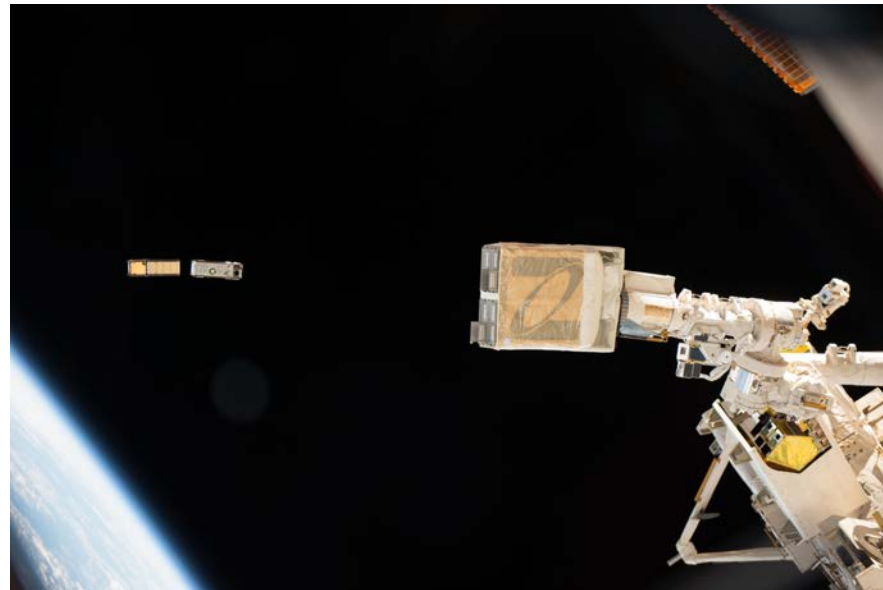# Applying Systems Engineering to CubeSat Missions

Mission Success Lessons from IceCube


WILLIAM MAST

CODE 598

AUGUST 17, 2018

- IceCube Mission Background

- Systems Engineering Applied to the IceCube Mission

- Recommendations for Improving Mission Success
  per. Mission Assurance Improvement Workshop (MAIW) AEROSPACE REPORT NO. TOR-2017-01689

  - 1. Build an experienced team—it matters
  - 2. Define your scope, goals, and success criteria at program start
  - 3. Conduct risk-based mission assurance
  - 4. Design for simplicity and robustness
  - 5. Maintain a healthy skepticism on vendor subsystem datasheets
  - 6. Plan for ample IV&T time
  - 7. Stock spare components
  - 8. At a minimum, perform the four mission assurance tests

- Lessons learned

- Knowledge Capture

- The Future
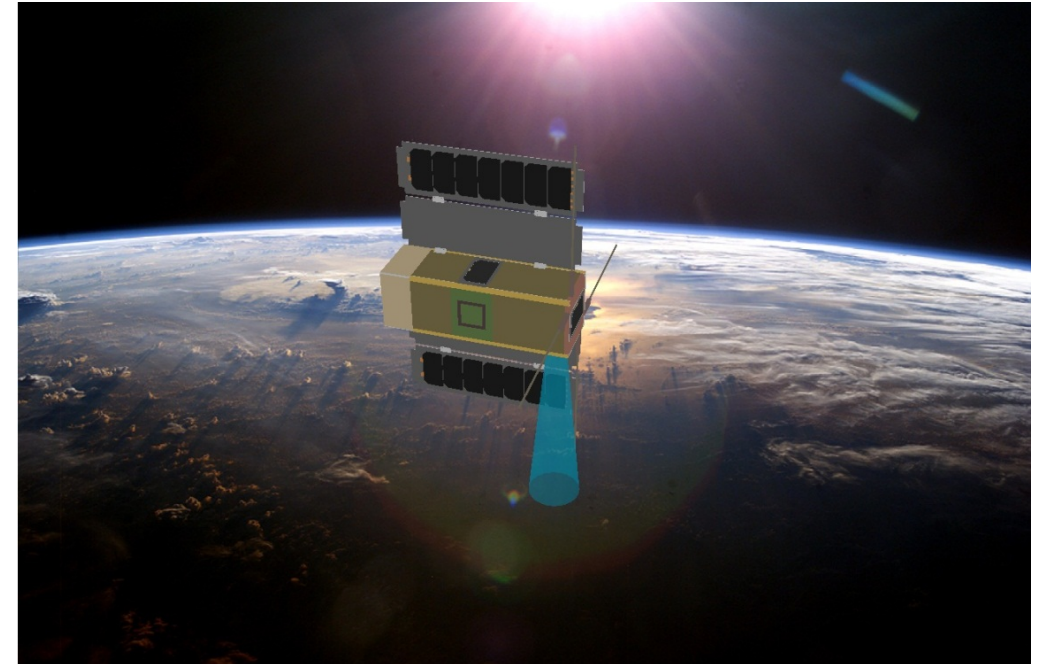
- The IceCube Mission was proposed and won by Dr. Jamie Esper (GSFC/592) and Dr. Dong Wu (GSFC/613) in 2013
- GSFC's First Science Mission on a CubeSat ---- Not a Tech Demo
  - Clear Objective "raise the TRL of a COTS 874 GH submillimeter wave radiometer technology from 5 to 6 with a ground test and from 6 to 7 with a 30 day on orbit test
  - PI, Science Team, and Instrument development and build at Greenbelt Campus
  - Budget and Schedule for COTS Integration effort only, no Bus technology development, 2 years to Launch
- AETD began mission support in May 2014
  - 1 full time SE to tailor 7123 processes tailored to CubeSat mission
  - Fractional FTE Support from Discipline Engineers at WFF campus ~0.1-.3 FTE per year
  - PM and Additional Discipline Support as available
  - Project worked seamlessly across two GSFC campuses

