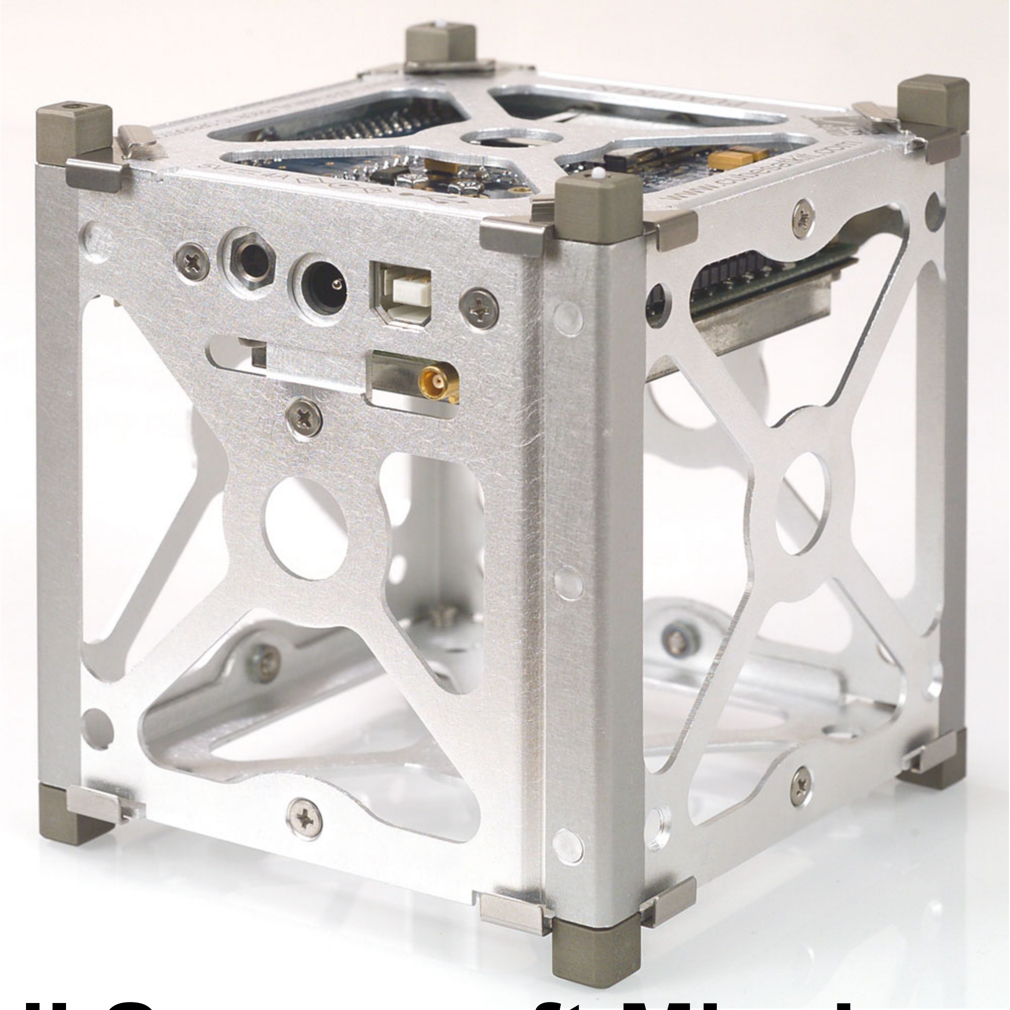


PUMPKIN INCORPORATED

www.pumpkininc.com

Small Spacecraft Missions – How About Flying a CubeSat?

Andrew E. Kalman, Ph.D.

Small Spacecraft Missions

- Starts with a **goal**
- Followed by
  - Obtaining **funding**
  - **Constructing** the spacecraft (SC)
  - **Integrating & launching** the SC
  - **Deploying** the SC into its orbit
  - **Operating** the SC
  - **Analysis** of the mission data

Mission Goal

- Obtain government grant?
- Science mission?
- Commercial opportunity?
- National prestige?
- Educational programs / benefits?
- Workforce & industry development?

