Designing for the form-factor: Key Considerations from both CubeSat and SmallSat perspectives

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Abstract

The CubeSat platform was initially created by Jordi Puig-Suari and Robert Twiggs as an educational tool to provide a full end-to-end mission design and space-flight experience to university students pursuing two to four year undergraduate and graduate level studies. Since the CubeSat’s invention and subsequent release of the CubeSat Design Specification it has been widely and successfully adopted by academia, government, and private industry. New developments like small launch vehicles have expanded CubeSat designs, hardware, and practices into larger SmallSat form-factors. These new form-factors can come with higher mission assurance requirements, longer design lifetimes, and different environments (i.e. GEO vs LEO). This presentation will focus on CubeSat principles followed by some key considerations when expanding these principles into larger SmallSat platforms.
Outline

• RF CMOS Overview
• CubeSat Overview
• CubeSat Standard
• CubeSat Canisters and Dispensers
• CubeSats – A Disruptive Innovation
• Trends – SmallSat Conference
• Trends – Recent CubeSat Developments
• Trends – University CubeSat Success Rate
• CubeSat Examples
• RF CMOS and CubeSats

• CubeSats and SmallSats
• SmallSat Overview
• SmallSat "Standards"
• SmallSat Launches and Rideshares
• SmallSat Example
• RF CMOS and SmallSats
• Summary
• References
CubeSat Overview

- Mass: 1 kg to <25 kg*
- Cost: $100Ks to <$25M*
- Typically shorter development cycle
- Higher Risk, Less Redundancy
- Applications
  - Targeted Mission Objectives
  - Lower cost constellation missions
  - Technology Demonstrations
  - Education and Workforce Development

- CubeSat Subsystems
  - Flight Computer
  - Communications
  - Guidance, Navigation, and Control
  - Power
  - Propulsion
  - Structures
  - Thermal

*Highly mission and organization dependent

Credit: Montana State University
CubeSat Standard

CubeSat Design on a Bar Napkin

- **1U CubeSat (1 x 1 Unit Cell)**
  - $10 \text{ cm} \times 10 \text{ cm} \times 10 \text{ cm} / \sim 1 \text{ kg}$
- **3U CubeSat (3 x 1 Unit Cells)**
  - $10 \text{ cm} \times 10 \text{ cm} \times 30 \text{ cm} / \sim 4 \text{ kg}$
- **6U CubeSat (3 x 2 Unit Cells)**
  - $10 \text{ cm} \times 20 \text{ cm} \times 30 \text{ cm} / \sim 12 \text{ kg}$
- **12U CubeSat (4 x 3 Unit Cells)**
  - $20 \text{ cm} \times 20 \text{ cm} \times 30 \text{ cm} / \sim 24 \text{ kg}$

**Power Rules-of-Thumb**

- Assuming an $\sim 27 \text{ cm}^2$ cell...
  - $\sim 1 \text{ W}$ per cell
  - $\sim 2$ cells per 1U face (no deployables)

- Assuming an 18650 Li-ion battery...
  - $\sim 2 – 4 \text{ A-hrs}$ per Li-ion Battery
  - $\sim 4$ Li-ion Batteries per 0.2U
CubeSat Canisters and Dispensers

- Do no harm.
- Enclosed container, lowers risk to the primary payload
- Satellites are powered off during flight, lowering risk to the launch and primary.
CubeSats – A Disruptive Innovation

• New Space
• New Science
• Underserved Community
  – Universities, State Schools, High Schools, Underserved Science and other Government Communities
• Lowers the barrier of entry for maturing new space technologies.
  – Opens the door for newer and innovative solutions
  – Allows for a more Rapid Prototyping or Agile approach to space technology development.
CubeSats – A Disruptive Innovation

- CubeSats as a “Disruptive Innovation” [7]
  - Shifts economics and influences policy
  - Significantly cheaper than the status quo.
  - Targets underserved or new application/user
  - e.g. Laptops, Smartphones, and Broadband internet

- High priority science, a mix of new and supplementary [7]
  - Not a replacement for large satellite platforms
  - Key Technology Limiters: Payload/Sensor Miniaturization, Comm, and Propulsion

