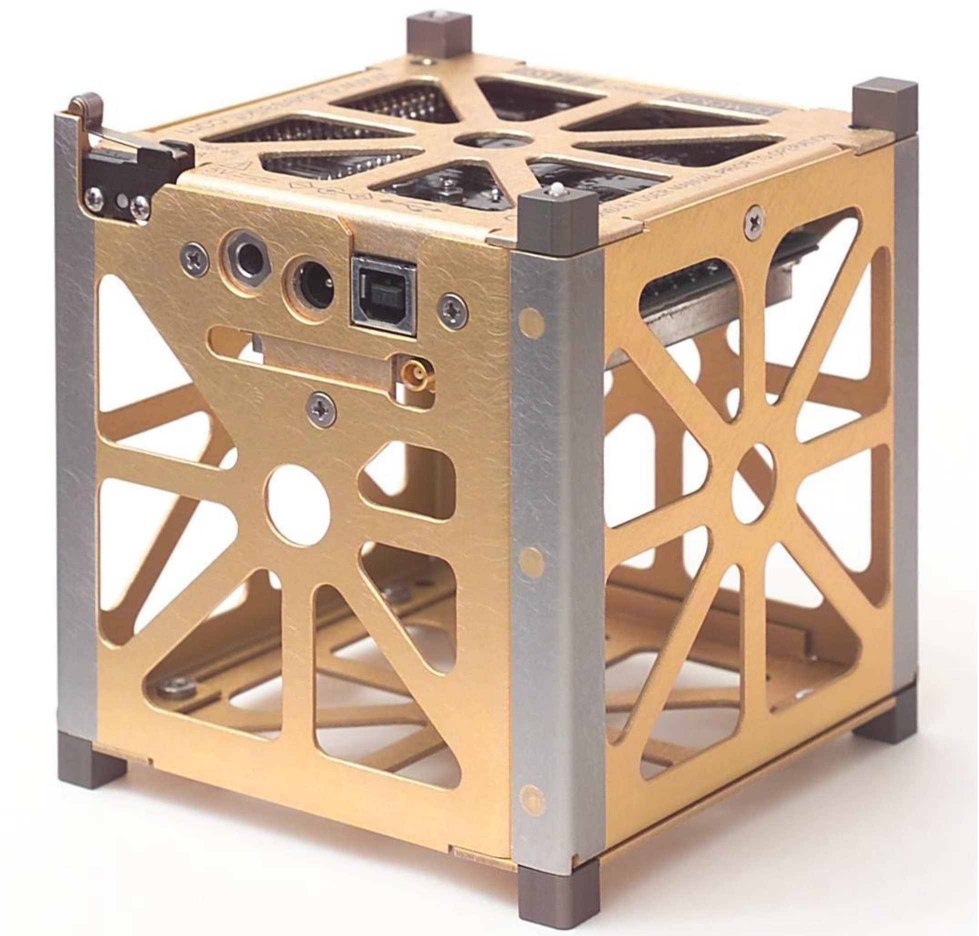

# Accelerated Picosatellite Design Cycle using the CubeSat Kit™

Andrew E. Kalman, Ph.D.

# Introduction

- Andrew E. Kalman
  - President and CTO, Pumpkin, Inc.
  - Author of Salvo™ — The RTOS that runs in tiny places.™
  - Creator of the CUBE SAT KIT
  - 20+ years of embedded systems design and programming experience.
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# Outline

- Overview: Seminar Goals
- Part I: A Technology Revolution
- Part II: The CubeSat Standard
- Part III: CubeSat Mission Planning
- Part IV: The CubeSat Kit Design Cycle
- Part V: The CubeSat Kit's Architecture
- Part VI: The CubeSat Kit's Structure & Layout
- Part VII: Real-world Experience
- Part VIII: Summary

# Overview

- This seminar is targeted at organizations planning their initial foray into the exciting realm of picosatellite missions.
- First, we note that there are many similarities between the rise of the Personal Computer and the emerging popularity of picosatellites. What can we learn from this to ensure the best chances for success for each low-cost picosatellite mission?
- Next, we present the fundamental building blocks of a picosatellite, and comment on the tradeoffs involved in building or buying components off-the-shelf.
- Lastly, we examine the CubeSat Kit in particular, and demonstrate how it can accelerate a mission timeline and free resources to focus on the particulars of the mission.

