


Sensor Model

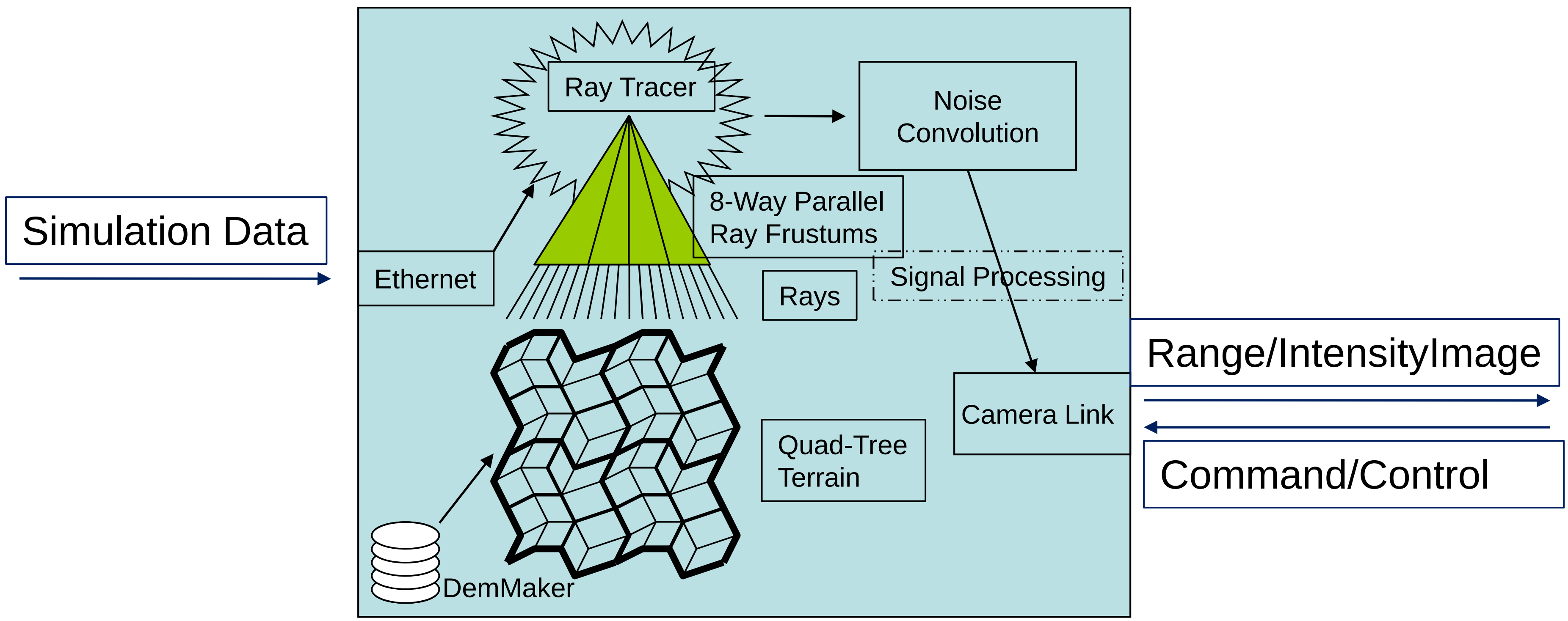
- Add Gaussian noise to each pixel in the image
  - Signal/Noise Ratio
  - Based on POST2 sensor model or actual hardware characteristics
- Pre-calculate random dead pixels
- Use intensity value for pixel cut-out
- Convolve with Gaussian filter for crosstalk or bleeding between pixels

General-Purpose computation on Graphics Processing Units

- A modern GPU is bigger and has more computational power than the CPU
- Massively parallel, multi-core processor
  - Hundreds of cores per processor
  - Each core is a vector processor
- Ideal for image processing
  - Each pixel will execute the exact same program, in parallel
- Implemented
  - Additive Gaussian Noise
  - Gaussian Convolution
  - Pixel Cut-Out
  - Image Formatting



Emulator Design



Application

- Original Problem:
  - How do we develop, test, and evaluate the ALHAT system in a lab environment when we can't use LIDAR in the lab?

- Field Test
  - All three LIDAR sensors were flown on a helicopter from NASA Dryden
  - The Avionics Processing Box was also flown, collecting data for the GNC and TSAR components
  - The Flash LIDAR was connected to the APB

  - The first time the Flash LIDAR was connected to the Avionics Processing Box
  - The first field test for the LIDAR to integrate image processing and active, intelligent camera control

Application

Problem: Although an Interface Documents (ICD) exists, the Flash LIDAR interface has never been implemented. How can we develop and test the interface for a camera when the camera hasn't been built yet?