Recommendations for improving Mission Success
per U.S. Space Program Mission Assurance Improvement Workshop (MAIW) OTR 2018-00851

At SmallSat 2018, Catherine Ventrini of the Aerospace Corporation presented 8 recommendations to improve mission success for CubeSats as the result of a 9 month study of 94 satellites. OTR 2018-00851

The Recommendations Span the Project Cycle and I found them to be essential to the success of the IceCube Mission. With permission, I am borrowing these to describe the structure of the IceCube Mission

1. Build an experienced team—it matters
2. Define your scope, goals, and success criteria at program start
3. Conduct risk-based mission assurance
4. Design for simplicity and robustness
5. Maintain a healthy skepticism on vendor subsystem datasheets
6. Plan for ample IV&T time
7. Stock spare components
8. At a minimum, perform the four mission assurance tests

The entire report is: AEROSPACE REPORT NO. TOR-2017-01689

- PI/Instrument team -- Many had just finished the SMAP mission. Expertise with radiometers on both space and airborne platforms.
- PM/Tech Advisor – Experience with Balloon and Small Orbital experiments
- Systems Engineer -- LADEE Deputy Mission SE, 2008 - 2013
  - Experience Applying NASA SE process to small platforms
- Discipline Spacecraft Team -- extensive hand on experience adapting and integrating COTS and low TRL hardware in suborbital applications
  - Mission Planning Lab Staff composed most of the team
  - Wallops 6U CubeSat Bus and Deployer – 2008
  - CREAM ballooncraft Mission, MLAS, Sounding Rockets
  - Firefly 3U CubeSat acquisition and tracking
  - Specialized Greenbelt support for thermal, grounding, electronics
- Cooperation and collaboration with Dellingr, CeRES, and DICE Ground Station teams.

1. Build an experienced team—it matters
-*What could have gone better*

- Team took several months to fully assign,
  - Most WFF discipline engineers were assigned to higher priority projects
  - PM, Thermal, and Electronics support available 6mo - 1 year into the project.

- Most Discipline Engineers were constrained to 10% - 20% of their time

- Entire team was on a CubeSat learning curve

- Reassignment and loss of key team members occurred throughout the project cycle

- SRR/MDR 3 months into the project
  - Requirements Matrix defined to level 4
    - High Level requirements remained stable through the project, lower level revisited often
    - Identified design tall poles to prioritize:
      - Instrument temp. between 20-30C stable to 1C over 1.5 minute observation
      - Nominal Spacecraft rotation about the sun vector of 3 minutes per revolution
      - Geolocate the observation within 15km
  - System Block Diagram -defining all interfaces
  - Science Operations and capabilities defined using MPL simulations
  - Baseline Concept of Operations Document for Space and Ground Segments
  - Baseline Master Equipment List (MEL)
  - Basic Instrument ICD