# Part I: A Technology Revolution

- A peek at two decades of personal computer development:

| | 1986 | 2005 | $\Delta$x (simple) |
|---|---|---|---|
| Processor | 12MHz 286 | 2.4GHz Celeron® | 200 |
| Memory | 640KB | 256MB | 400 |
| Mass Storage | 30MB hard disk<br>5¼" floppy drive | 80GB hard disk<br>CD-RW drive | 2600<br>600 |
| Video | Monochrome graphics | Integrated Intel® Extreme 3D Graphics | 100 ? |
| Operating System | MS-DOS® 3.1 | Windows XP® | ? |
| Cost | \$1,495<br>(= ~\$2,900 in 2005) | \$299 | 1/10 |

# Part I: (cont'd)

- In two decades, the price/performance ratio of the PC has improved by a factor of 1,000.
- Is it even possible today for an individual to assemble a complete PC with Windows XP for $299? Not really. It nearly always makes more sense to *buy* rather than *build*.
- The computing status quo in 1986:

| | Desktop PC | Mainframe |
|---|---|---|
| Model | PC's Limited 286-12 | IBM 3090 Model 200 |
| Cost | $1,495 | $5,000,000 |

- In 1986 the cost of a mainframe exceeded the cost of a desktop PC by over 1,000 times.

# Part I: (cont'd)

- *The personal computer represented a radical new way of using computing power. PCs made adequate computing power ubiquitous, enabling a wide variety of applications.*
- Early PCs were not designed to "be the best" at anything. They were simply *good enough* to do the task at hand.
- The PC succeeded primarily because of its *low cost* and because it was a relatively *open standard*. It knocked down the barriers to entry to the computing market. Hardware and software vendors quickly embraced it. For not too much money, users could do useful work with a PC.

# Part I: (cont'd)

- Turning our gaze to the heavens:

| Satellite Class | Cost w/Launch |
|---|---|
| DOD, NASA, ESA | $ 500M and higher |
| Geosynchs (e.g. satellite TV) | $ 200-500M |
| LEOs (e.g. Iridium) | $ 50-200M |
| Micro- and Nanosatellites | $ 5-50M |
| Picosatellites (e.g. QuakeSat) | $ 0.1-1M |

- The fact that picosatellites pool their launch opportunities is an important reason for $ 1-5M cost gap above.

# Part I: (cont'd)

- Picosatellites today vs. the PC industry in 1986:
  - Like the PC industry of 1986, the biggest satellites are around 1,000 times more expensive than the smallest ones.
  - Like early PCs, picosatellites have *modest high-tech content* and rarely use very high technology. Picosatellite designers tend to to use low-cost, commodity parts wherever possible.Yet the power, size and availability of commercial off-the-shelf (COTS) components to build a picosatellite still enable it to perform very useful applications.
  - Like the buzz that accompanied the arrival of the PC, picosatellites are generating a lot of *good press and interest worldwide*. Suddenly everyone has ideas for picosatellite missions.
  - Just as the PC provided a low-cost entry to computing, picosatellites provide a *low-cost entry to space*.

# Part I: (cont'd)

- How can picosatellites develop like PCs did?
  - By following *standards* and using *standardized software and hardware components* wherever possible.
  - Through short mission timelines, thereby introducing *new generations of picosatellites* every 2-3 years.
  - *Via cooperation throughout the picosatellite community*, particularly among the end-users / picosatellite builders. Sharing experience and technology will build a database with information, tools, designs and even parts that can be used by future missions.
- What does the future hold for picosatellites?
  - The technology that drives the PC market trickles down to the technology found in picosatellites. If picosatellites develop at only 1/100$^{th}$ the rate of the PC market over the next 20 years, we will still see a 10-fold price/performance improvement.
  - We can barely imagine what kind of technology will fit inside a picosatellite in 2025. But it will surely be impressive.

# Part II: The CubeSat Standard

- The CubeSat is a 10x10x10cm, 1kg public picosatellite design specification proposed by Stanford and Cal Poly San Luis Obispo universities in the USA.
- To date, low-earth orbit (LEO) CubeSat missions have had typical lifespans of 3-9 months.
- Cost to complete a CubeSat mission (inception to launch to operation to end-of-life) ranges from <$100,000 to $1,500,000, depending on a variety of factors.
- Working from a standard promotes rapid development and idea sharing
- Picosatellites are already a hot topic in aerospace. Worldwide interest is focused on CubeSats in particular, partly because they are becoming a *de facto standard*.

# Part III: CubeSat Mission Planning

- This is not the $10,000,000-and-up satellite market! *User expectations* must be adjusted accordingly.
- High percentage of potential end-users represented by educational organizations (universities and high schools) with *little aerospace knowledge or experience*.
- Timelines often allow *less than 24 months* from mission inception to launch.
- CubeSat projects should be kept simple in scope, *especially first missions*. Avoid feature creep.
- Good design takes time. Good *integrated* design takes even longer. *Buy as much as you can*, and design from scratch only when absolutely necessary.
- Even with a COTS approach, every mission will have a sizeable number of *unique requirements*. They will consume time and money – be sure to ask for help!

