THE AEROSPACE CORPORATION

Aerospace CubeSat Program: Software Uploads

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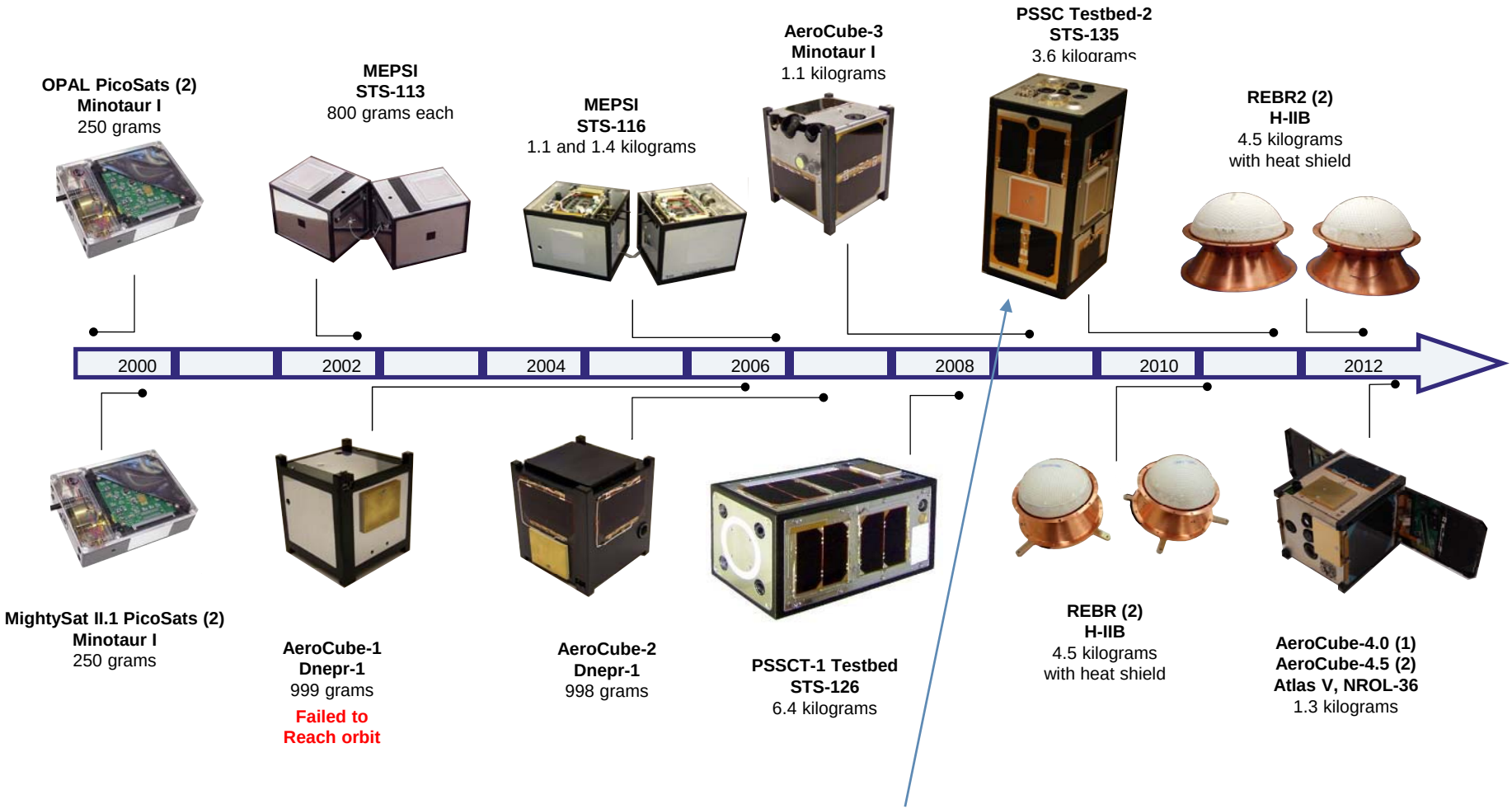
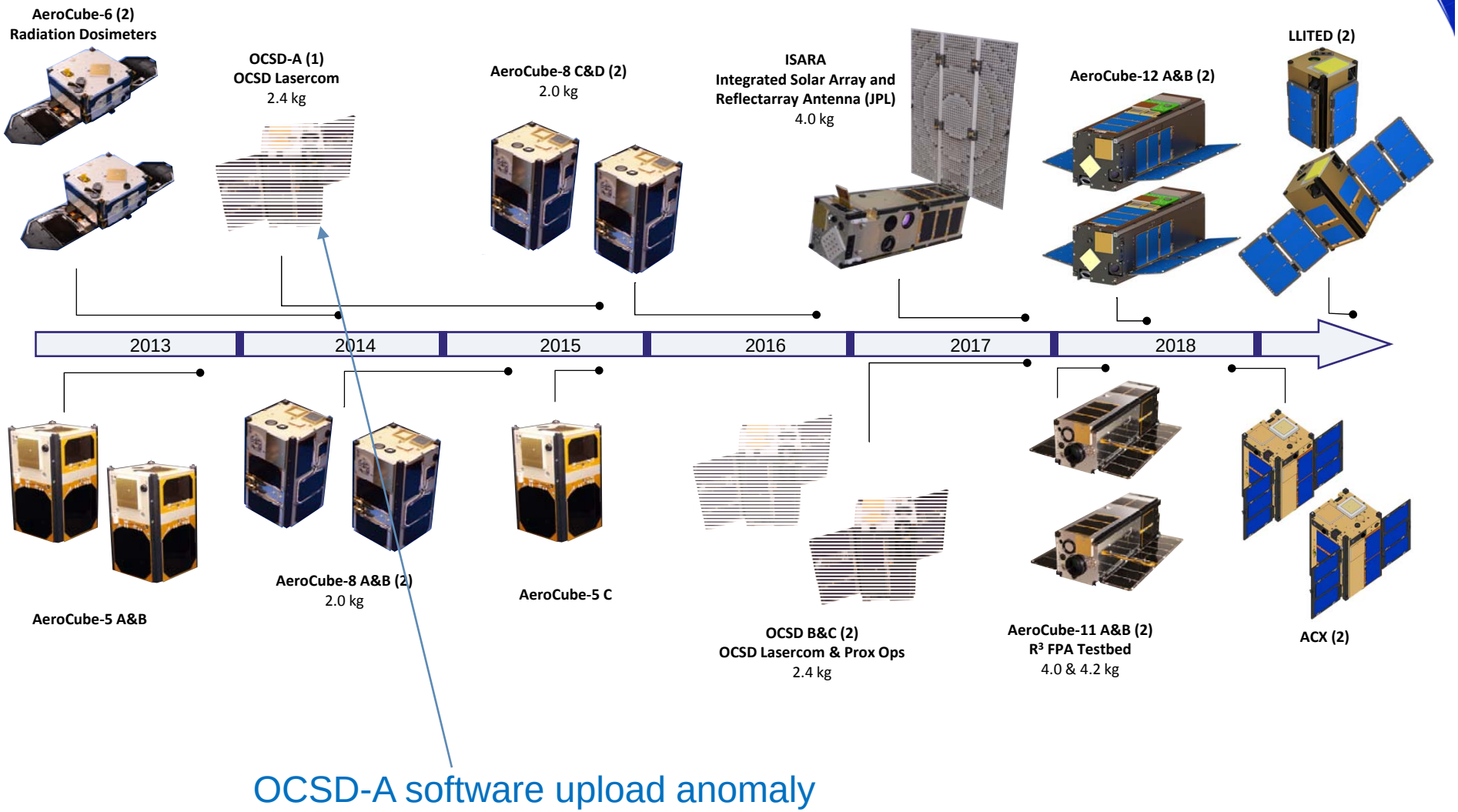
Aerospace Nano/PicoSatellite History (1999-2012)