Requirements and Risk Tracking

	Verification	Level 1	Level 1	Level 2	Level 3	Level 4
		L0 Scientific/Technical Objective				
3/27/2015 Changed		L0_HQ1	Raise the technology readiness of 874 883-GHz receiver technology for use in a future space flight missions			
		L0_HQ2	Directly benefit the submm-wave imaging radiometer on the advanced science payload of the ACE mission.			
		L0_HQ3	Reduce the cost and risk of future submm-wave cloud sensors with flight demonstration of key-enabling receiver tech			
3/30/2015 Changed		L0_HQ4	Raise flight readiness of commercially available 874 883-GHz radiometer technology by acquiring calibrated measuren			
		Level 1 Baseline Mission Success Objective				
3/30/2015 Changed		L1_RMS1	Raise the TRL of 874 883 GHz commercial receiver from 5 to 6 with a Ground Test			
		Verification / Measurement				
3/30/2015 Changed			Demonstrate that the response of 874 883 GHz to the presence of a black body and calibration source ha			
		Science Instrument Requirement				
12/8/2015 Changed		L2MS1	In order to meet L1_RMS1, the Science Instrument shall be operated by the spacecraft in a th			
		L2MS2	The thermal vacuum chamber shall contain a "black			
		Ground Test GSE:				
		L2MS3	Ground support equipment including electrical powe			
		Test Performance:				
		L2MS4	The IceCube ground test shall include sufficient hot			
		L2MS5	The IceCube spacecraft shall record a sufficient num			
3/30/2015 Changed		L1_RMS2	Demonstrate the response of 874 883 GHz to the presence of i			
		Verification / Measurement (Space Environment)				
3/30/2015 Changed			Demonstrate that the response of 874 883 GHz to the presence			
		Mission and Systems				
		Science Instrument Requirement				
		L2MS6	In order to meet the science requirements, the Spac			
		L4MEST3	the mechanical subsystem shall carry the			
		Mission Duration:				
4/7/2015 Changed		L2MS7	The IceCube mission shall include 30 5 days for the			
		L3MOS1	The IceCube mission shall include 5 days			
		L3LVS3	The IceCube mission shall include 5 days			
4/7/2015 Changed		L2MS8	The nominal minimum Science mission shall consist			
4/7/2015 Changed		L3LVS1	The nominal science portion of the missic			
4/7/2015 Changed		L3MOS2	The nominal science portion of the missic			
		Orbit Description:				
		L2MS9	The IceCube Satellite shall achieve a LEO orbit that s			
		L3LVS2	The IceCube Satellite shall achieve a LEO			
3/27/2015 Changed		L3_IP13	Instrument components shall tolerate 35			
		L2MS10	The Ice Cube orbit shall target an inclination less tha			
		L3LVS3	The Ice Cube orbit shall target an inclinat			
		Spacecraft Bus:				
		L2MS11	The spacecraft shall provide the required subsystem			

