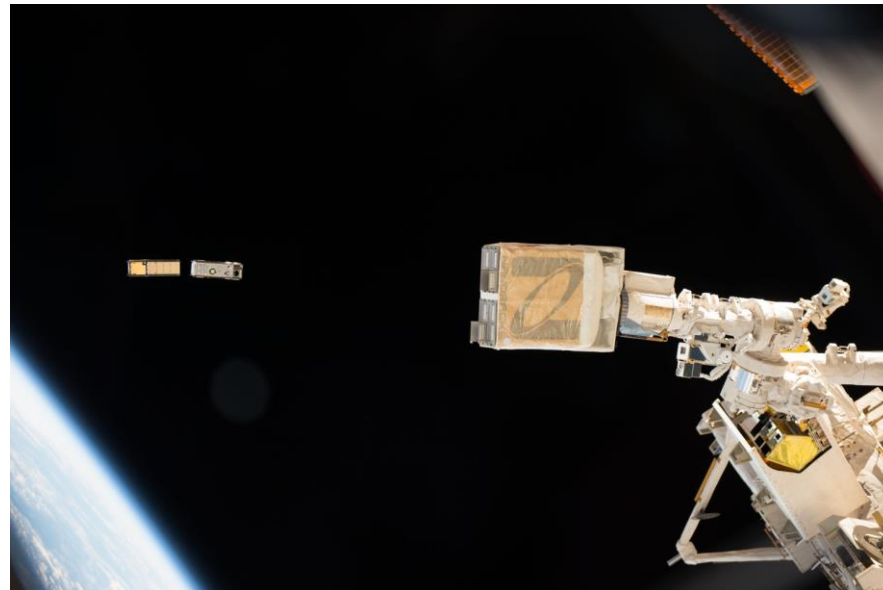# Applying Systems Engineering to CubeSat Missions

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
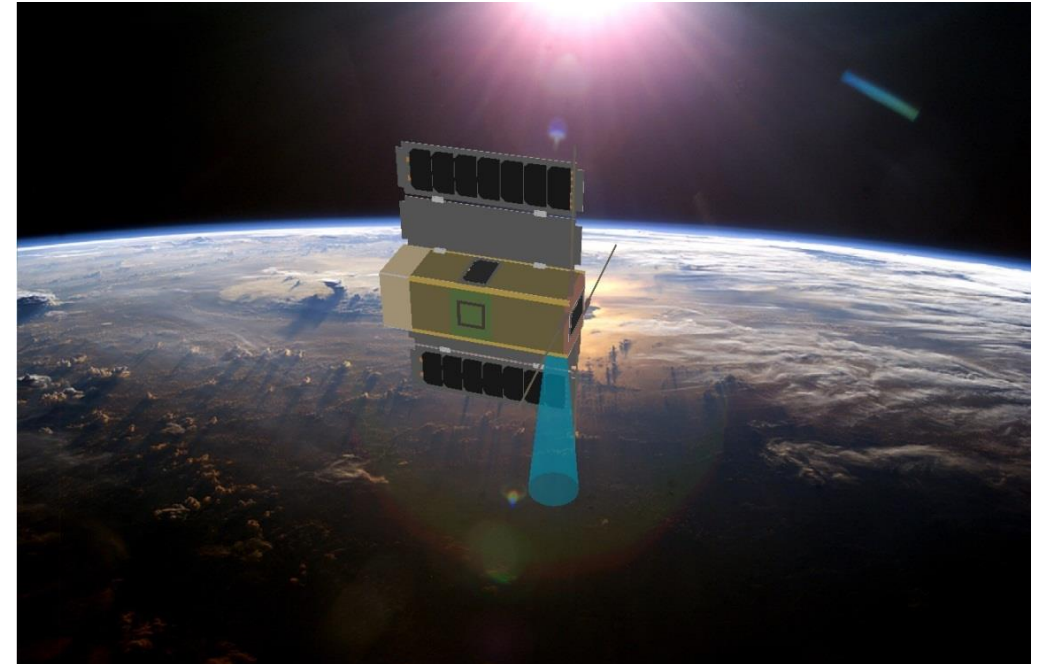
- The IceCube Mission was proposed and won by Dr. Jamie Esper (GSFC/592) and Dr. Dong Wu (GSFC/613) in 2013

- 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

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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
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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.