First Aerospace satellite with on-orbit reprogrammability

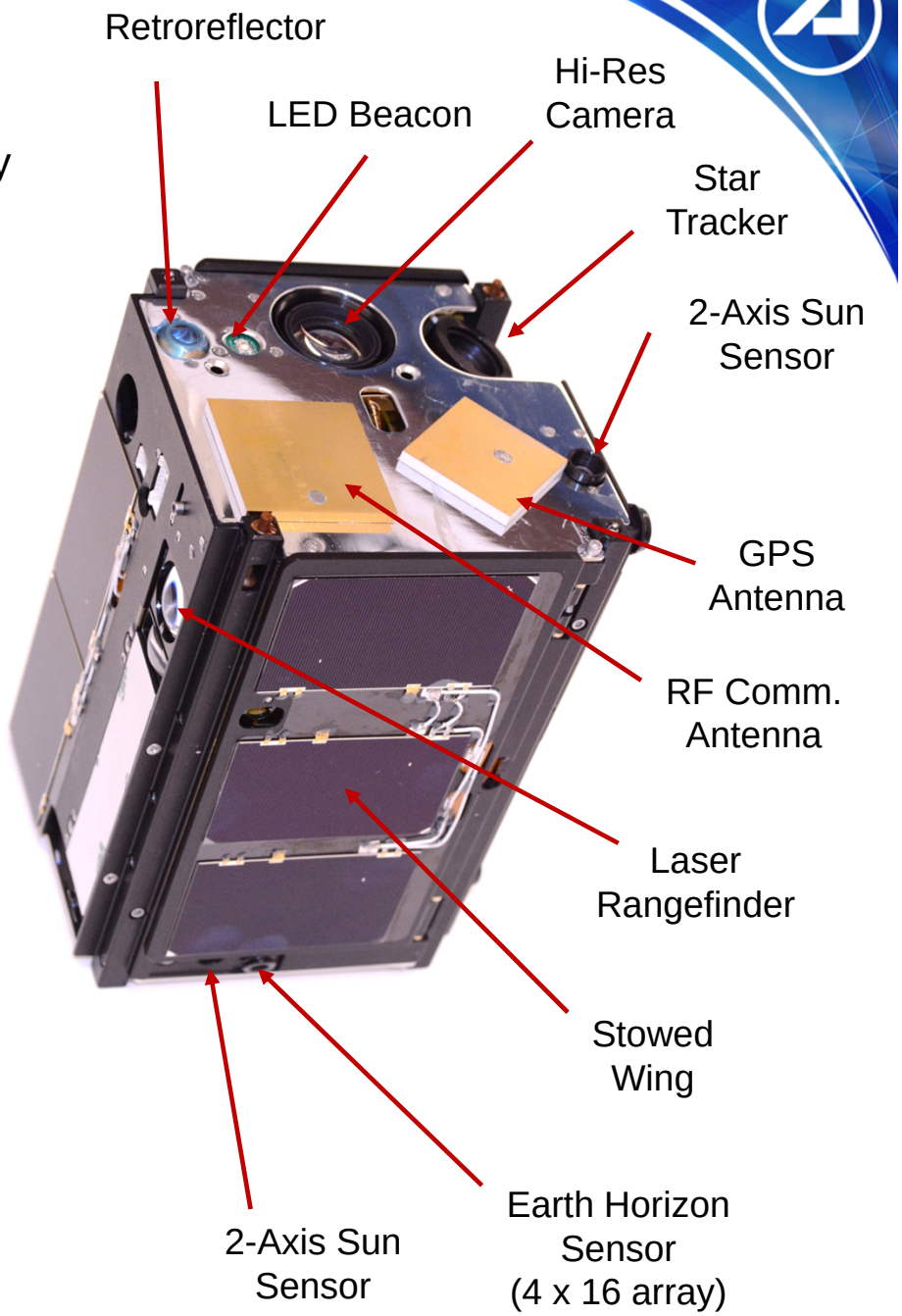
Aerospace Nano/PicoSatellite Active Projects



OCSD-A software upload anomaly

OCSD (AeroCube 7)

- Funded by NASA's Small Satellite Technology Program
- Goals:
  - *Demonstrate optical communications from a CubeSat to a 30-cm diameter ground station from low Earth orbit (LEO) at rates between 5 and 50 Mb/s*
  - *Demonstrate tracking of a nearby cooperative spacecraft using a commercial, off-the-shelf (COTS) laser rangefinder*
  - *Demonstrate attitude determination using a sub-cubic-inch star tracker.*
  - *Demonstrate orbit control using variable drag*
  - *Demonstrate propulsive orbit control using a steam thruster*
- Pathfinder spacecraft, OCSD-A, launched October 8, 2015
  - *Mission of opportunity to fly engineering model*
- Two flight units launched November 12, 2017
  - *System checkout complete*
  - *Laser testing under way*