- >41 Science peer-reviewed publications [7]
  - Highest number in Heliophysics (Space Weather) research
  - Space Weather researchers were early adopters

- Technology Needs
  - More integrated electronics, High Data Rate Comm links, large compaction ratio deployables, other antennas, and Payloads

Theory of Disruptive Innovation

- Starts at lower performance but low cost enables rapid innovation and evolution to higher performance [8]
Trends – SmallSat Conference

- **First Arrow (2003):** Indicates when mostly university-based CubeSat teams began participating [7]
- **Second Arrow (2013):** Indicates the inception of CubeSat commercial players, NASA and other federal agency attendance also increased [6]
- **Third Arrow (2016):** LEO constellations receive high levels of funding (e.g. OneWeb, SpaceX’s Starlink, Amazon’s Kuiper Project)
• Missions launched have increased overall, total of 1011 CubeSat’s have flown from 2000 to 2018
• Launch failures have decreased overall, from 12% (2014) to 9.5% (2018).
• Launch Failure Risk Mitigation: Build a Spare
Trends – CubeSat On-Orbit Success Rates

- Biggest Risk to developers: “Not trading scope against schedule and cost.”
- On-Orbit Risk Mitigation: Build a Spare
CubeSat Examples:
Montana State University – Space Science and Engineering Lab

The Space Science and Engineering Laboratory (SSEL) at Montana State University is an interdisciplinary center for space research, space technologies and collegiate-level experiential hands-on training in spaceflight systems.

“Today’s students, tomorrows engineers and scientists.”

CubeSat Program:
10 CubeSat’s delivered for launch
6 CubeSat’s on-orbit
And many other funded efforts

- High altitude balloons (BOREALIS)
- Solar Physics Instruments (MOSES, IRIS)
- Space Physics Instruments (BARREL, BOOMS)
**CubeSat Examples:**

**CubeSat “Crash Course” (Enter Lesson 1: Always Build a Spare)**

**MEROPE**

“Went with the Russians”

Failed launch on a Russian rocket (Dnepr 7), 2006

One of many early rideshares

“crater-synchronous” or *extremely* low earth orbit.

**Explorer 1 [Prime] – Flight Unit 1 (E1P-FU1)**

“Should have gone with the Russians”

First ELaNa Launch (Glory) – LV Failure, March 4, 2011

PPOD deployed at 500km, insufficient ΔV to maintain altitude.

De-orbited over the south pacific.
CubeSat Examples:
Hiscock Radiation Belt Explorer (or E1P-FU2)

Hiscock Radiation Belt Explorer (HRBE)

NPP Rideshare
October 28th, 2012
CubeSat Examples:
HRBE Operations, April 2012

- Primary Mission: Student Education
- Secondary Mission: Particle detector PL (Geiger tube)
- Short period science collection only
  - Data storage in volatile flash memory
- Large improvements were made to MSU-SSELs System Engineering process after this mission
CubeSat Examples:
FIREBIRD-I Mission

- Focused Investigations of Relativistic Electron Burst Intensity Range and Dynamics
- Two 1.5kg (1.5U) CubeSat spacecraft
- National Science Foundation sponsored CubeSat Science mission.
- Collaboration between UNH, MSU, and Aerospace Corp
- Publishable science using CubeSats

**Science Objectives**
1) What is the spatial scale size of an individual burst?
2) What is the energy dependence of an individual burst?
3) How much total electron loss do bursts produce globally?
CubeSat Examples:
FIREBIRD-I Mission

- Delivery to CalPoly
  - August, 2013
- Launch from VAFB:
  - December 6th, 2013
- NPSCuL with 8 PPODs on NROL-39
- Partial mission success achieved on-orbit
CubeSat Examples: FIREBIRD-II Mission

- Primarily built using flight spares from FIREBIRD-I
  - See Lesson 1
  - Also had updates to Power and Fault Management (iteration).
- Technology Rideshare (solar cell demonstration)
  - Low impact experiment insertion into mission
  - IV curves for experimental IMM cells
  - Automated on-orbit collection using a sun-sensor
  - Coarse sun-sensor also able to provide a spin rate measurement.
CubeSat Examples:
FIREBIRD-II Launch and Ops