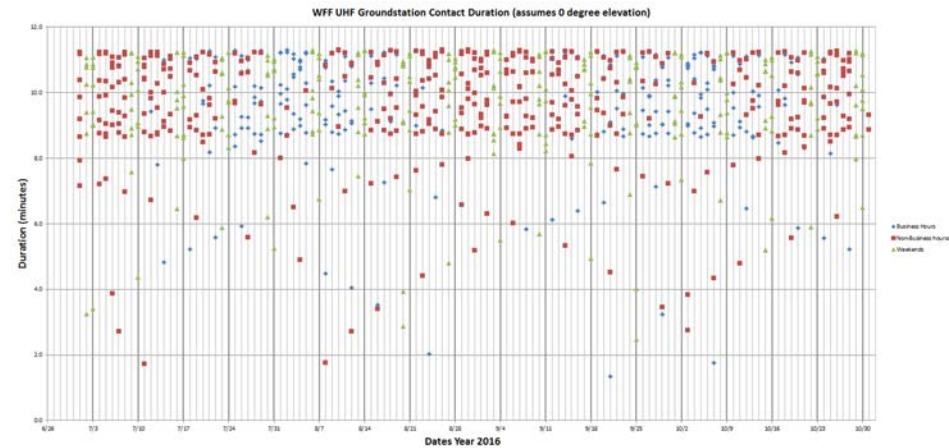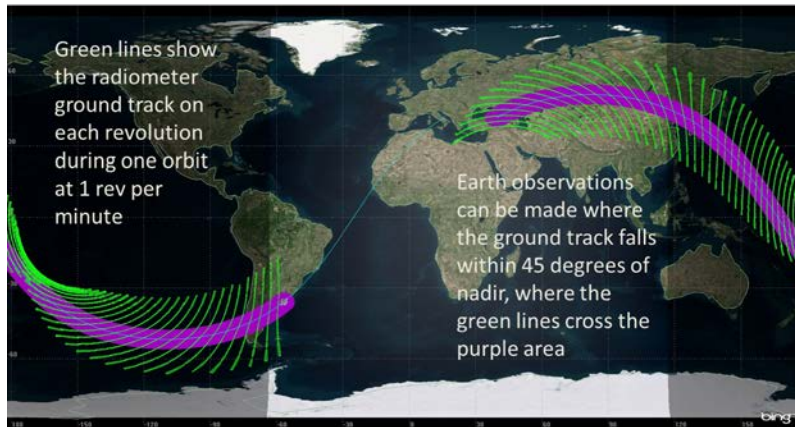| Number	Date Due	Closure Date:	Subsystem	Assigned to	Assigned by	Description	Disposition
34	10/23/2014		Software	Ted Daisey		Define spacecraft simulator software and hardware interface requirements for the December Delivery to instrument for instrument prototype tests. In broad terms, define requirements for what must be delivered for each instrument test.	No support is required for ir
35	10/23/2014		Project Management	Tom Johnson		Produce a Purchasing Plan for 2015 and 2016	completed
36	10/23/2014		C&DH/ Power	Scott Heatwole		Determine if the software in the ACS system can be reconfigured in flight to use new alignment parameters calculated from moon or limb observations.	Some ADCS parameters can ones related to alignment ca
37	10/23/2014		Systems	Will Mast		Post all component manuals and meeting notes on TDMS, Put folders on TDMS for each Subsystem	IN WORK
38	10/23/2014		Instrument	Negar Ehsan		Send pinout diagrams of AD chip to Chris Lewis	Completed
39	10/23/2014		Software	Negar Ehsan		Send invite for software requirements mtg.	Completed
40	10/23/2014		Instrument	Negar Ehsan		Send MICD to Spacecraft for review when ready	Mechanical Interface Descri
41	10/23/2014		Instrument	Negar Ehsan		Send Revised Instrument Mass and Power to Will for Mike Choi and Chris Purdy	Completed
42	10/23/2014		Systems/C&DH/ Power	Ted Daisey Paul Racette Bob Stancil		Develop a baseline Con Ops for downlinking science data and commanding based on the capabilities and operational modes of the Cadet Radio.	IN WORK
43	10/23/2014		Instrument	Negar Ehsan		Send the changes in the instrument data and software requirements that occur when the science data period is reduced by half to Ted Daisey	Completed
	From October 23, Table Top Design Status Review						
44			Science	Dong	Esper	Confirm required spin rate is 1 min/rev or 3 min/rev.	For the baseline design, let's 0.5 s integration time for da 2.25 min/rev. for the spinni
45			Systems	Will	Esper	NanoRacks maximum mass for 3U is 4.8kg (not 8.4kg, which is on their website) determine the true mass limit	Nanoracks document NR-SR 3U form factor of 4.8Kg
46			Systems	Will	Esper	Mass capability for PPOD Mk. III Rev. E per private conversation with CalPoly is 5kg. The value 4 kg is nominal, and is used to estimate PPOD mass properties.	overcome by events, P-Pod i
47			Mechanical Systems	Solley/ Hudeck	Esper	Review instrument volume allocation, and reconcile with bus volume allocation. Look at coaxial cable bend radius, and fine-tune volume requirement.	Instrument fits inside origina
48			Instrument	Heatwole	Esper	Define EMI/EMC and magnetics test (and magnetic calibration) requirements (imposed by the ACS) , do we need a post-vibe magnetics test?	The biggest magnetic field X Am^2, they fire every 200ms This can be up to 170ms. Th dipole. Cheers, Ryan
49			Systems	Mast Negar	Esper	Incorporate changes to the EMI/EMC and magnetics plan into I&T plan	
			Science	Dong	Esper	Can 25 km geolocation requirement be relaxed, or at least	

Concept of Operations Formulation

- Produced detailed simulations of instrument FOV, Solar Exposure, and Ground Station Access to validate the operations concept and define the quantity of data

Orbit Sun Duration - 2016

WFF UHF Groundstation Contact Duration (assumes 0 degree elevation)
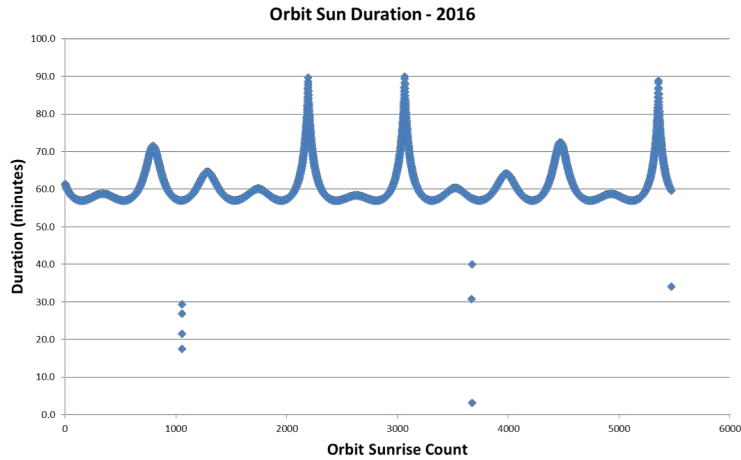
Radiometer Ground Track superimposed on area 45 degrees from Nadir (data on Equinox)