- A mission can be as simple as constructing a desk model, to balloon-launching a payload, to a full-fledged orbital deployment.

Mission Goal

- Constraints:
  - Time
  - Money
  - Launch opportunities
  - Manpower
  - Available technology
  - Capabilities of selected SC platform
  - **Risk**
- Process (the NASA way) vs. People (the CubeSat way)

Mission Goal

- Focus on the mission / payload
- Buy as much as possible, so as to accelerate development and capitalize on the rapid pace of technology. You'll be very busy developing all the unique things for your mission / payload anyway.

CubeSats

- Why build your SC to the CubeSat standard?
  - Rapid development cycle – not “career satellites”
  - Large, open community
  - Simple specification
  - Reasonable chance of success (see track record)
  - Low per-mission costs (though high per-kg costs)
  - LEO orbits for now, GTO etc. later w/rad-hard.
    - LEO orbits are a relatively benign environment, therefore COTS components are OK
  - Now accepted as secondary payload
  - Current trends in technology (low-power, miniaturization, large feature set) are ideal fit to small spacecraft
  - No experience required!

CubeSats

- CubeSat specification proposed by Stanford Prof. Bob Twiggs, maintained & upgraded by Cal Poly
- Very stable specification – few changes over time
- Standardization has created a growth industry serving the CubeSat community's needs
  - Deployers – P-POD (Cal Poly), X-POD (SFL/UTIAS), etc.
  - Solar panels
  - Power systems
  - Radios
- Popular – ca. 20 10x10x10cm (1U) CubeSats launched
- Launch costs have stayed at \$30-\$50k / CubeSat
- Launch providers now showing strong interest (NASA, SpaceX, Russia, India, etc.)

Fundraising

- $100k-$150k “hard” costs per 1U CubeSat
  - Electronics
  - Structure
  - Radio(s)
  - Solar Panels
  - Tools (software, hardware, etc.)
  - Ground stations (modest)
  - Launch
- “Soft” costs (I.e. labor, testing, travel, program management, etc.) are typically 1x to 3x hard costs

Fundraising

- 1U CubeSats (1 liter volume, 1 kg mass) are relatively small – only ca. 30% of the mass and volume are available for an internal payload. Such spacecraft are constrained to one or maybe two payloads / experiments.
- Therefore it's harder to attract multiple partners to join you in the development of a 1U CubeSat.
- 1U CubeSats are great starter spacecraft – they lay the foundation (construction, operation, technology) for later, more sophisticated missions.
- Nevertheless, when designing your 1U CubeSat you should strive to be as efficient as possible (space- and volume-wise) so as to be able to attract other parties to aid in funding by carrying their payload, too.

Fundraising

- Having a hands-on prototype to display / show to potential funding sources is an excellent way to raise awareness. N.B. AEK's experience at trade shows.
  - Buy one (e.g. CubeSat Kit (CSK))
  - Build one in a machine shop, etc.
  - Build one via Rapid Prototyping (RP) machine from 3D CAD model
  - Paper cut-out (inexpensive!)

Fundraising

- Be realistic about what you are promoting. A 1U CubeSat cannot deliver Hubble-telescope-like images.
- A 1U can grow to 1.5U or 2U or 3U if it better meets your mission requirements.
- Be as public as possible. “Broadcast yourself.”You never know when an interested party may find you and your project. N.B. AEK’s contact with Company E.

Fundraising

- Opportunities
  - National and global advertising are expensive. Even at >$200K, CubeSats are cheap at this level. With the space race now on, consider your CubeSat's advertising potential.
  - Bob Twigs / KatySat / KYSat – "multimedia CubeSats" with classroom involvement.
  - "Social conscience" investors. "Giving back to the community", esp. by investing in space, education and global awareness.
  - Government funding. Chances of winning grant / funding can be small. Long approval times. Not too expensive to put togeter proposals, however – just man-hours. Competing against "proposal mills". Fosters a disciplined approach due to required accountability.