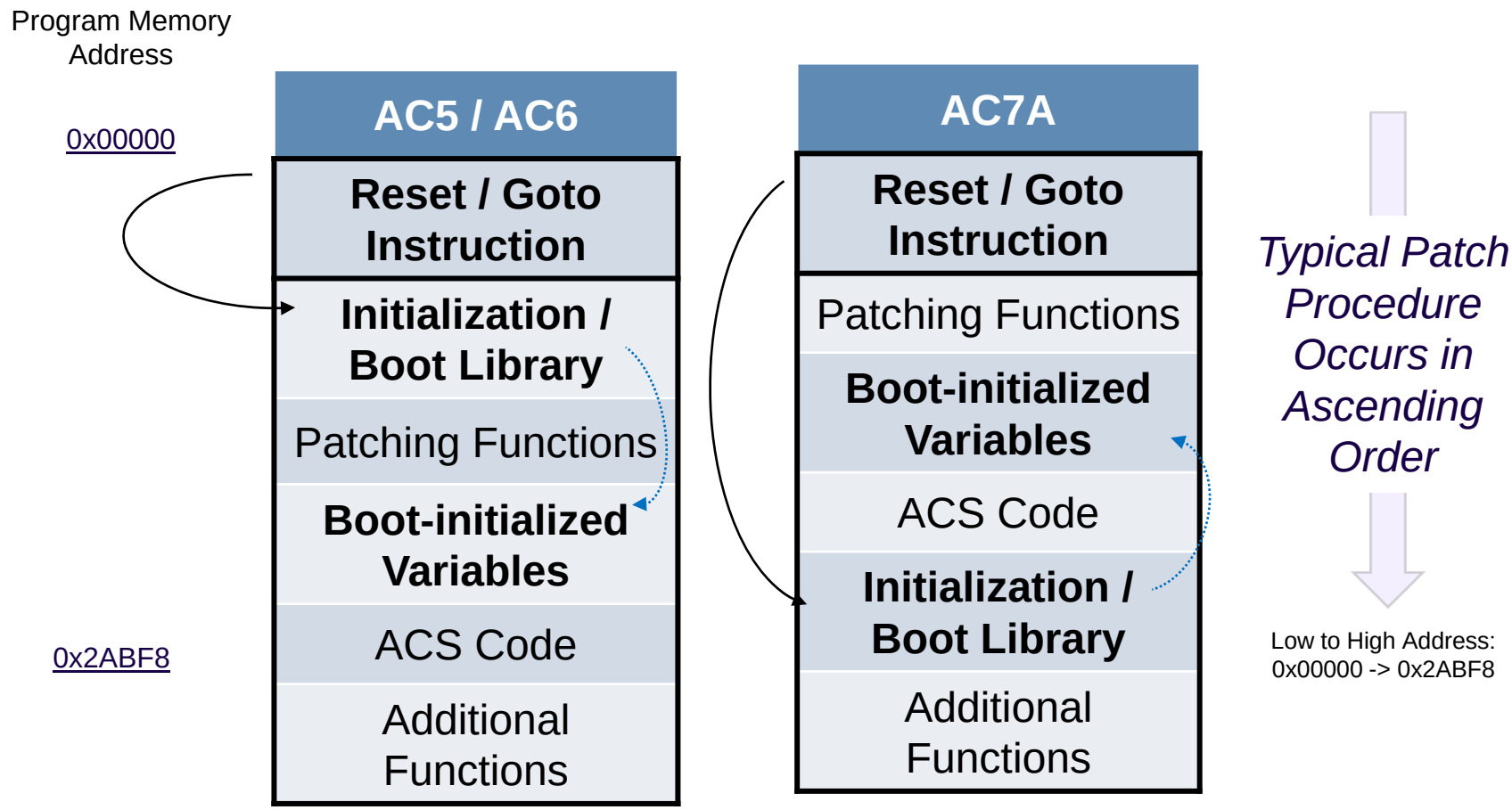
OCSD-A Software Update Anomaly Overview

- The ACS main microcontroller was rendered permanently unresponsive during a software update
- The pre-upload verification process did not exactly match actual upload process
  - *Verification process:*
    - Program an engineering unit to match the flight configuration then load the update and verify a match to the desired program binary after update
  - *Flight upload process:*
    - Update loaded incrementally over several ground contact periods
    - Between ground contacts, the vehicle executed a regularly scheduled power-cycle
    - The power-cycle process re-booted the ACS processor into a partially updated program which prevented proper initialization
  - *The power-cycle re-boot was not included in the pre-upload ground simulation*
- Prior flight vehicles had experienced similar conditions, but a change in the partition order necessitated a different upload sequence to preserve proper initialization when the processor is in the partially updated state