# Part III: (cont'd)

- CubeSats are comprised of various hardware and software subsystems. How mission-specific does each subsystem need to be?

| Component | Uniqueness | Comments |
|---|---|---|
| Structure | 3-4 | Constrained by CubeSat standard externally. Internals likely to be unique. |
| Electronics (C&DH) | 4-5 | Many options available. |
| Communications (COM) | 3-4 | History of using amateur radio. |
| Payload | 1 | Every mission is unique. |
| Power (EPS) | 2-4 | Primarily affected by payload and communications. |
| Environmental & Thermal | 2 | Dictated primarily by payload. |
| Attitude (AD&CS) | 2-4 | Dictated by orbit. Passive is easy. |
| Ground Station | 4-5 | Well-understood. |

1: most unique  5: most generic

# Part III: (cont'd)

- Note that there is very little that is completely generic in a CubeSat because of environmental and power requirements. But mission have flown with off-the-shelf generic components (e.g. consumer digicams) on-board and in ground stations.
- Uniqueness applies to both hardware *and* software.
- The more unique a component is, the less likely it can be purchased off-the shelf, and the more expensive (in time and money) it is likely to be to implement. Some vendors are beginning to address some areas (e.g. sun sensors) at low(er) price points.
- Therefore CubeSat mission planners should focus their resources on payload, power, environmental/thermal and AD&CS – the truly unique requirements of their mission.

# Part III: (cont'd)

- Building vs. Buying:
  - Advantages of building something from scratch:
    - Pride in building something yourself.
    - Educational experience.
    - Size / power / functionality requirements.
    - Exactly what you wanted.
  - Advantages of buying off-the-shelf components:
    - Much faster design & integration process.
    - Often cheaper, especially when time is factored in.
    - Effort is the same for 1 or 100 units.
    - Let someone else worry about the details.
    - You're not alone.
- A combination of these two approaches may be the best solution for your particular CubeSat mission.

# Part III: (cont'd)

- A COTS approach to building a CubeSat should:
  - Assure conformance to the CubeSat specification.
  - Enable easy integration of mission-specific components.
  - Accommodate a wide variety of user payloads and support high levels of mission complexity.
  - Have a low-power yet powerful architecture, since CubeSats are by nature low-power due to the available solar radiation (<1W for typical 10x10x10cm "1U" cube).
  - Be scalable, expandable and have a non-obsolescent modular architecture, thereby protecting the end-users' design & development investment in current and future missions.
  - Include a dedicated test & debug platform for laboratory development work, separate from flight hardware.
  - Use modular RTOS software to facilitate rapid development and reliable operation.
  - Result in launch-ready flight hardware.

# Part IV: The CubeSat Kit Design Cycle

- The CubeSat Kit is a low-cost *integrated hardware and software solution* for facilitating CubeSat design, development, debugging, test and deployment.
- The CubeSat Kit provides ready-to-launch hardware solutions for:
  - Structure
  - C&DH
  - COM
- The CubeSat Kit software provides an expandable multitasking software foundation for C&DH, COM and other on-board satellite applications.
- Its architecture is highly open-ended to accommodate a wide variety of additional user requirements.
- End-users are still responsible for their payload, EPS, antennas, AD&CS, testing and ground station.

# Part IV: (cont'd)


Figure 1: CubeSat Kit Contents

# Part IV: (cont'd)

- The CubeSat Kit *separates the laboratory environment from the flight hardware*. Design, development and debugging are all done on the Development Board without the constraints of working inside a 10x10x10cm box. This protects the expensive flight hardware, provides a better test environment, and promotes a modular design.
- The modularity of the development environment – both in terms of hardware and software – means that various CubeSat subsystems can be developed, debugged and tested in independently and in parallel, thus greatly shortening mission timelines.