Radiometer Ground Track on Equinox

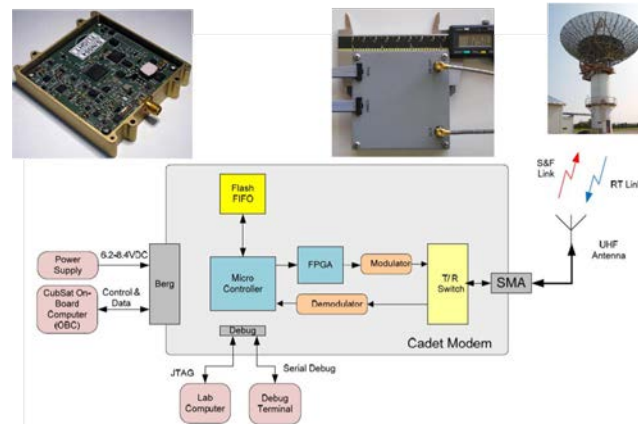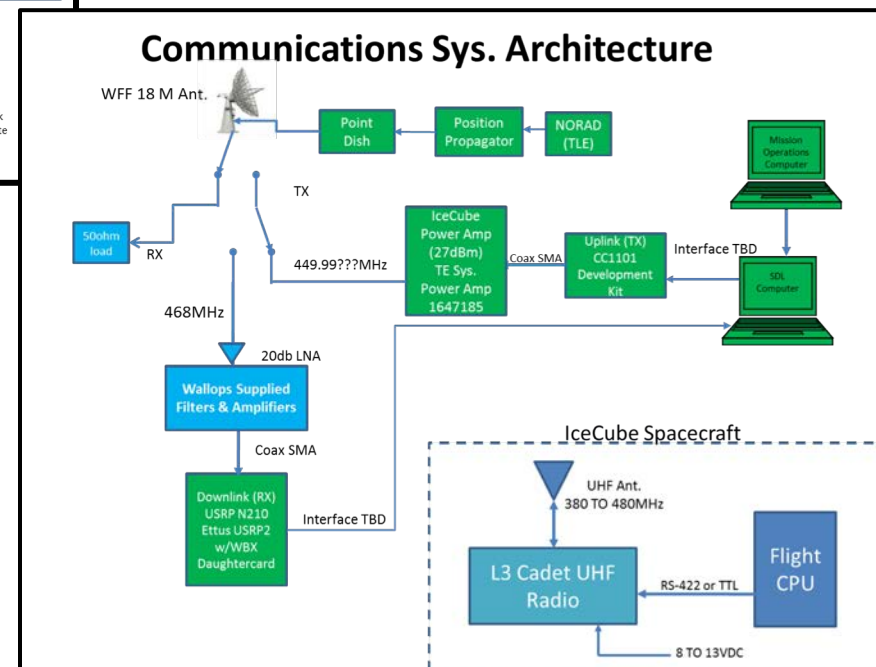Green lines show the radiometer ground track on each revolution during one orbit at 1 rev per minute

Earth observations can be made where the ground track falls within 45 degrees of nadir, where the green lines cross the purple area

Spacecraft does not see earth for these periods, but has extended views of the limb