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- 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

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- 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

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
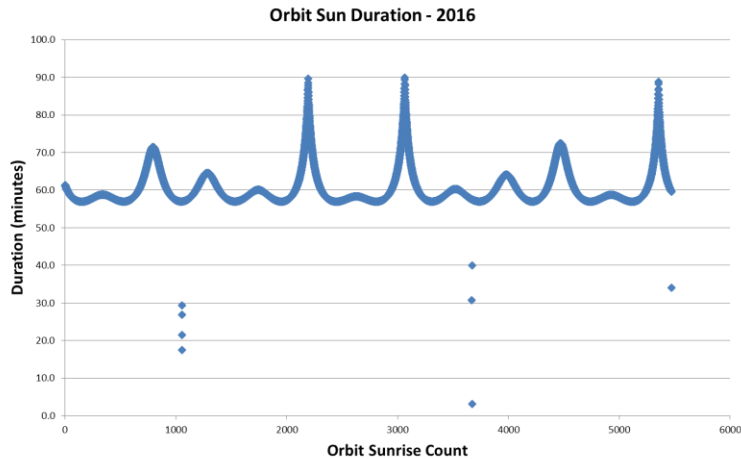
Radiometer Ground Track superimposed on area 45 degrees from Nadir (data on Equinox)
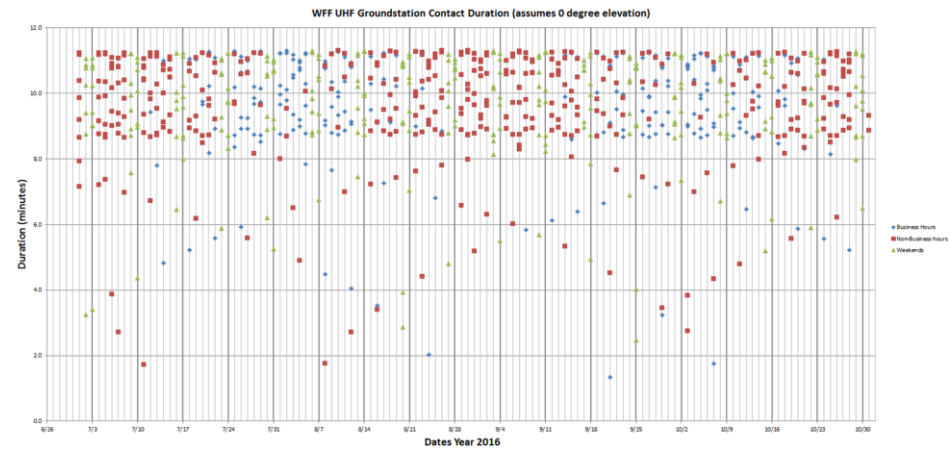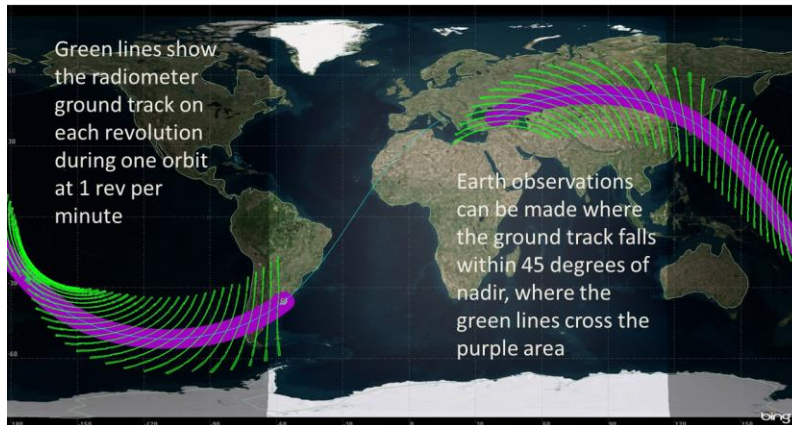
Radiometer Ground Track on Equinox