Construction

- CubeSat specification (from Cal Poly)
  - 100mm x 100mm cross-section
  - 1kg mass
  - 113.5mm height (1U), 227mm height (2U), 340.5mm height (3U)
  - 6.5mm from each face (CSK: 7mm top & bottom)
  - Spec allows for 113mm diameter structure
- Materials
  - Spec essentially requires aluminum (Al), esp. for contact surfaces
  - 6061-T6 & 7075-T6 common, machinable Al
  - 5052-H32 is bendable Al as used in CSK
  - Titanium (Ti) too heavy
  - Carbon Fiber (CF) has outgassing and consistency problems
- Fasteners
  - Non-magnetic, Stainless-steel preferred

Construction

- Understanding CubeSat sizes
  - P-POD can accommodate up to three 1U CubeSats
  - To date, only 1U & 3U CubeSats have been built / launched
  - X-POD (SFL/UTIAS version of P-POD) also 3U
  - P-POD might be extended to 5U for ESPA ring use
  - CSK available in 0.5U, 1U, 1.5U, 2U, 3U sizes
  - PCBSat (concept) ca. 22mm (0.2U) thick.
  - MAST was a 3U that separated into three CubeSats of different shapes and sizes

Construction

- Purpose of corner foot springs (x2)
  - Push neighboring Cubesats apart after ejection from P-POD
- Purpose of Remove-Before-Flight (RBF) switch
  - Satisfy certain safety requirements of launch provider
- Purpose of Launch switch
  - Energize / start CubeSat after ejection from P-POD

Construction

- Faces of a CubeSat and some uses
  - Left/right sides – often totally covered in solar cells
  - Front – access port for RBF, PC link, antenna, etc.
  - Rear – Often with sensor, antenna, etc.+ solar cells
  - Top/bottom – antennas, sensors, etc. Usually the fewest solar cells here
- Shock / G-loads
  - Not a major issue, in that CubeSats don't seem to have much trouble surviving shake table tests and launch. Some delicate components may pose issues (e.g. solar cells). Delfi-C3
  - Fasteners should be staked or potted. Conformal coatings on PCBs are probably a good idea, but not required.
- Tin Whiskers
  - More and more components are RoHS/Pb-free. Aerospace technically exempt in most markets. Limited lifespan mitigates this problem somewhat.

Construction

- Thermal issues
  - Lots of analysis has been done
  - While not immune to thermal issues, CubeSats don't seem to be too sensitive to this. On-orbit data shows that most electronics is happy.
  - Batteries are the most thermally-sensitive component – many failures suspected due to temp (and outgassing)
  - On-orbit thermal data is available for several CubeSats. Also, GeneSat (active control) has bio temp data as well.

Construction

- Attitude determination and control (ADAC)
  - Passive AC via magnets quite popular
  - Torque coils sandwiched in Solar Panel PCBs also popular
  - Active ADAC via momentum wheels and torque coils, with sensors (e.g. IMI-100)
  - All active AC requires power – may exceed 1U CubeSat's power budget
- Delta-V possible, but not much room for existing thrusters

Construction

- Electronics Layout
  - Horizontal stacking – "most obvious / common"
  - Vertical stacking – has benefits for > 1U sizes (e.g. long PCBs in a 2U)
  - Perimeter arrangement – lots of room centrally, more difficult to rigidize PCBs (they flex relative to one another), no ability to stack connectors
- Connectors vs. Wires
  - Wires are more likely to fail simply because they are more complex – endpoints, crimps, chafing, etc.
  - May be best solution for certain applications (e.g. high-current runs, solar panel connections)
- Point-to-point wiring is theoretically optimal in terms of minimizing mass, but practically speaking it's a big problem, esp. in assembly / disassembly