- The ACS processor must be functional to load further updates, so the error was non-recoverable

Memory Partitioning

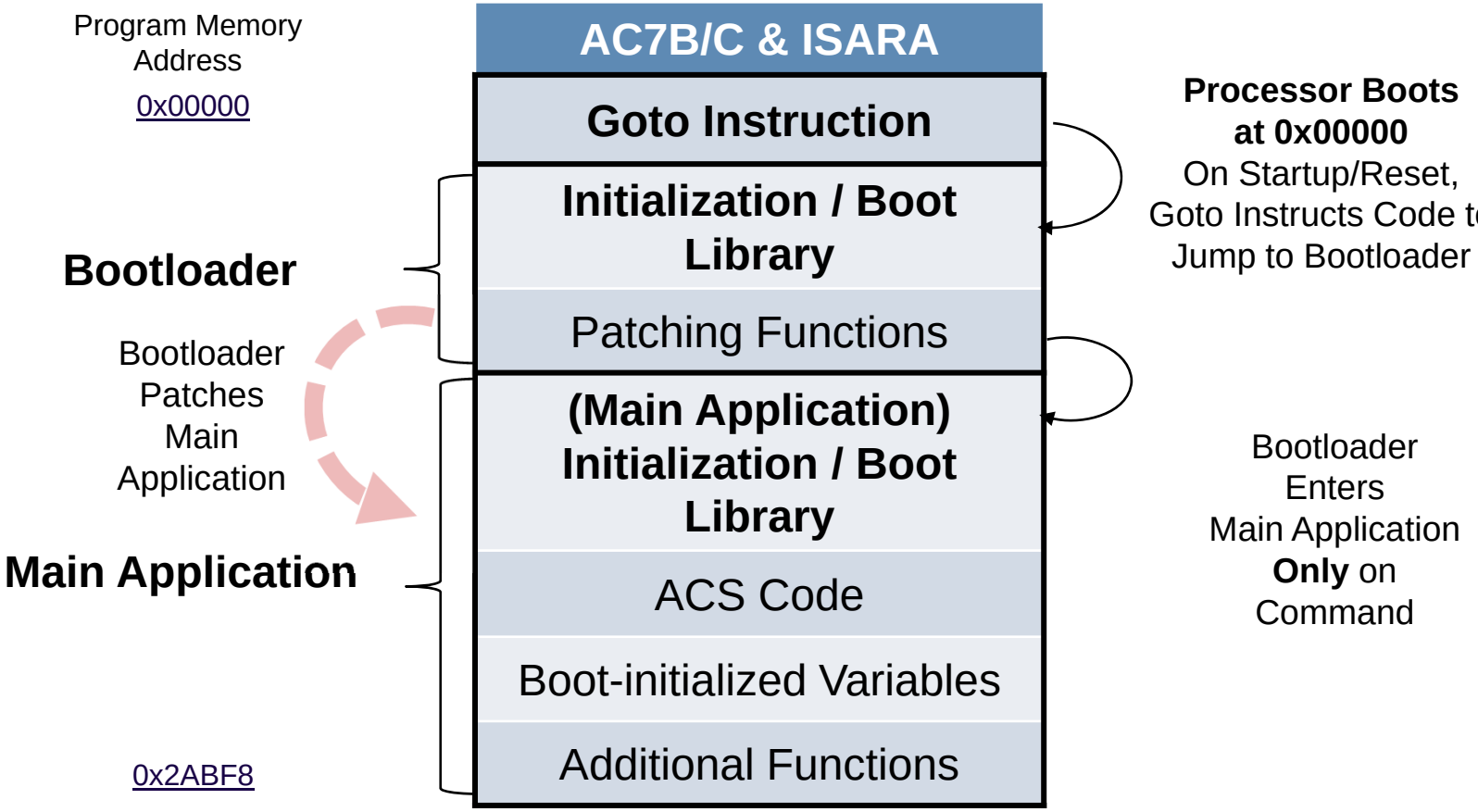
Example Memory Map of 16 Bit PICs used on AeroCube



> Boot Library references table of Boot-initialized variables
> Table must match Boot Library or reset will cause errors