Solution: Use the emulator as the testbed to develop the interface

- The ICD and interface needed to be modified for FT4
  - Image header
  - Image resolution
  - System timing
  - Command/control
- The interface was first implemented in the emulator
- The APB was designed, developed, and tested using the emulator interface
- The Flash LIDAR system used the same interface code as the emulator
- The emulator was the first to implement the interface, and all other implementations were based on it, so the emulator became the de facto interface standard

Application

Problem: JSC needs a Flash LIDAR to develop their avionics software. Sending a Flash LIDAR (and person to operate it) to JSC would cost a great deal of time, money, and inconvenience

Solution: Send an emulator to JSC for their use in software development

- Since JSC didn't have to wait for the LIDAR to be finished and delivered, The APB and the LIDAR could be developed in parallel
- The emulator does not require an operator to be with it, so no personnel were required to go to JSC
- The emulator can be quickly modified for future field tests with very little cost or effort

Application

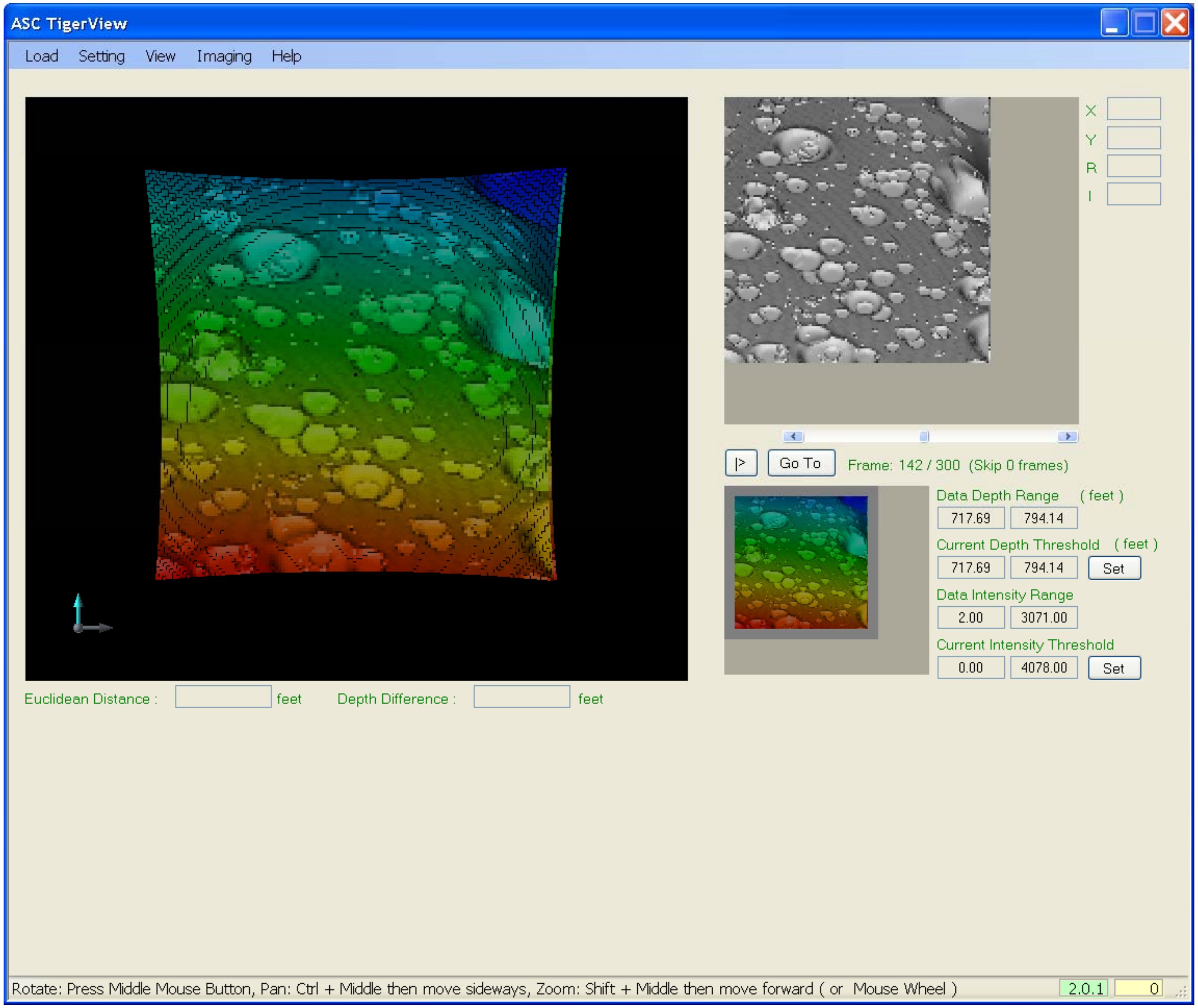
Problem: It is difficult to develop, test, and debug the image processing and active camera control software using the LIDAR camera

Solution: Use the emulator as the data source for the system software

- The emulator provides a controlled input with known, well-defined values
- The software and LIDAR camera could be developed in parallel
- The emulator can produce data files that can be used to help model and simulate the FPGA code for image processing
- Based on the emulator using the proprietary Ethernet interface, not the ALHAT ICD.

Results

Autonomous Landing and Hazard Avoidance (ALHAT)



Results

- An emulator was delivered to JSC in August 2009
- JSC used the emulator to develop their APB interface software in preparation for the flight test
- There were no significant interface issues in the flight test, despite the APB and the LIDAR never being physically connected until the field test
- An emulator was used extensively in the development process at Langley. All initial FPGA code was developed and tested using the emulator first
- An emulator was sent to the test site and used for debugging and integration leading up to the test

Future Work

- Integrate the image processing algorithms into the emulator
- Develop an emulator for the velocimeter and altimeter LIDAR systems
- Revise for use in future field tests