IceCube Block Diagram

Ground Station MOC / SOC Setup

Software Defined Radio Setup
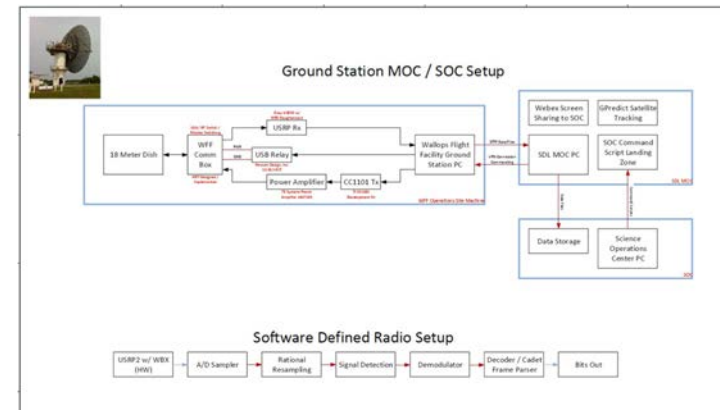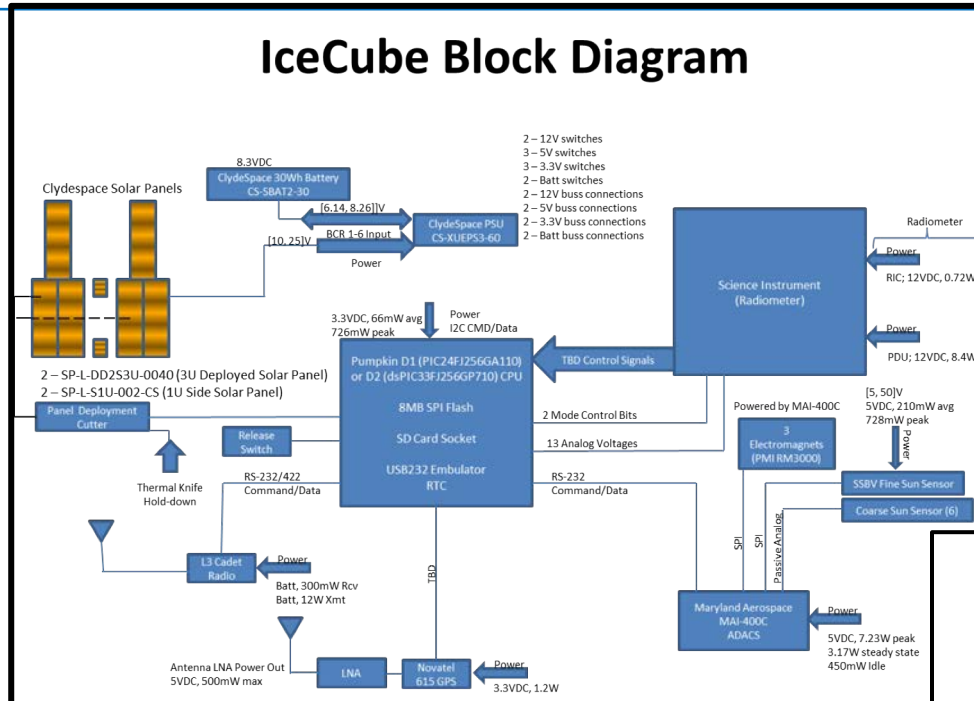
Communications Sys. Architecture

- Project would have benefitted from a Safety and Misson Assurance (SMA) Plan and a Systems Engineering Management Plan (SEMP) rolled into the Project Plan.
  - This is where tailoring would have been defined and documented
  - Needed a Clear definition of Stakeholders expectation for reliability
    - "Do No Harm" – (*launch constraint, not an SMA level)* "It has to work"

- Many Unanticipated Development Efforts were encountered over the course of the project
  - **Not requirements creep**, these are problems that need to be solved beyond the budget and schedule reserves.
  - **CubeSats require much larger reserves as a percentage than larger projects**

Examples:

- Designed a first of it's kind "Smart Beacon" to facilitate ground contact and troubleshooting
- Custom Bus Structure was needed to accomodate unique assembly, thermalm and bonding req.
- First-of-its-kind ISS compliant battery, charging, power distribution system
- EPS card and Flight computer cards were made to different CubeSat Bus Standards required clipping pins and adding jumpers
- New Star tracker capable of 3-axis attitude control,
- New ADACS software for a rotating platform,
- ADACS was incompatible with latest GPS firmware, had to have previous firmware installed
- Custom Flight Software interfaces had to be written for most components
- Errors in Flight Radio Command software found by trial and error and blocked out of flight software
- Custom Designed and spun science interface card
- Custom Designed Paraffin phase-change thermal control device first on a CubeSat
- Search and research for reliable deployment switches,
- Design and addition of Break-out Umbi connector to enable testing
- Design and implementation of Grounding Plan. (every component handled power and RF grounds differently)
- 3D printed wiring mockup so wiring could be done in parallel
- 3D printed demonstration model for HQ while in the middle of integration

3. Conduct risk-based mission assurance

- Maintained, a comprehensive list of both Action Items and Worries **from every meeting**

- Racked and tracked the top 10 risks

- Change Control Board
  - Decisions based on risk, cost, benefit considerations
  - I&T plan produced for CDR, based on LADEE plan, updated continuously
  - Leverage experience of other CubeSat missions to assess risks