Construction

- Tradeoffs of connector types
  - Board-to-board: pin current ratings are just what you need (+), more flexible inter-PCB spacing (+), pin out only those signals that you use (+), totally custom boards (-), only one assembly sequence / layout (-), rigid / no wiping (-)
  - Board stacking: typically large inter-board spacing (+/-), all pins (even unused ones) carried through (-), more general, more standard (+), pins all high-current (excess capacity) (-), arbitrary assembly sequence (+), wiping action (+)
- Boards can be interconnected via
  - Unique point-to-point / board-to-board topology (e.g. CP series)
  - “Backplane” topology (e.g. GeneSat – dedicated slots)
  - Stacking approach (e.g. CubeSat Kit)

Construction

- Payloads
  - Internal payloads – common to most 1U CubeSats. Constrained by internal volumes, walls, connector pinouts.
  - Semi-internal payloads – e.g. GeneSat, PharmaSat where the payload is an integral but separable part of the overall CubeSat structure. May have more internal volume available, usually employ a custom electrical interface, are tied to the structural design of the CubeSat structure
  - External payloads – "bolt-on", like 4th-generation CSK. Have the potential to be highly modular, since tied primarily to CubeSat specification for dimensional issues, not to CubeSat itself.

Construction

- Electrical Power System (EPS)
  - Simple EPS – batteries (or solar) only
  - Standard EPS – solar cell interface, PPT, batteries
- Li-Ion & Li-Poly rapidly becoming battery of choice. We probably won't see NiCd & NiMh on future CubeSats
- Lithium cell voltage is nom. +3.7V – this impacts power systems directly, as combining them in series introduces many concerns, primarily safety.
- Batteries are there for **peak** power consumption.
- QuakeSat – 15W – dead batteries – reset out of eclipse.

Construction

- EPS features
  - Status / telemetry should be available at all times (ground, flight)
  - Should be chargeable on the ground (e.g. USB or external source)
  - PPT is useful, but not absolutely required
  - Overcurrent trip protection / fault detection and resolution a must
  - EPS can be analog or digital control
  - Battery temp range should be EPS' first priority – e.g. heat to above 0C for Li-Poly, disconnect in overtemp conditions

Construction

- Operating voltages
  - Transceivers run at +5V due to power considerations. Typical efficiency is < 25%.
- uC's run at +5V, +3.3V, …, +1.8V.
- Various peripherals have narrower ranges. E.g. SD card: +3.3V (low-voltage cards do exist)
- Most flash memory (e.g. in the uC) cannot reprogram itself at very low voltage. Charge pumps (big power consumer) are required.
- Many +3.3V parts are +5V I/O tolerant.
- Recommend +5V and/or +3.3V EPS outputs, I/O at +3.3V
- Level-shifting can consume a lot of power, esp. if charge pumps are used.

Construction

- Solar cells
  - 85mm (?) width across face of CubeSat for solar cells
  - Some USA cells are ITAR-controlled, similar available outside USA
  - Cover glass (protects against micrometeorites) is likely unnecessary (saves mass), but cover glass adhesive is required to protect cells against atomic oxygen
  - Cells in series should not be too high (> 28V) nor too low (< 5-8V). Efficiencies favor buck (I.e. down) converters. Redundant strings of cells a must.
  - Pumpkin's idea of low-cost TASC cells treated as surface-mount components being tested successfully on KySat project
  - 0.062" (1.5mm) PCBs form a nice, strong but heavy substrate for solar cells. CF might be a lighter and better option.
  - SC with distributed power may want to route solar cell output voltage to all corners of SC

Construction

- Radios
  - Many different ones, some COTS, some home-made
  - Existing radios have been small and simple
  - They've also been slow (e.g. Libertad-1 at 300bps with AX-25) or power-hungry (MHX series receive idle current @ 115mA)
  - **This is an unfinished / unresolved area of concern for the CubeSat community.**
- Bands / Frequencies
  - Primarily amateur due to licensing restrictions: 144MHz, 433MHz, 920MHz, 2.4GHz
- Antennas
  - Patch (GeneSat), x4 (Delfi-C3), stubby (MAST), tape measure (CPn), genetic algorithms (NASA ARC)
  - Omni required if no attitude control. With ADAC, can improve antenna gain

