SmallSats and Systems Engineering

S3VI – July 15, 2020 – Pauline Faure

LEARN BY DOING CAL POLY

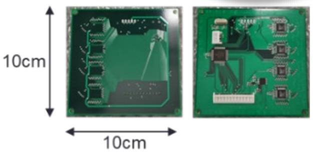
CUBESAT

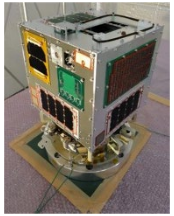
AGENDA

- Ice Breaker
- Cal Poly CubeSat Lab Mission
- Use of CubeSats
- The Problem: What, Where, What To Do About It?
- Systems Engineering Toolbox
- Other Tips
- Summary
- Going Further

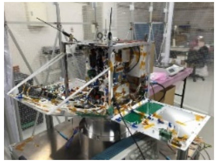
ICE BREAKER – WHO AM I?

2010 – 2018
Kyushu Institute of Technology, Japan





HORYU-II – Payload development



HORYU-IV – Project manager

Capacity building lead

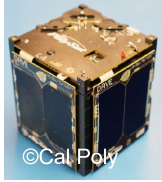
September 2018 -
Cal Poly SLO, U.S.

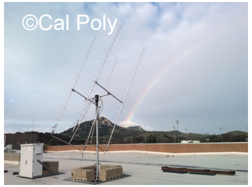
Teaching – Spacecraft Design Course; Systems Engineering; Aerospace beyond Engineering

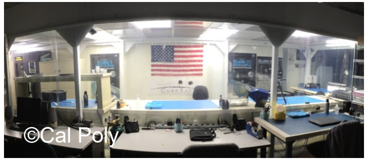
Research Activities – CubeSat Kit; Deep space communications; Spacecraft design

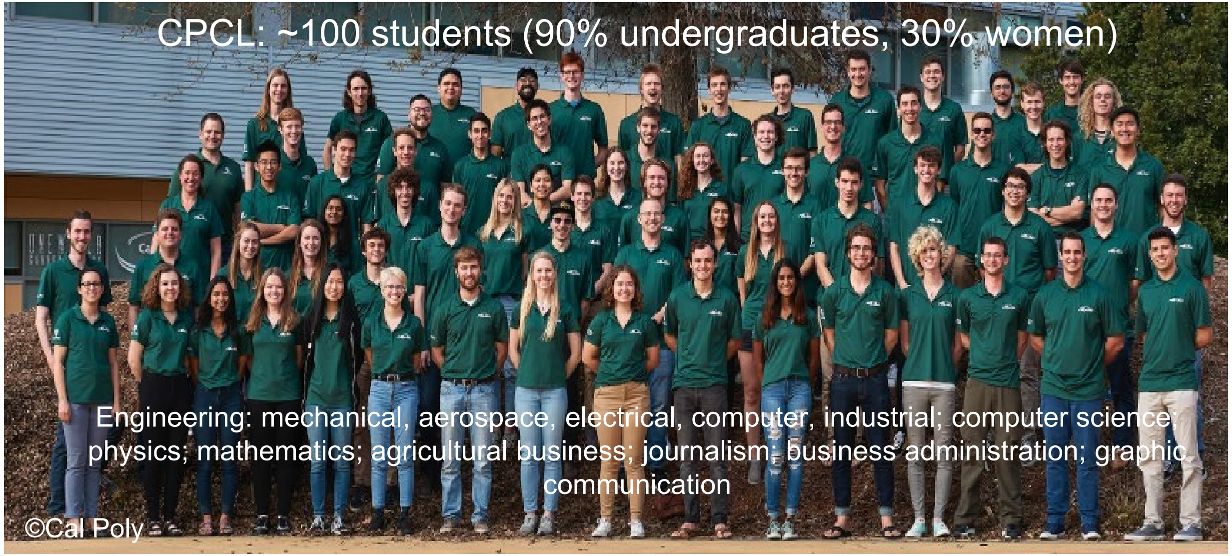
CAL POLY CUBESAT LABORATORY MISSION

- Mission statement is to: *“advance the space industry by providing inclusive, high-quality workforce development and community engagement programs that enable the next generation of space discoveries”*