- Some Long lead time Hardware has to be Purchased at-risk prior to CDR

- Testing based on mission simulations

4. Design for simplicity and robustness

- No redundant systems

   "Robustness" driven by risk mitigation

- De-Rated power system and ACS Standard using Spacecraft margins

- Able to charge batteries in random tumble without arrays deployed

- Distributed processor architecture allows numerous paths to resets after lockups

- ConOps designed to compensate for hardware limitations

- Smart Beacon

- Common Ground system shared with Ceres and Dellinger

- All data sheets checked prior to component acceptance testing
  - EPS manual found to have significant errors and sent back for revision
  - Small errors found in many other datasheets
- Acceptance testing is where you will find the errors
  - Lock up your hardware, DO NOT LOOSE CONTROL OF YOUR HARDWARE
    - You will never know if the component has a vendor error or was damaged after receipt
  - Some Radio commands had sw bugs – worked on this up to 2 days before delivery
  - ADACS received in wrong configuration, sent back for re-programming
 - ADACS found to be incompatible with newer GPS firmware, had to have firmware backdated

- MAIW Paper Recommends that I&T should be 1/3 to ½ of schedule.
  - IceCube I&T was roughly half of schedule.
  - Significant overlap Between Design and I&T – July 2015 – March 2016
  - Graceful transition of technical leadership between design and test
    - I&T manager and Payload Engineer brought onto project in July 2015
    - Systems Engineer transitioned off project in February 2016
  - No "Time Crunch Factor", Testing was not shortened to accommodate the launch
    - Project ran out of schedule and funds near the start of I&T, but found more funding rather than launch untested.
  - There is a point in I&T when changes to the hardware are too costly and risky and problems must be solved with operational changes

- Spares Limited by Budget and Procurement Process
  - GPS Antenna
  - Battery
    - Engineering Unit procured and controlled as flight spare
  - Radio
   - Spare planned, but prohibited by price increase
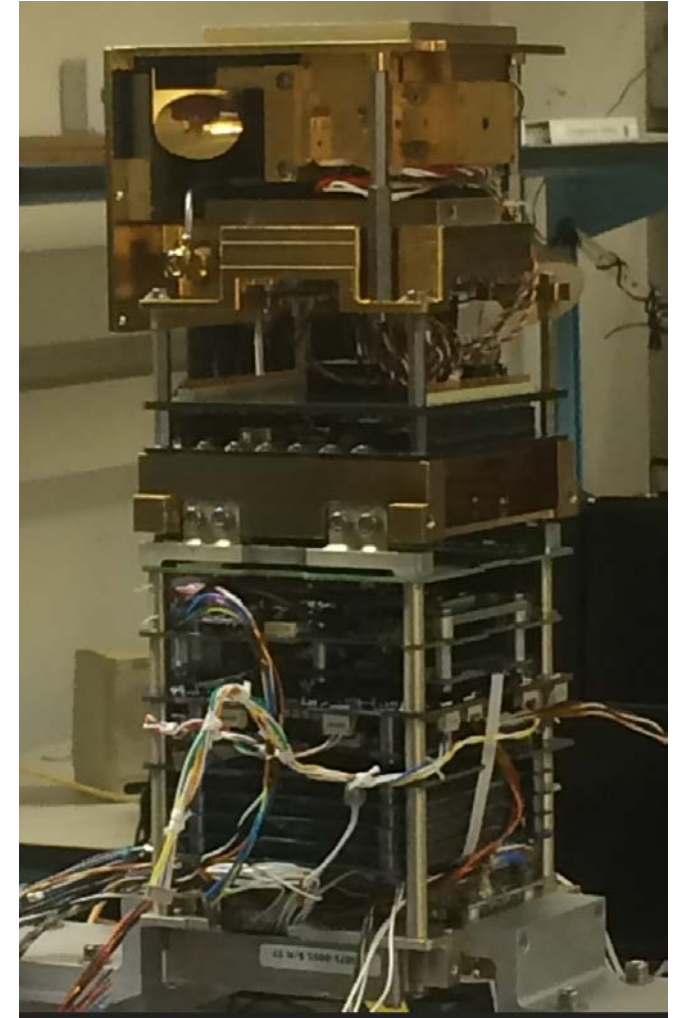
8. At a minimum, perform the four mission assurance tests

✓ 1. Day-in-the-life (or longer) testing
✓ 2. Communication link testing with the ground station
✓ 3. Power system charge/discharge testing
✓ 4. Thermal testing (in vacuum)