• >5 years of on-orbit operations.
• Major discoveries into radiation belt physics.
  – One of the most published CubeSat missions
  – On Science Campaign #26 (February 2020)
• **Data Rate Limited**: Data Generated >> Data Downlinked
  – Utilizes on-board processing to downlink “Context” data so
    scientists can choose the “Hires” data to downlink

• Delivery to Cal Poly: September, 2014
• Launch from VAFB: January 31st, 2015
• Delta-II rideshare with SMAP
• Continues to return science
  – Most recent data product: March 13th 2021
CubeSat Examples: EPISEM
Energetic Particle Integrating Space Environment Monitor: Provided 14 flight instruments in ~6 months

- Hosted instrument aboard NASA Ames’ Edison Demonstration of Satellite Networks (EDSN). 8 Launched on ELaNa VII (Launch Failure), 2 Flight Spares Deployed off ISS
- **Comm capabilities limited**: CubeSat form-factor comms hardware limited at time of mission design / development.
  - Limited instrument collection due to downlink power considerations
  - State-of-Art has increased since, many times at the growth of Volume/Mass/Power
- **Sensor capabilities limited**: Simple radiation detector (based on Explorer-1)
  - CubeSat platform allows for multiple co-temporal / spatial measurements of the environment (first of a kind measurement).

Credit: NASA [12]
Credit: Adam Gunderson
Montana State University [12]
RF CMOS and CubeSats: Use Cases

- Higher Data Rate and more capable Comms
- Demonstration of new RF technology (bridge over the TRL “valley of death”)
- Miniaturized Payloads
- Miniaturized Sensors
  - CubeSat’s excel at specialized missions, small number of sensors vs everything on one platform (traditional space)
- Satellite Network Missions (EDSN) and Distributed Sensor Missions (CubeSat Constellations)
- Single Use and High Risk / High Reward Missions (MarCO – Mars Relay, Ingenuity – Mars Helicopter)
RF CMOS and CubeSats: Use Cases
MarCO Mission

- Comm relay for EDL Phase
- Deployable Reflect-array
- High Gain Feed and Antenna
- Integrated RF Electronics into a 6U platform
CubeSats and SmallSats Platforms

Disclaimer: Some items below are broad generalizations for presentation purposes only.

CubeSats
- Canisterized
- Unit Level Design Oriented
- Non-traditional design solutions
- Broad Range of Stakeholders
- Roots in University Research
- Very Low SWaP Constraints
- Limited mission life (generally)
- Single Payload (generally)
- Hobbyist / Educator appeal
- Lower Entry Costs
- Highly Integrated

SmallSats
- Dedicated Launches
- Launch Vehicle Interfaces
- System Level Design Oriented
- Traditional Satellite Design Solutions
- More Limited Stakeholders
- Higher Entry Costs
- Medium to Low SWaP Constraints
- Multiple small payloads or a single larger payload
- Can have Class-B/C Assurance

Rideshare
Tech Demo
Rapid Timelines
Class-C/D Assurance
Targeted Missions
Constellations
SmallSat Overview

Much more open-ended platform than CubeSat's

- Mass: <500 kg*
- Cost: <$150M*
- Development Cycle: Varies
- Risk Posture: Class C/D*

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**Applications**

- UNP: University Nanosat Program (Education)
- Technology Demonstration (Yellowfin)
- IRIS: Single Instrument Mission (Targeted Science)
- Comm payload platform (OneWeb, Starlink)

**SmallSat Subsystems**

- Flight Computer
- Communications
- Guidance, Navigation, and Control
- Power
- Propulsion
- Structures
- Thermal

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*Highly mission and organization dependent*
SmallSat “Standards” and Mission Assurance