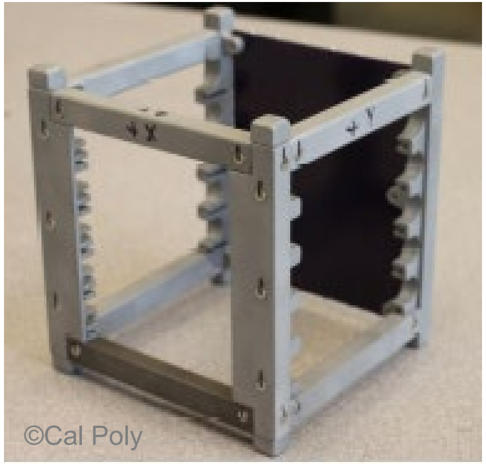




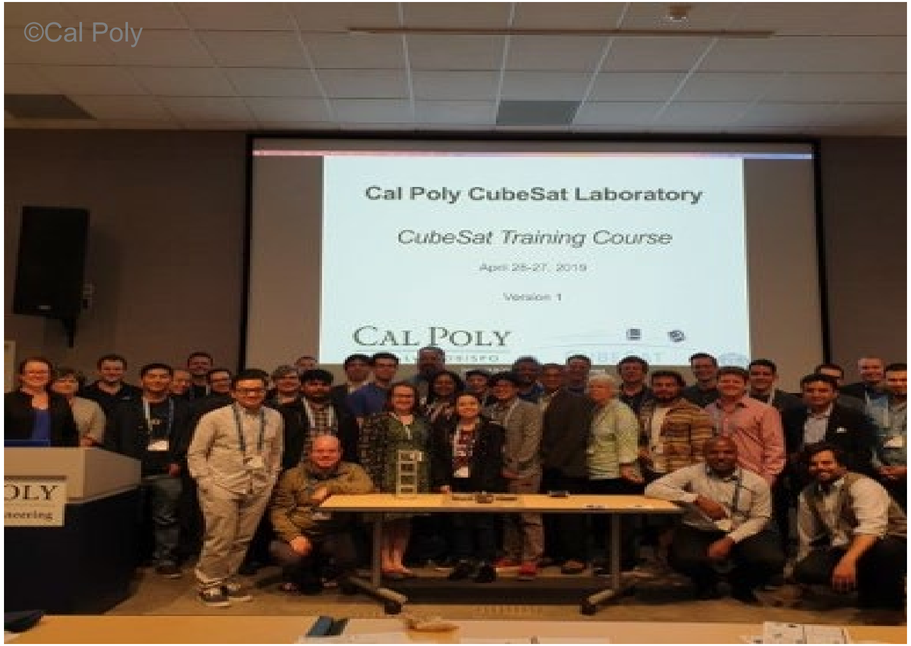
CAL POLY CUBESAT LABORATORY MISSION

- Main mission of the lab: **educate**
- CubeSats (SmallSats) as a tool for hands-on education
  - CubeSat Kit under development
  - Training Course

Additively manufactured CubeSat Kit structure

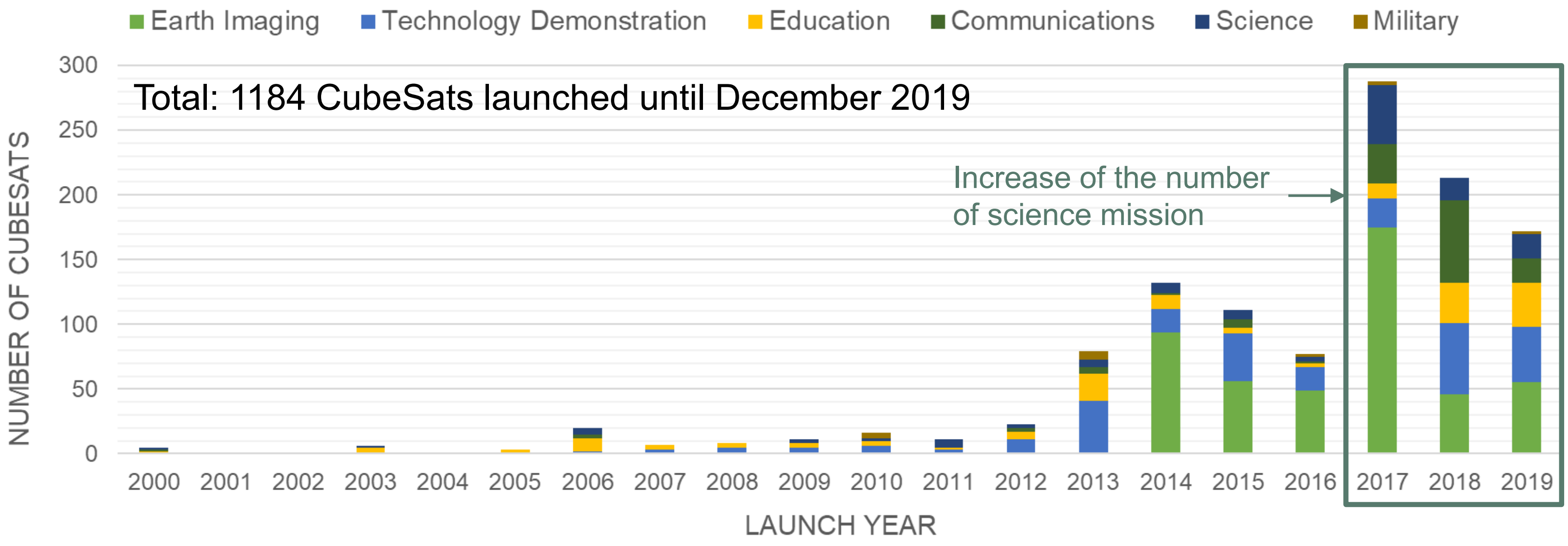


1st Cal Poly CubeSat Training Course



WHAT ARE CUBESATS USED FOR?

- CubeSats (SmallSats) as a tool for advancing engineering, science, and exploration



Adapted from M. Swartwout's CubeSat Database: https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database

WHAT IS THE PROBLEM?