- Additional testing performed
  - ✓ Vibration testing
  - ✓ FlatSat component testing prior to integration
  - ✓ Deployment Switch, Antenna and Solar Array deployment testing
  - ✓ Vacuum Deployments
  - ✓ Mission simulation test with solar arrays illuminated and thermal simulators to exercise all software functionality – this test revealed a critical software error

- Testing Omitted
  - EMI/EMC test, Open air Com Test, Phase Change Device Functional (Thermal) Test
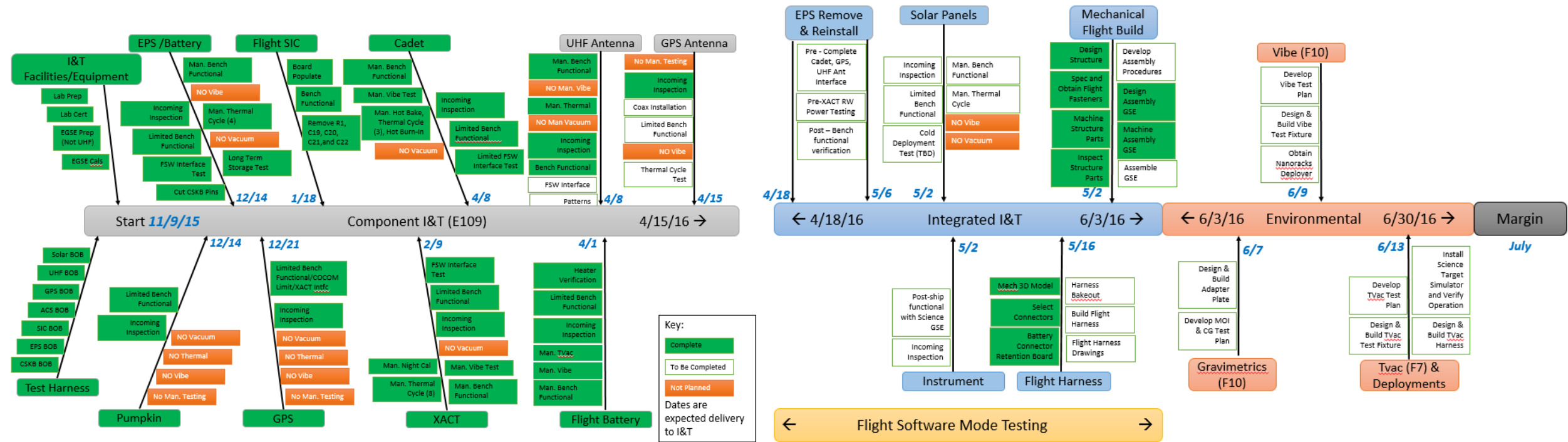
IceCube I&T Flow

Don't !!!

Skimp on Formulation

- Instead, Use Mission Planning Lab Simulations
- And Learn from other CubeSat missions

Skimp on Documentation

- Instead, Keep the content, simplify the format
- And Implement Configuration Management

Skimp on Reviews - Peer reviews don't negate Milestone

lose Control of your Baseline – this is the only way to control creep

Lose Control of your Hardware – WOA and secure it

Lose Track of your Risks and worries - You need these to make decisions

Procrastinate

- Everything needs to start earlier than you expect
- mission phases will overlap

Applying SE lessons to Planetary SmallSats

- The Systems Engineering Process seems to scale better down than up.
  - LADEE started with larger GSFC missions and scaled down to Class D+
  - IceCUBE started with the LADEE documents and scaled down

- The CubeSat industry has matured Quickly and some of the development work needed to complete IceCube would not be needed today
  - Determining the right amount of reserves is challenging
  - This is why the TRL definition effort is so important

- Planetary SmallSats are today where LEO CubeSats were ~5 years ago
  - NASA to lead in developing successful planetary SmallSat capabilities
  - The first generation of Planetary SmallSats will experience a similar level of developmental challenges as IceCube.
  - Following the 8 Recommendations from the onset of a project will improve mission success overall

➢Apply a Systems Engineering Process Beginning to End

➢Allocate sufficient schedule and budget reserves for completion

➢Early and Complete documentation is a good financial investment

➢Assign a stable dedicated multidiscipline Core team.

How can the Science Community Help?

❖Mine your housekeeping data to characterize your components for future missions

      -Battery Charge/Discharge, Solar Panel Aging, Contamination, ACS jitter

❖Allocate the final portion of your CubeSat mission to exercising the hardware and characterizing the limits of hardware capability and durability for the benefit of future missions

      -Antenna off-pointing, new ACS algorithms, Thermal model validation, exercise and characterized unused hardware modes.