Construction

- Command & Data Handling (C&DH)
  - Processors used: 8051, AVR, PIC, MP430, x86/Pentium, etc. (all COTS parts, industrial temp range –40C to +85C
  - Programming & debugging environment is perhaps more important than the choice of processor, though some choices will be based on uC's peripherals
  - The more data you need to process, the better the architecture needs to be
  - C&DH may be done on a dedicated processor or on the SC's sole processor
- Watchdogs
  - Internal (sw) watchdog – simple and window-style
  - External (hw) watchdog – independent operation
  - DTMF decoder → system reset via GS (e.g. QuakeSat)

Construction

- Software
  - The best software is the software you and your team understand best
  - As complexity increases, an RTOS or other structured framework will help you in managing the complexity to achieve reliable operation
  - RTOS-enabled products are all around you (e.g. MHX-920A, MHX-2420)
  - Complex monolithic software is hard to understand and even harder to maintain / grow. Strive for **modular** software. Build, test & verify incrementally. Don't forget to backup.

Construction

- Tools
  - Dedicated Lab
- Team areas / assignments
  - Software
  - Electronics
  - Structures / Mechanics / Thermal
  - Communications & GS
  - Power
  - Documentation / Web
  - Project Management
- Clear documents (e.g. pin allocations on bus) are a requirement
- Team-based approach, with regular oversight and mentors' meetings

Construction

- Current state-of-the-art low-power x86/Pentium-class SBCs consume ca. 5W for “Windows useable” processor speeds.That is too high to run 24x7 in a 1U CubeSat. May be OK for a larger CubeSat. Alternatively, may need to be controlled (sleep, run, sleep) to maximize utility while minimizing power consumption

Integration & Launch

- Luckily for the CubeSat builder, this stage of the mission is beyond your control!
- You:
  - Ensure your CubeSat meets the CubeSat specifications
  - Send it to your integrator (e.g. Cal Poly)
  - Wait for launch
  - If possible, send team to launch site in order to observe & learn
- Launches are often delayed. You should be prepared for this, with procedures to (re-)charge batteries while in storage, verify functionality, even update software fix bugs.
- Launch is risky! Rocket may explode! E.g. Russia 2006.

Integration & Launch

- Traditionally, CubeSats were considered low-priority and risky, and so were ejected **last** from the rocket as a safety precaution. This severely limited the orbits available to CubeSats. However, the thinking vis-à-vis CubeSats is now changing, as rockets are now willing to “drop off” CubeSats at low orbits before the primary payload is released. Why? Because carrying just 3 P-POD deployers (9 1U CubeSats) is worth $0.5M to the launch company. It’s good business for them.
- Also, the fully enclosed P-POD has proven itself to isolate the primary payload(s) from any bad behavior (early turn-on, parts falling off) of the low-cost, low-priority CubeSats inside.

Integration & Launch

- The Test & Integration (T&I) stage may be the first time your CubeSat is verified by a third party against the specification. The integrator takes a “hands-off” view of your SC during T&I. Decision is simply Pass/Fail.
- Traditionally, 1U CubeSats must conform strictly.
- 3U CubeSats (10x10x30cm) have more leeway, as they are alone in the P-POD. Some P-POD customizations have been done, e.g. Delfi-C3 w/X-POD.

Deployment

- Deployments is also beyond our control.
- P-POD has an excellent deployment record.
- An independent (VHF/UHF) beacon is extremely important for getting an initial fix on your CubeSat. TLEs, etc. may be incorrect / swapped via-a-vis another CubeSat. Beacons should transmit at least once per minute to allow multiple detections per pass per ground station. Libertad-1 experience (10 minute interval, QSL cards for initial fix).
- Beacon data should be simple, unencoded, with health & status info (e.g. time, battery status, etc.)
- Companies (e.g. 1Earth Research) can do initial acquisition for a fee.

Deployment

- Orbits are based on the requirements of the primary payload. Must choose what's available.
- With no delta-V, constellations are dependent strictly on drift and staggered deployments.