- Mission assurance

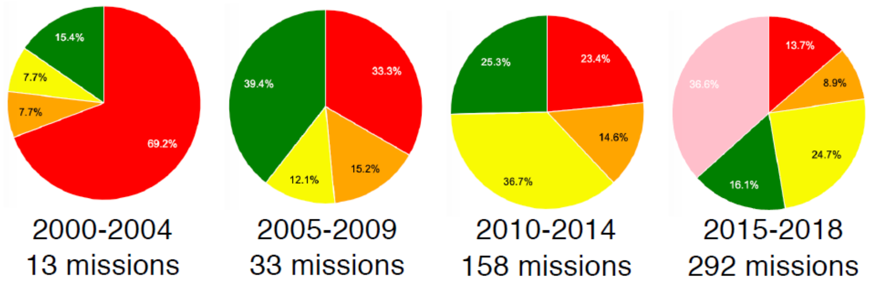
- Overall, CubeSats are getting better are achieving their mission

- First time developers still have a hard time achieving this

  Swartwout: *“It’s hard to improve when you do it only once”*

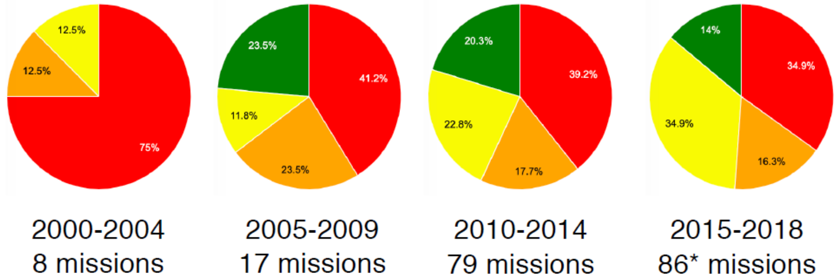
DOA
Early Loss
Partial Mission
Full Mission
Unknown

All CubeSats Class (w/o constellation)



Hobbyist*-class CubeSats

**Universities, secondary schools and others for whom this is an exciting opportunity to learn. Hobbyists are characterized by having low resources, a strong willingness to try risky approaches and -this should come as a surprise to no one - high failure rates.*

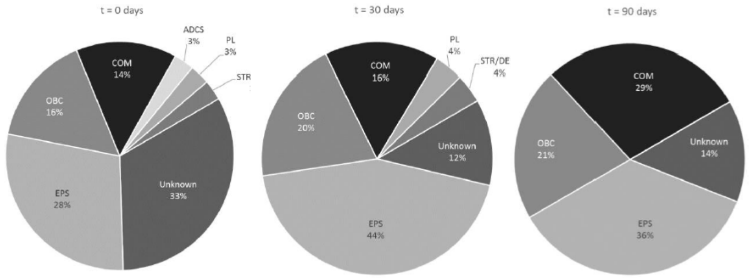


Source: M. Swartwout, CubeSat Mission Success: Are We Getting Better?, Proceedings of the 2019 CubeSat Developers’ Workshop

WHERE IS the PROBLEM?

- In many places: Satellites are multi-disciplinary systems
  - Subsystem
  - Integration
  - Testing
  - Processes

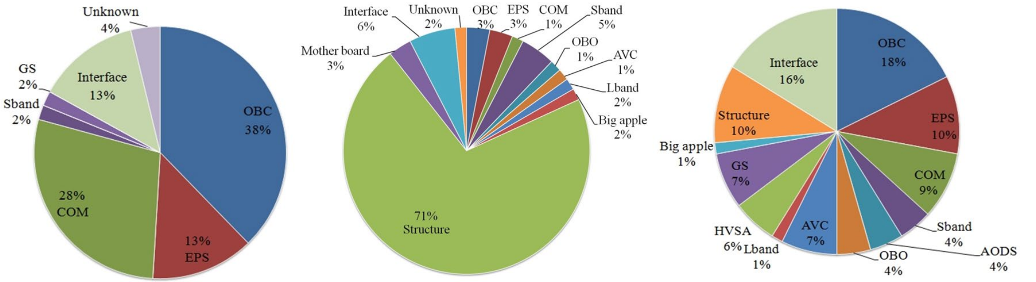
Subsystem contributions to CubeSat failure after ejection (incl. DOA)



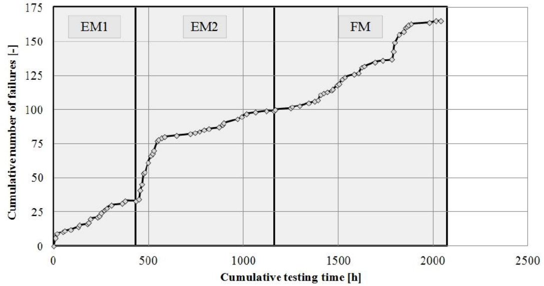
Source: M. Langer and J. Bouwmeester, [Reliability of CubeSats – Statistical Data, Developers' Beliefs and the Way Forward](), Proc. of 30th Annual AIAA/USU Conference on Small Satellites

Subsystem contributions to CubeSat failure during development

Engineering Model 1 (EM1) | Engineering Model 2 (EM2) | Flight Model (FM)



Observed number of failure vs. testing time



P. Faure, A. Tanaka, and M. Cho, *Toward lean satellites reliability improvement using HORYU-IV project as case study*, Acta Astronautica (2017), DOI: 10.1016/j.actaastro.2016.12.030

WHERE IS the PROBLEM?