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

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IceCube Block Diagram

Ground Station MOC / SOC Setup

Software Defined Radio Setup

Communications Sys. Architecture
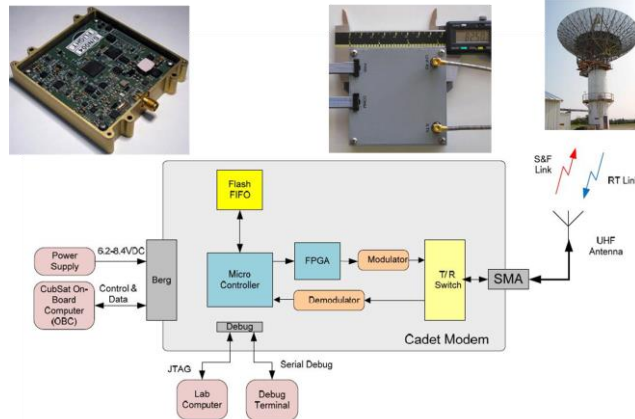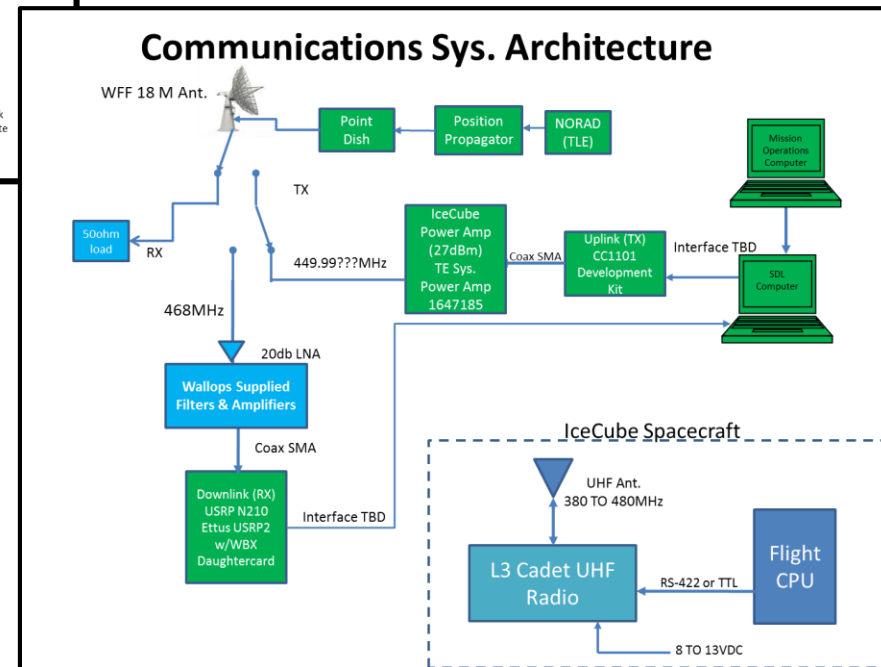
- Project would have benefitted from a Safety and Misson Assurance (SMA) Plan and a Systems Engineering Management Plan (SEMP) rolled into the Project Plan.
  - This is where tailoring would have been defined and documented
  - Needed a Clear definition of Stakeholders expectation for reliability
    - "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
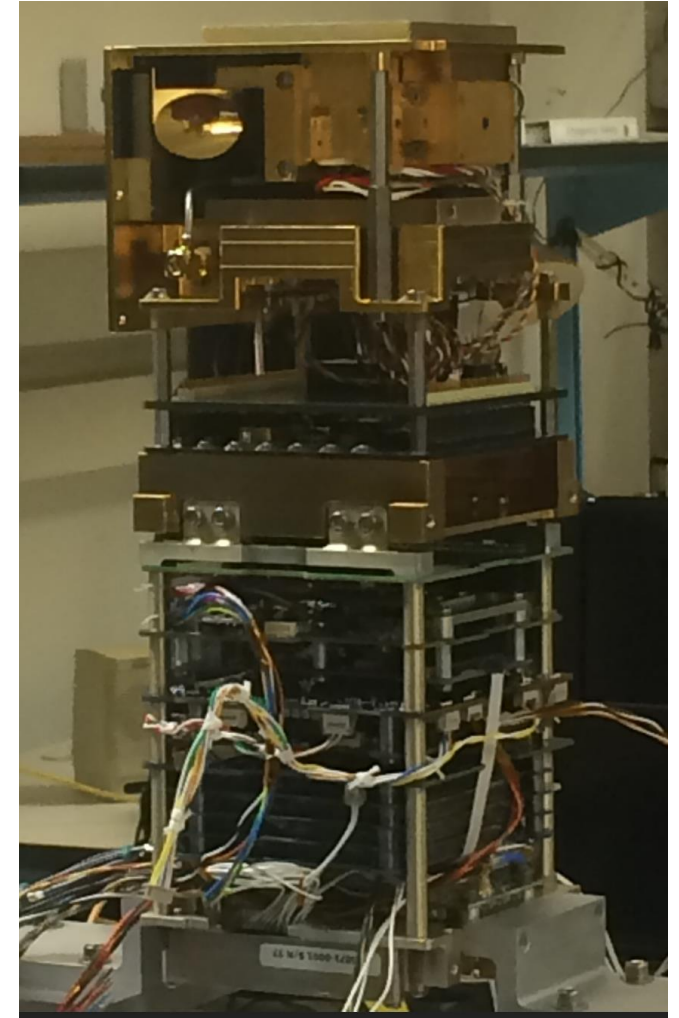
8. At a minimum, perform the four mission assurance tests