# Part IV: (cont'd)

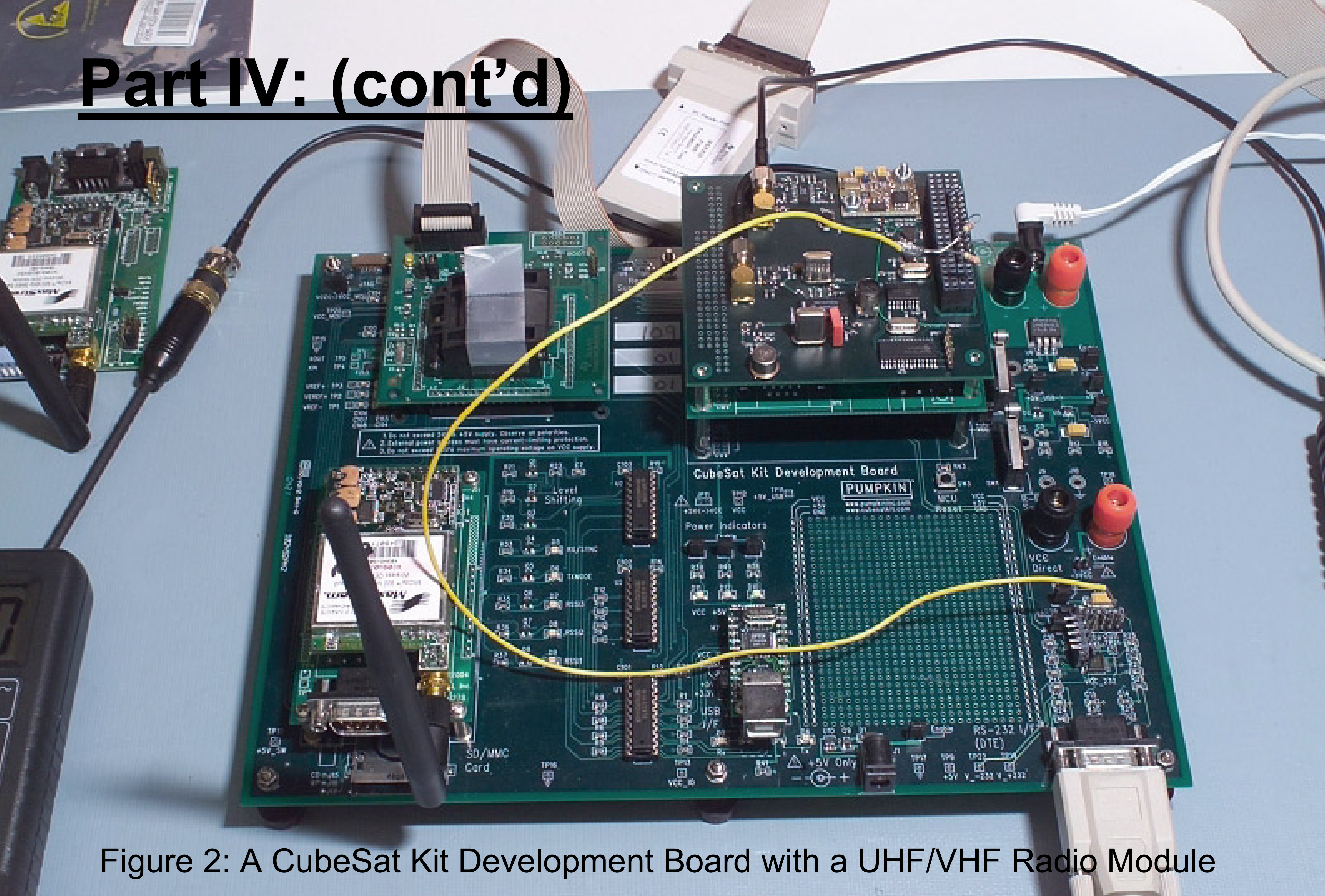


Figure 2: A CubeSat Kit Development Board with a UHF/VHF Radio Module

# Part IV: (cont'd)

- The CubeSat Kit Rapid Design Cycle:
  - Develop *user hardware modules* (e.g. EPS, payload) *that plug into CubeSat Kit Bus*. Each module performs a single function and can be tested independently of the others, or all together. Use CubeSat Kit software as the foundation for mission-specific software (e.g. C&DH, supervisor) to run on Development Board. Design external components (e.g. antennas, solar panels) and test with them.
  - Once the hardware design is tested and working with software, integrate multiple functions onto single user modules if volume & mass budgets require this. *This requires no changes to the software.* Test and iterate back through Step 1 if required.
  - *Copy software to the Flight Module and move user modules and external components from the Development Board to the Flight Model.* Test and iterate back through Steps 1 & 2 if necessary.
  - Submit CubeSat to launch facility for final test & integration.
  - Launch. Communicate with CubeSat via ground station. Deorbit to end mission.