- Other challenges, sociotechnical systems – How people and organizations behave and act in the context of a project

- E. Honoré-Livermore, *CubeSats in University: Using Systems Engineering Tools to Improve Reviews and Knowledge Management*, Procedia Computer Science 153 (2019), pp.63-70

  Issues on conducting engineering projects at universities:

  - Ever-changing teams and short time for on-boarding new members – Knowledge transfer
  - Balancing coursework and satellite building – Variety of duties
  - Ensuring momentum – Scattered team; Feeling of ownership
  - Ensuring mission success – Formality of design reviews; Documentation; Timeliness

WHAT CAN WE DO ABOUT IT?

- A lot… *(Non-exhaustive list)*

Before delivery/launch

- Structure the project – Design review; schedule; hierarchy; scope; success criteria
- Test, test, test – Include margins, verifications always take longer than what we think
- Documentation – What has been done? How? Why?
- Building the team – Experienced developers; renewal of departing members
- Trust, but verify – Performance margins; inspection upon parts reception

After launch/deployment

Failing, fully or partially, can be acceptable. At least, we should strive to understand the failures, record them, share them, and make sure they are not repeated (craziness prevention)

- Root cause analysis – Fishbone; failure tree analysis; five whys

WHAT CAN WE DO ABOUT IT?

<u>Before delivery/launch</u>

- Structure the project – Design review; schedule; hierarchy; scope; success criteria
- Test, test, test – Include margins, verifications always take longer than what we think
- Documentation – What has been done? How? Why?
- Building the team – Experienced developers; renewal of departing members
- Trust, but verify – Performance margins; inspection upon parts reception

Today's focus

Let's see what tools from the systems engineering toolbox we can use to address some of those aspects

GENERAL WARNINGS

- There are many tools in the systems engineering toolbox
  - The intent is to introduce you to the tools I found to be the most useful
  - Please **explore and customize** as you see fit for your project, organization, and intents
- Learn to **become comfortable with uncertainty and not achieving perfection**
  - Design is an iterative process. Even after product delivery, it could be improved. The secret is to be good enough, i.e., the product achieves and behaves as the stakeholders need
  - We do what we do because we don't know about X, Y, or Z
- Similarly **systems engineering is iterative**
  - Develop the framework once, improve contents regularly as more is learned on the project
  - At first, tools development might appear daunting. Ultimately those tools aid develop good practices, which will benefit the institution, its people, and the community in the long-term

GENERAL FLOW

STEP 1 – Define stakeholders and their needs

STEP 2 – Develop requirements, work breakdown structure, schedule, interface definition, concept of operations, statement of work, budget, and risks assessment for system level n

STEP 3 – Repeat STEP 2 for system level n+1

- 5W2H: who, what, why, where, when, how, how much/long
  - Who – Stakeholders definition
  - What – Requirements; work breakdown structure
  - Why – Stakeholders' needs definition; risks assessment
  - Where – Interface definition; work breakdown structure; statement of work*
  - When – Schedule
  - How – Concept of operations*; interface definition
  - How long – Schedule
  - How much – Budget*

*Out of today's scope

STEP 1 – Stakeholders and Needs Definition

- **Stakeholders:** Any people (entities) that can affect the development of the satellite
  - University, students, faculty
  - Company board of directors, project manager, engineering team
  - End users – Could be the same as internal stakeholders
  - Regulators – FCC, NOAA, range safety, etc.

Internal stakeholders

Customers

External stakeholders

- **Needs:** As diverse as the stakeholders, but not all are of equal importance
  - Educate students, gain skills, contribute to research community
  - Generate profit, ensure mission success within resources, innovate
  - Obtain information
  - Ensure compliance with national and international policies

STEP 1 – Stakeholders and Needs Definition

Why is it important?

- Understanding stakeholders' needs establish basis for defining requirements
- Without a common understanding of what the needs are, the right system cannot be built, the system cannot be built right

Implications

- Define scope of the project and success criteria
- Help manage expectations and guide design decisions

Examples

- Publications and research/work dissemination to the community
- Continuous improvement of the development processes

STEPS 2,3 – Requirements

Platinum rules of a good requirement

- You shall use ‘shall’ statement
- One thought per requirement
- Only define what, not how
- Subjective language you shall ban (small, large, reliable, fast, etc.)
- Each requirement is traceable – Parent/Child
- Each requirement is verifiable – Analysis, demonstration, test, or inspection

! Requirements drive design decisions. Design decisions shall not drive requirements

STEPS 2,3 – Requirements

Suggested syntax for requirements

“The system shall do X (function) within Y (performance)

- Function - What the “system” does
- Performance - How well the “system” executes the function

STEPS 2,3 – Requirements

Requirements organization – Requirement allocation sheet, requirement breakdown structure

ID	Requirement	Verification	Rationale
1.	The project shall gather daily photographs of the earth	Analysis and test	Derived from stakeholder need
1.1	The spacecraft shall be capable of transmitting at least one image per day on orbit	Analysis and test	Minimum success criteria is to obtain one image per day to satisfy project requirement
1.1.1	The COM system shall transmit image data at a minimum of TBD bps	Test	Pending link budget calculations, the COM system needs to achieve a certain data rate to enable the transmission of one image per day

STEPS 2,3 – Requirements

Why is it important?