Bootloader Application

Separate Patch Functions from Main Application



If Main Application Fails, Bootloader can still patch/update the application

Patch Generation and Verification

Process for Verifying Software Updates Prior to Upload

- For code changes, new code is exercised using canned sensor data, telemetry is downloaded, and results are compared to simulation
- Designed patch is validated:
  - *Program memory is read from processor after compilation of new software*
  - *Bootloader applies patch over radio*
  - *Program memory is read from processor after the patch is applied*
  - *Binary match of program space is required for patch validation*
- Bootloader is tested to ensure that entry into the main application works on command
- Rerun canned sensor data test and validate results

- Bootloader has the ability to patch the entire main application
- Bootloader can patch the main application even if there is a failure within the main application
- Remaining in bootloader until commanded precludes the ability to execute partially updated code

> Test like you fly: patches are applied over the radio
> Designed patch is validated by comparing program space binaries

Impact of OCSD-A Code Upload Anomaly

- Attitude control main processor was permanently disabled, which resulted in the following loss of functionality:
  - *Inability to control the spacecraft attitude or spin rate*
  - *Inability to communicate with or operate the laser downlink communication payload*
  - *Inability to communicate with or operate the laser range finder payload*
  - *Inability to propagate & estimate the spacecraft attitude in real-time*
    - Discrete attitude solutions using the star tracker are possible, but only when the tracker happens to be pointed in a favorable orientation

- OCSD-A still reduced risk for the primary mission, although a sub-set of the risk reduction objectives could not be accomplished:
  - *ACS verification and pointing accuracy goals (Partial, limited to Star Tracker Checkout)*
  - ~~*Laser*~~ *and other subsystems verification (Other subsystems were tested: Power, Camera, GPS, Radio, Deployment Mechanisms)*
  - ~~*Laser Downlink CONOPS refinement*~~
  - *Calibration procedure & tool refinement (Partial, limited to Star Tracker Checkout)*

OCSD-A Inoperable Components

- The following items were rendered inoperable by the software update anomaly (items in BLUE were tested prior to the update):
  - *Sun Sensors*
  - *Earth Nadir Sensor*
  - *Earth Horizon Sensor*
  - *Rate gyros (STIM & VectorNav)*
  - *Reaction Wheels*
  - *Laser transmitter (powered on digital electronics and got response but did not fire laser)*
  - *Torque rods*
  - *Laser Range finder*
  - *Magnetometer*

Many of the inoperable components were tested prior to the update

OCSD-A Operable Components and Available Functionality

- Note that the vehicle can still be utilized to test multiple sub-systems to increase the readiness level for the OCSD-B/C Flights
- The following items are operable and have undergone at least an initial check-out (note items in BLUE are first of flight items on OCSD-A):
  - *Star Trackers (2 units)*
  - *Software Defined Radio (SDR)*
  - *Solar Wing Release Mechanism*
  - *Star Tracker Baffle Release Mechanism*
  - *Electrical Power System control board & batteries*
  - *Camera Control Board & Prox Ops Detection Camera*
  - *GPS Receiver*
  - *Heritage UHF Radio (ADV Radio)*
  - *Temperature Monitors*
  - *Flight Computer*

Ability to test and characterize multiple first of flight items still significantly reduces risk for the later flights