Operating the SC

- CubeSat-class SC comms are highly directional – low BW uplink (command and control), high BW downlink (data).
- Receiver(s) must be as low-power as possible to be able to operate 24x7.
- Tx must be high-power (esp. with omni antennas) to close the loop and maintain a decent link margin.

Operating the SC

- The challenge is to balance the opportunities to download data from the SC against the on-board power required to process and compress the data. Storage capacities (e.g. SD cards) greatly exceed the daily download capacity of a typical CubeSat Kit to a single Ground Station (GS). Therefore you need either multiple GS's to maximize downlink contact, or you need to process and compress data on board for the relatively rare GS contact. A 1U CubeSat does not have much power on board to spend all its time crunching large amounts of data … especially if a Pentium-class processor is required for this task.

Operating the SC

- Jamie Cutler's Mercury Ground Station software provides a scalable foundation upon which to add a variety of GS-centric software packages (e.g. GSEOS). Runs on Virtual Machines (VM), which has multiple advantages, not the least of which is resistance to being hacked (just reboot VM from image). Isolated testing, etc.
- Very important to be able to script the SC's operation as QuakeSat did via Linux scripting – fully unattended operation, with daily script uploads from the Mercury GS to the SC, and daily data sent via email to operations team.

Operating the SC

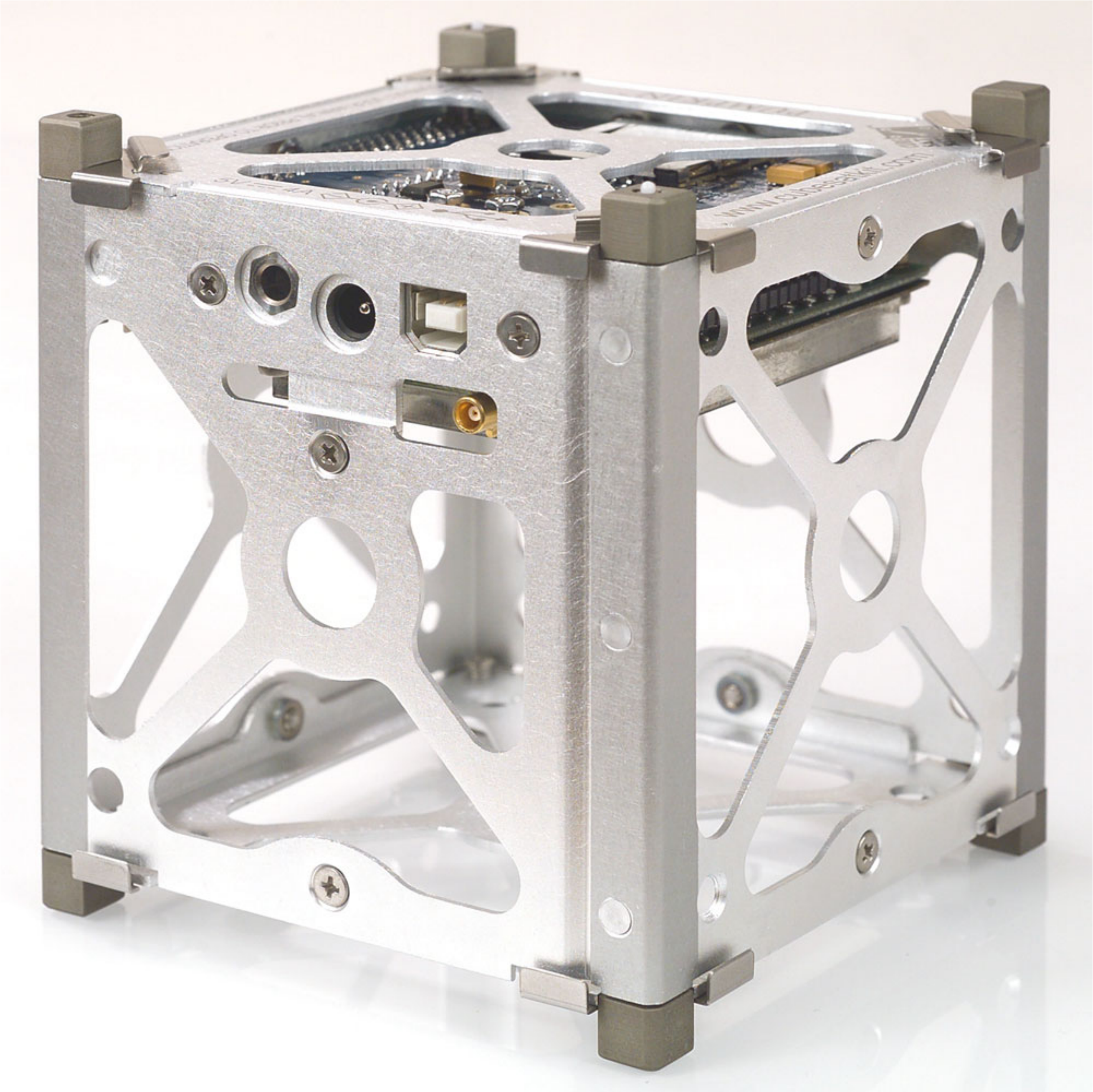
- GS "hardware creep". Many of the "higher performance" GS setups (e.g. using MHX) have dedicated comm hardware on both ends. Such pairings make the GS incompatible with other SCs.
- Currently, the small SC community is faced with the problem of "We have a 1000W, 2m^3 mobile GS. Won't you please install this at your GS site? No!
- So, working towards a common radio that satisfies the community requirements and can (in a GS) communicate simultaneously with multiple SCs would be a big step forward.