- Define what the satellite project does
- Ensure the right system is built, i.e., the built system corresponds to stakeholders' needs

Verification Rationale

Implications

- Manage scope of the project
- Help manage expectations and guide design decisions

Examples

- 3-axis control system
- Adding missions

STEPS 2,3 – Work Breakdown Structure

- Decomposes the project into product and tasks
  - **Products –** Anything that can be built (e.g., structure), created (e.g., software), or bought (e.g., solar cells)
  - **Tasks –** The work that need to be executed throughout the project (e.g., manage requirements; perform vibration test; carry out the integration of the payload with the satellite bus)
- Do you need to decompose the project to nuts and bolts? Possibly…

STEPS 2,3 – Work Breakdown Structure

- Example of work breakdown structure

  1. Project Vega → Random name I chose for the project. Level 1 of WBS

     1.1. Spacecraft Vega-1

     1.2. Ground segment

     1.3. System engineering

     } Level 2 of decomposition

STEPS 2,3 – Work Breakdown Structure

- Example of work breakdown structure

1. Project Vega
    1.1. Spacecraft Vega-1
        1.1.1. Payload
        1.1.2. Electrical power system
        1.1.3. Communications system
    1.2. Ground segment
    1.3. System engineering

Level 3 of decomposition for the 'spacecraft Vega-1' element

STEPS 2,3 – Work Breakdown Structure

- Example of work breakdown structure

  1. Project Vega

     1.1. Spacecraft Vega-1

        1.1.1. Payload

        1.1.2. Electrical power system

        1.1.3. Communications system

           1.1.3.1. Antenna

           1.1.3.2. Transmitter

           1.1.3.3. Receiver

     1.2. Ground segment

     1.3. System engineering

Level 4 of decomposition for the ‘communications system’ element (1.1.3.1–1.1.3.3)

STEPS 2,3 – Work Breakdown Structure

- Example of work breakdown structure

  1. Project Vega

     1.1. Spacecraft Vega-1

       1.1.1. Payload

       1.1.2. Electrical power system

       1.1.3. Communications system

         1.1.3.1. Antenna

Level 5 of decomposition for the ‘antenna’ element:

1.1.3.1.1. Design in-house the antenna

1.1.3.1.2. Trade antenna types (dipole vs. patch vs. helical)

→ Lowest level of decomposition reached for this project = **Work package**

STEPS 2,3 – Work Breakdown Structure

- Example of work breakdown structure

    1. Project Vega

        1.1. Spacecraft Vega-1

            1.1.1. Payload

            1.1.2. Electrical power system

            1.1.3. Communications system

                1.1.3.1. Antenna

                1.1.3.2. Transmitter

Level 5 of decomposition for the ‘transmitter’ element:

1.1.3.2.1. Investigate commercially available UHF system

1.1.3.2.2. Trade commercially available UHF system

STEPS 2,3 – Work Breakdown Structure

Why is it important?

- Define what the system is made of and what needs to be done
- Enable to verify whether requirements are missing (and vice versa)

Implications

- Establish foundation for schedule
- Establish basis for resources management

Examples

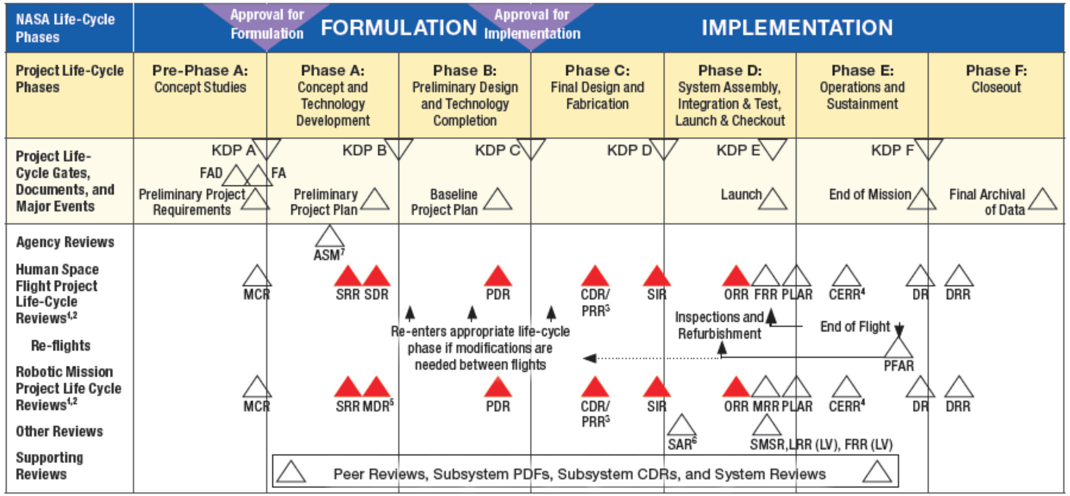
- Number of team member
- Facilities management
- Procurement

STEPS 2,3 – Schedule

What is needed to define the schedule?