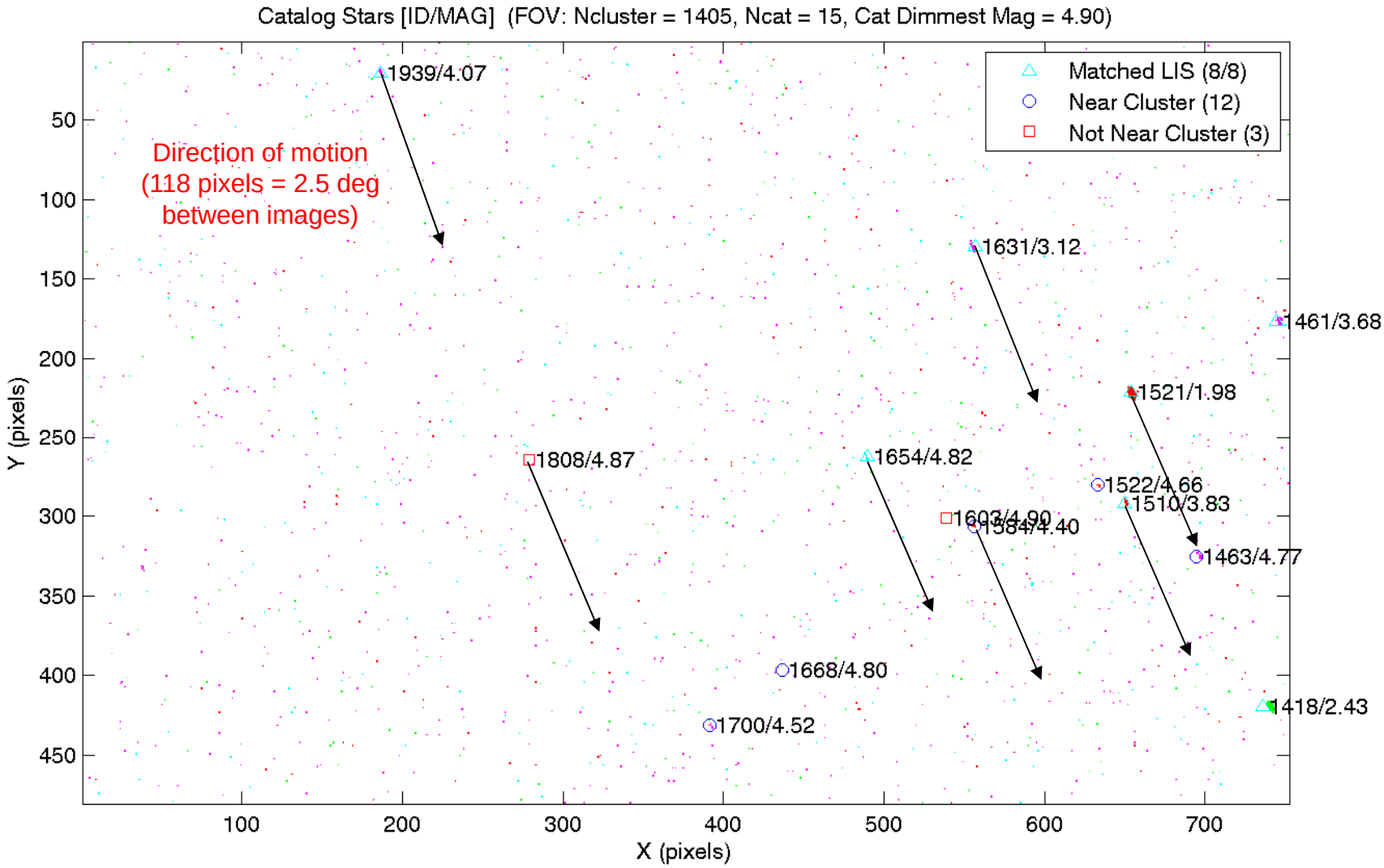
On-orbit re-programmability: Value and History

- Many missions would not have achieved full mission success without the ability to re-program due a variety of unpredictable issues
  - *AeroCube 4 was ejected from the launch tube with a spin rate > 1 rotation per second. Re-programming allowed for a revised detumble algorithm that could operate quickly enough to slow down the vehicle*
  - *AeroCube 4 mission extension enabled by modifying camera code to produce video files*
  - *AeroCube 6 rate gyro performance anomaly (either calibration or installation issues) required modification to ACS software*
  - *AeroCube 6 utilized new torque rods with magnetic hysteresis large enough to corrupt the magnetometer readings and hinder attitude control. A software update allowed for the upload of compensation table for the magnetometer readings*
  - *AeroCube 7A (post ACS upload error) required numerous software uploads for non-ACS processors to bypass bus internal communication issues generated by malfunctioning ACS processor – allowed testing of many OCSD-A systems*
  - *AeroCube 7A: entire new experiment created on SDR to investigate single-event upsets in FPGA*
  - *AeroCube 7B&C star camera readout anomalies required software uploads to fix various issues that could not be tested on the ground*

- Numerous software updates over many programs and several years, combined with the experience of the AC7A anomaly, have led to a polished processes for version control, patch generation, verification, and upload

On-orbit re-programming is vital to allow work-arounds for unpredictable events, on-orbit calibration, and bugs not caught during ground test

Post-Processed Star Tracker Image 1 (0.97 deg/s)



Yukon Delta (Alaska) & Bering Sea
10MP imager test photos