✓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
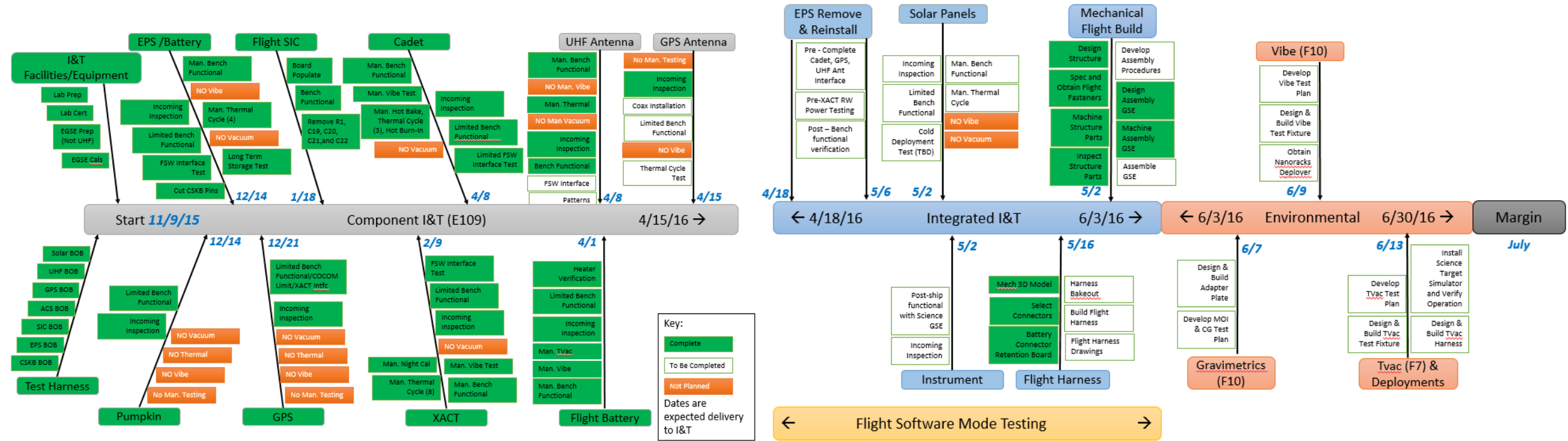
IceCube I&T Flow

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

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➢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.

- IceCube operated ~500 days, imaged Typhoon Trami Sep 29th 2018, saw ice crystals distributed in the arms.

- Credit IV&V, Cadet Working Group

- Problems Encountered by IceCube

 GPS lockup

 ACS Error Accumulation, IMU Firmware

 Too many commands blocked out to troubleshoot

 7-8 flight computer resets

No real-time commanding, had to wait for confirmation

- Issues for formulating ESPA class missions
  - Are there any lessons learned for ESPA missions?
  - Cost and schedule estimates for CubeSats are still too low, we need a better basis of estimate.
  - Need for real data on cost -- ex.Hardware vs. FTE ratio. Account for donated labor
  - I&T costs will remain the same, but a delta cost for addressing problems and learning curve will need to be added to the first generation of missions.
  - I&T will require more I&T time for the first generation of missions
  - Need a deliberate and coordinated effort to mature and characterize hardware and processes
    - SPOON database is a good start
    - "Gold Rules" for Small Satellites
    - Standard SEMP and MAR templates for Small Satelites

- # SmallSat reliability
  - ## Consider the purpose of adding Reliability
    - This is a cost/benefit trade what are you buying?
    - Longer life = more science? – may be limited by de-orbit time
    - Better Science? = bus more likely to meet specifications
    - Works vs. doesn't work? = will we hear from it at all?
    - What does launching multiple copies of a small sat buy toward reliability?
    - What do University Missions value?

  - ## How much Reliability can or should we outsource to vendors?
    - Gap testing - vendor testing for acceptance instead of repeating tests
    - Parts list, radiation screening
    - Flight heritage – vendors cannot give specifics on many customers