- Overall understanding of project life cycle
- Project milestones definition
- Work breakdown structure
- Evaluation of each work package duration
- Understanding of interdependency between work packages

NASA Space Flight Project Life Cycle



FOOTNOTES

1. Flexibility is allowed as to the timing, number, and content of reviews as long as the equivalent information is provided at each KDP and the approach is fully documented in the Project Plan.
2. Life-cycle review objectives and expected maturity states for these reviews and the attendant KDPs are contained in Table 2-5 and Appendix D Table D-3 of this handbook
3. PRR is needed only when there are multiple copies of systems. It does not require an SRB. Timing is notional.
4. CERRs are established at the discretion of program .
5. For robotic missions, the SRR and the MDR may be combined.
6. SAR generally applies to human space flight.
7. Timing of the ASM is determined by the MDAA. It may take place at any time during Phase A.

▲ Red triangles represent life-cycle reviews that require SRBs. The Decision Authority, Administrator, MDAA, or Center Director may request the SRB to conduct other reviews.

ACRONYMS

ASM – Acquisition Strategy Meeting
CDR – Critical Design Review
CERR – Critical Events Readiness Review
DR – Decommissioning Review
DRR – Disposal Readiness Review
FA – Formulation Agreement
FAD – Formulation Authorization Document
FRR – Flight Readiness Review
KDP – Key Decision Point
LRR – Launch Readiness Review
LV – Launch Vehicle
MCR – Mission Concept Review
MDR – Mission Definition Review
MRR – Mission Readiness Review
ORR – Operational Readiness Review
PDR – Preliminary Design Review
PFAR – Post-Flight Assessment Review
PLAR – Post-Launch Assessment Review
PRR – Production Readiness Review
SAR – System Acceptance Review
SDR – System Definition Review
SIR – System Integration Review
SMSR – Safety and Mission Success Review
SRB – Standing Review Board
SRR – System Requirements Review

Source: NASA, Systems Engineering Handbook, NASA SP-2016-6105 Rev2

STEPS 2,3 – Schedule

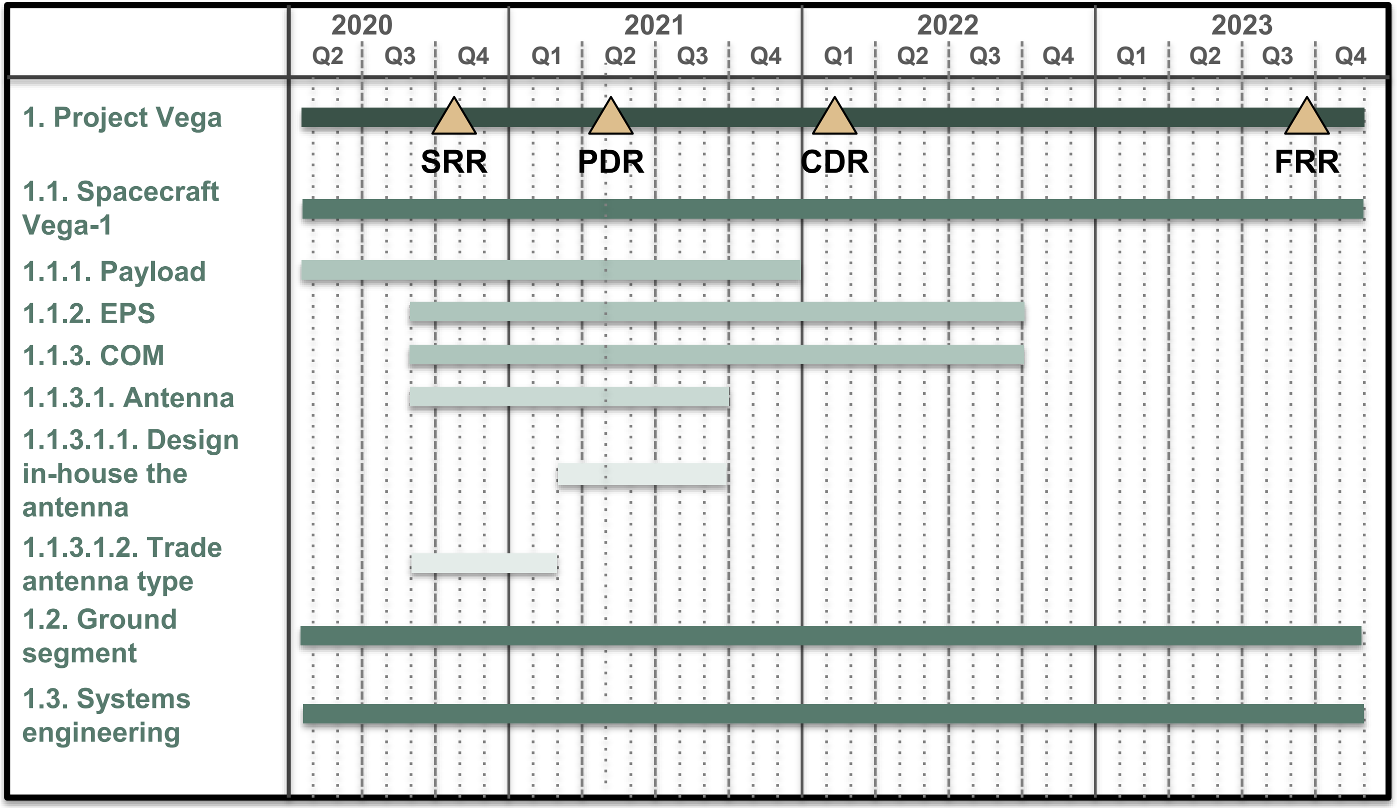
How to do it?