- Tailored internal/external process are key to executing a SmallSat Program.
- Top Level Guiding Documents:
  - NASA Systems Engineering Handbook
  - Space Mission Analysis and Design (SMAD)
  - DOD-HDBK-343: Class A/B/C/D Assurance Guidelines
  - GSFC-STD-7000: General Environments (NASA)
  - MIL-STD-1540: General Environments (DOD)
  - MIL-STD-461: EM Interference/Compatibility
  - EEE-INST-002: Parts Selection, Screening, Qual., and De-rating
  - TOR-2009(8591)-14: Fault Management Guidelines
  - TOR-2009(8591)-15: Test Like You Fly Checklist
  - TOR-2010(8591)-6: Test Like You Fly Implementation
  - TOR-2010(8591)-20: Unit Qualification Guidelines
  - TOR-2011(8591)-21: Class A/B/C/D Assurance Guidelines
  - TOR-2013-00294: Class C/D Mission Success Considerations
  - TOR-2017-01689: Improving Mission Success of CubeSats
SmallSat Launches and Rideshares

**Rideshare**
- NASA LSP’s ELaNa Program
  - Limited to Education Institutions
  - Various USG and Commercial Launch Partners
- Other Rideshare examples:
  - Spaceflight Services
  - Tyvak Nano-satellite Systems
  - Nanoracks
  - SpaceX
  - ULA

**Dedicated**
- Rocket Lab Electron
  - Traditional Launch
  - 165 kg to LEO
- VOX LauncherOne
  - Air Launch System
  - 225 kg to LEO
- Astra
  - Traditional Launch
  - 150 kg to LEO
SmallSat Platform Example: Yellowfin

- SmallSat RF Risk Reduction Deployment Demonstration (R3D2) for DARPA [14].
  - 150 kg Satellite launched on Rocket Lab Electron out of Mahia, New Zealand.

- Demonstration Mission [15]
  - Deploy 2.25m diameter antenna
  - Monitor antenna deployment dynamics, survivability, and RF characteristics.
  - Prove smaller, faster-to-launch, and lower capability systems for the Department of Defense and other users.

- Very Rapid Development
  - How fast can you go, accepting high risk.
  - "Whiteboard to Orbit" time of ~20 months
  - “Pole-vaulted” the Valley of Death (TRL4-6)
    - Was the first flight for the majority of the hardware and leveraged high knowledge base of a defense prime (NG) and partnerships with commercial suppliers.
SmallSat Platform Example: Yellowfin

• High risk mission which was approached through applying SmallSat standards and tailoring NG’s Mission Assurance profile to meet the different risk level [14].

• The program leveraged: large prime bench depth, supply chain, vertically integrated manufacturing capability, I&T personal/facilities, and the sharing of key performers across other programs.

• Demonstrated many new technologies
  – RF CMOS technologies can benefit in flying on these types of SmallSat demo missions.
  – This mission may have specifically benefited from RF CMOS by a possible decrease in the payload’s overall Size, Weight, and Power.
SmallSat Platform Example: Yellowfin

Credit: Northrop Grumman [13]
RF CMOS and SmallSats: Use Cases

- Demonstration of new RF technology (bridging the TRL “valley of death”)
- Higher Data Rate and more capable comms
- Higher capability multi-mission comm payloads
- Allowing for a platform to carry multiple miniaturized sensors (vs single sensor on CubeSat's)
- Missions utilizing larger deployable apertures (Yellowfin / R3D2)
- More integrated electronics for operational commercial constellations (OneWeb / Starlink)

Credit: Creative Commons (SpaceX)
Credit: NASA (Airbus / OneWeb)
Credit: Northrop Grumman
RF CMOS and SmallSats: Use Cases
Phased Array Application

• RF CMOS can decrease overall volume of a phased array through miniaturization of functions.
  – Right: The multiple components required to make up the PHI’s can be replaced with a more integrated RF CMOS components to reduce size and mass.
  – Middle: Hardware slices or cards can be reduced into a System-on-Chip form-factor, reducing overall unit size to much less-than a mousepad.
  – Left: multiple individual stacked components circuits can be combined into a single RF CMOS component.
Summary

• Potential benefits of RF CMOS to the CubeSat Platform
  – Platform is fixed in size due to canisters (no bigger than a microwave).
  – Miniaturized RF electronics will greatly increase platform capability
    • High data rate communications
    • High capability software defined radios
    • Satellite networking