Operating the SC

- In the future, a software-defined (SD) radio with a simple but powerful transmitter and complex receiver software in the GS will allow the GS to listen to multiple SC, reconfigure on-the-fly, and permit utilization of new encoding schemes.
- GPS: Space GPS is now available, at $15-40K. Hasn't flown in a CubeSat yet.

Analysis

- Analysis on
  - Mission (payload) data
  - SC (operational) data
- Satellite may live much longer than you anticipate (e.g. QuakeSat) or primary mission may be short-lived (e.g. GeneSat). If operation is autonomous / scriptable, you may get a lot more data than you bargained for.
- Uploadable or alternate stored code enables multiple, different missions to be performed after the primary mission is over (e.g. GeneSat and injecting faults to see if GS software can detect them heuristically)



PUMPKIN INCORPORATED

www.pumpkininc.com

Q&A Session

Thank you for attending!

Notice

This presentation is available online in Microsoft® PowerPoint® and Adobe® Acrobat® formats at:

www.pumpkininc.com/content/doc/press/Pumpkin_CSMO2007.ppt

and:

www.pumpkininc.com/content/doc/press/Pumpkin_CSMO2007.pdf

Appendix

PUMPKIN™ INCORPORATED
www.pumpkininc.com

- Speaker information
  - Dr. Kalman is Pumpkin's president and chief technology architect. He entered the embedded programming world in the mid-1980's. After co-founding Euphonix, Inc – the pioneering Silicon Valley high-tech pro-audio company – he founded Pumpkin, Inc. to explore the feasibility of applying high-level programming paradigms to severely memory-constrained embedded architectures. He is the creator of the Salvo RTOS and the CubeSat Kit. He holds two United States patents and is a consulting professor in the Aero & Astro department at Stanford University. Contact Dr. Kalman at aek@pumpkininc.com.
- Acknowledgements
  - Stanford Professors Bob Twiggs' and Jamie Cutler's continued support for the CubeSat Kit, and their inputs on enhancements and suggestions for future CubeSat Kit products, are greatly appreciated.
  - Pumpkin's Salvo and CubeSat Kit customers, whose real-world experience with our products helps us improve and innovate.
- Salvo, CubeSat Kit and CubeSat information
  - More information on Pumpkin's Salvo RTOS and Pumpkin's CubeSat Kit can be found at http://www.pumpkininc.com/ and http://www.cubesatkit.com/, respectively.
- Copyright notice