- Start from the end and work backwards
  - For satellite to be delivered by December 2020, when should I complete vibration test?
  - To complete vibration test by end of November 2020? When should I finish assembling the spacecraft? Etc.
- Add buffer
  - Nothing ever goes as planned, include margin
  - We tend to be optimistic and underestimate testing time (or overestimate our wonderfulness)

    E.g. assembly, integration and test can take as much as half the overall schedule (C. Venturini, *Improving Mission Success of CubeSats*, The Aerospace Corporation, Aerospace Report No. TOR-2017-01689)

STEPS 2,3 – Schedule

- Example



STEPS 2,3 – Schedule

Why is it important?

- Keep track of the project
- Visual reminder of team members’ accountability
- Demonstrate the importance of each team member work within the whole project context

Implications

- Decrease schedule slip
- Discuss earlier schedule modifications

Examples

- Whole team can take ownership and responsibility of the project timeline
- Maintain team morale (though sometimes it also has the reverse effect)

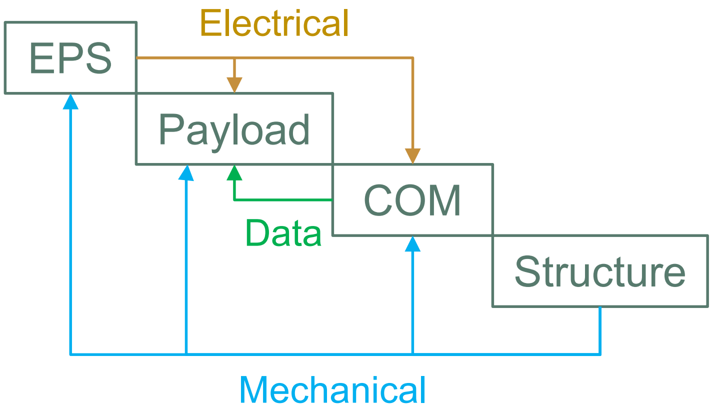
STEPS 2,3 – Interface Definition

- Interface identification between elements within a considered level
- Definition of the type of interface
    - Electrical
    - Mechanical
    - Data
    - RF
    - Other

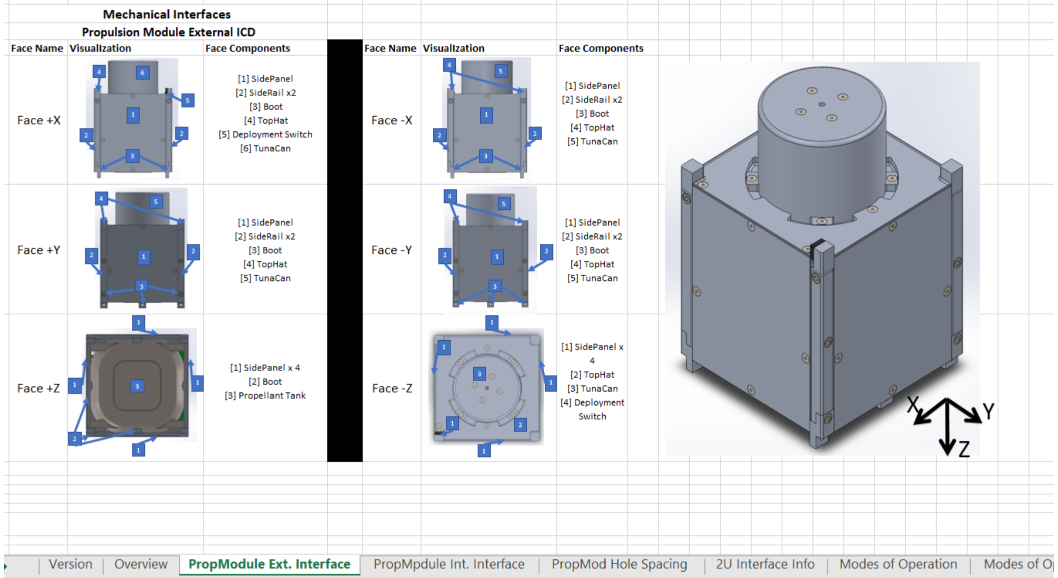
STEPS 2,3 – Interface Definition

- Examples

N2 - Level 3



Interface Control Document



Source: James Harper, *Pocket Rocket: A 1U+ Propulsion System Design to Enhance CubeSat Capabilities*, Master Thesis, Cal Poly SLO, June 2020

STEPS 2,3 – Interface Definition

Why is it important?