• Potential benefits of RF CMOS to the SmallSat Platform
  – Platform is less constrained but does have its limits
  – Size, Weight, and Power reduction of RF electronics would enable much more complex payloads.
    • Lower SWaP Phased Arrays
    • Smarter and more integrated RF apertures
    • Better integrated RF feeds and RF electronics
References


Questions?
Backup
CubeSat Overview

• What is a CubeSat? [1]
  – https://www.youtube.com/watch?v=HZMiJ_Q47qk

• What does a CubeSat do? [1]
  – https://www.youtube.com/watch?v=BLJBVkJVGHE

• How do CubeSat’s get into orbit? [1]
  – https://www.youtube.com/watch?v=pnRdIlylWI0k

• NASA CubeSat User’s Guide [1]
  – https://www.nasa.gov/content/cubesat-launch-initiative-resources
CubeSat Resources

• CubeSat Launch Initiative (CSLI)
  – https://www.nasa.gov/content/cubesat-launch-initiative-resources

• Cal Poly CubeSat Standard
  – http://www.cubesat.org/resources/

• “NASA CubeSat 101”
  – https://smdepo.org/post/10058

• NASA Outgassing Material Database (do no harm)
  – https://outgassing.nasa.gov/

• Space Studies Board: Achieving Science with CubeSats: Thinking Inside the Box
  – https://www.nap.edu/catalog/23503/achieving-science-with-cubesats-thinking-inside-the-box
SmallSat Resources

- NASA SmallSat Institute
  - [https://www.nasa.gov/smallsat-institute](https://www.nasa.gov/smallsat-institute)
- NASA Small Spacecraft State of the Art
  - [https://www.nasa.gov/smallsat-institute/sst-soa](https://www.nasa.gov/smallsat-institute/sst-soa)
- SmallSat Conference Proceedings
  - [https://digitalcommons.usu.edu/smallsat/](https://digitalcommons.usu.edu/smallsat/)
- Radiation Effects Data, IEEE Workshop
- Military and NASA Standards / Specifications
  - [http://everyspec.com/](http://everyspec.com/)
Radiation Effects

- Employ “Careful COTS” techniques for TID mitigation [16]
  - Many of today’s COTS electronics are radiation tolerant.
- Use available radiation data to determine destructive SEEs
  - Consider test if none exist.
- Addition of monitors and watchdogs for SEE recovery
  - Assumes no destructive latching.

Identify Requirements
Define Orbit and Duration
Define Shielding
Evaluate Environment
Detailed Design, Best Practices, Buy Parts in Lots, Prototypes, Radiation Test, Post-Test Analysis

Test Passed?
No
Yes
Design Qualified

TID > 30 krad?
No
Yes

Test Passed?
No
Yes
Design Qualified

[12]
Radiation Effects: TID Mitigation Approach

- **Total Ionizing Dose (TID)** – Long term damage due to low energy electron and proton radiation, in the units of “rads”
  - Drift in transistors threshold voltage
  - Timing shifts which hinder logic circuit operations
  - Leakage currents which ultimately destroy the device
  - TID rating of a part is very process dependent

- **Mitigation Approaches for LEO:**
  - Ensure low lifetime: <3 years
  - Shielding: Al enclosures and Al S/C walls
  - TID parts testing as needed

[Image of NMOS Transistor Cross-Section]

1000 krad
100 krad

Low Earth Orbit
TID is orbit alt/incl and lifetime dependent

[Image of Dose vs. Shield Thickness (mil of Al)]

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Radiation Effects: SEE Mitigation Approach

• Single Event Effects (SEE)
  – Linear Energy Transfer (LET) threshold of energy tolerated in a device before a latch-up will occur measured in MeV-cm²/mg. Single Event Latch-up (SEL): produces a "latched" current condition, remedied only by power cycling.
  – Single Event Upset (SEU): produces a bit flip in one or more logic circuits

• SEE Mitigation Approaches
  a) SEL – SOI, Epi layer, or other RadHard parts
  b) SEL – Current limiting and latch-up detection: protection if non-destructive, part dependent.
  c) SEU – Temporal TMR + Scrubbing: Majority voter, real-time fault correction.

a) Epitaxial Layer
b) Latch-up detect / protect
c) TTMR + Scrubbing