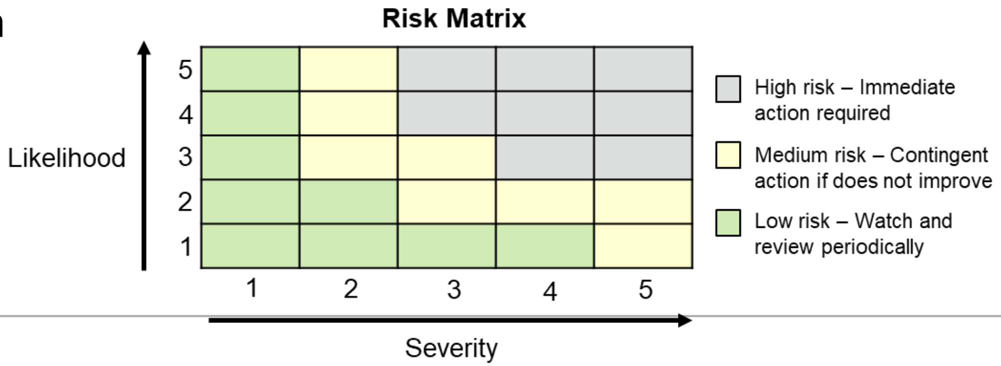
- Understanding of impact the various spacecraft elements have on one another
- Keep track of needs from multiple discipline
- Safety

Implications

- Foster collaborative work
- Help improve requirements
- Prevent misunderstandings

STEPS 2,3 – Risks Assessment

- **Risk –** An event that negatively impact the system
    - Safety
    - Programmatic
    - Performance
- Risks cannot be avoided
    - Sometimes, even if a risk has been identified, there is no possibility to mitigate or eliminate it and the risk needs to be accepted
- Risk categorization



STEPS 2,3 – Risks Assessment

Why is it important?

- Anticipate possible issues
- Improve design

Implications

- Identify single point of failure
- Assist debugging throughout development or during on-orbit operations

Examples

- Uncontrolled reset
- Sensor incorrect calibration

OTHER TIPS

- Design reviews formality: define review objective, entrance criteria, success criteria
- Decision making
  - Cut the ‘I can’t do that because X shall first be done’
  - Make sure you have a common place for assumptions and variables
- Tie students research to satellite project development
  - ! But shall not depend on satellite successful deployment or successful operations
- File sharing, editing, naming
- Organization chart: to whom do I answer to and who answers to me?
- Testing strategy
- And more…

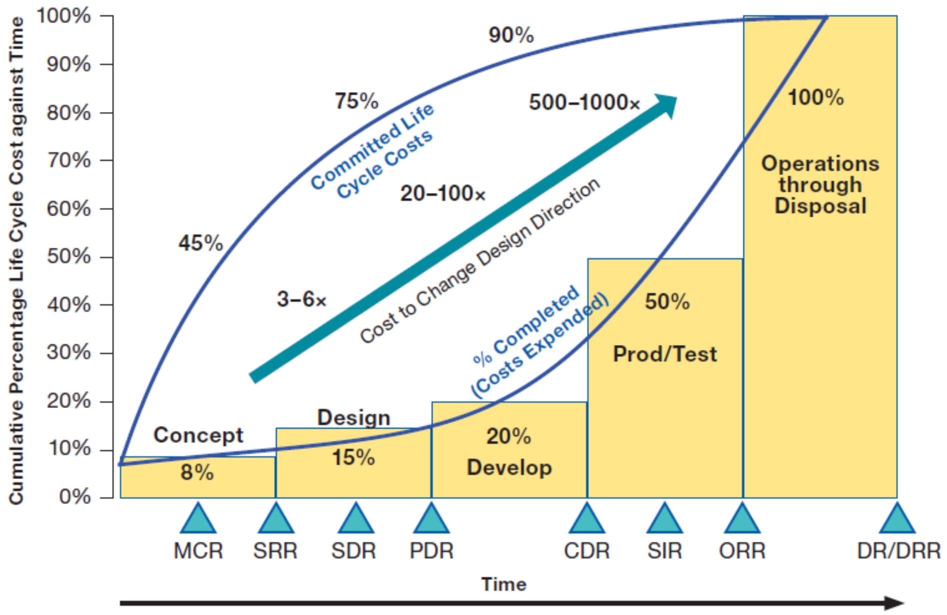
SUMMARY

- Applying systems engineering doesn’t have to be daunting
- As any toolbox, you can decide which tools matter the most to you, when and how to use them
- My recommended tools
  - Stakeholders and their needs definition
  - Requirements
  - Work breakdown structure
  - Schedule
  - Interface definition
  - Risks assessment

SUMMARY

- Improve knowledge transfer
- Enhance satellite design
  - Observe, think, act
  - Each tool describes the system from a different perspective
- It’s a fun, lively, iterative process

Life-cycle Cost Impacts from Early Phase Decision-Making



MCR	Mission Concept Review	CDR	Critical Design Review
SRR	System Requirements Review	SIR	System Integration Review
SDR	System Definition Review	ORR	Operational Readiness Review
PDR	Preliminary Design Review	DR/DRR	Decommissioning/Disposal Readiness Review

Source: NASA, *Systems Engineering Handbook*, NASA SP-2016-6105 Rev2

GOING FURTHER

- CubeSat 101: here
- NASA Systems Engineering Handbook: here
- NASA Work Breakdown Structure: here
- International Council on Systems Engineering (INCOSE): here
- NASA Space Systems Engineering: here
- Swartwout's CubeSat Database: here
- C. Venturini on Improving Mission Success of CubeSats: here
- Me, CubeSat Lab, the community, don't hesitate to reach out!

Contact Information

Pauline Faure

Aerospace Engineering Department

Cal Poly CubeSat Laboratory

805-756-6043

pfaure@calpoly.edu

Cubesat.org; Polysat.org