# Part V: The CubeSat Kit Architecture

- CubeSat Kit architectural details:
  - The CubeSat Kit's FM430 architecture has drop-in COTS support for multiple channels of communications, along with software to run C&DH and COM tasks.
  - The on-board Flight MCU is powerful enough to run many of a CubeSat's subsystems. Yet it operates at very low power levels, enabling continuous 24x7 satellite operation.
  - Helpful additional features like mass storage and USB are already implemented.
  - The CubeSat Kit Bus provides unlimited flexibility for connecting to user modules and/or additional on-board processors.
  - Multitasking Salvo RTOS software facilitates rapid and independent development of CubeSat subsystem applications.
  - Very high-level software development tools (compilers, IDEs, debuggers) are available.

# Part V: (cont'd)

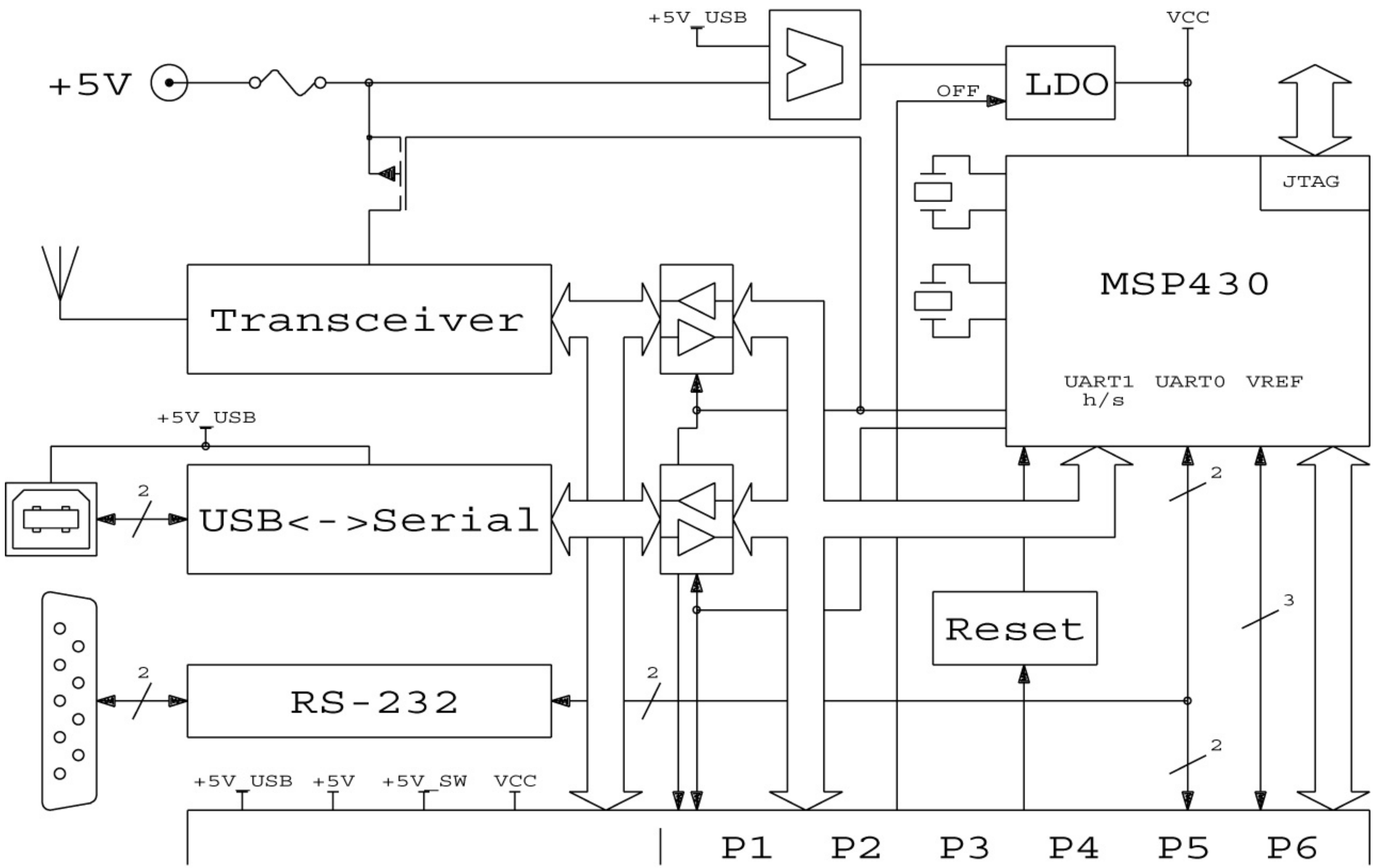


Figure 3: FM430 Flight Module Block Diagram



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# Part V: (cont'd)

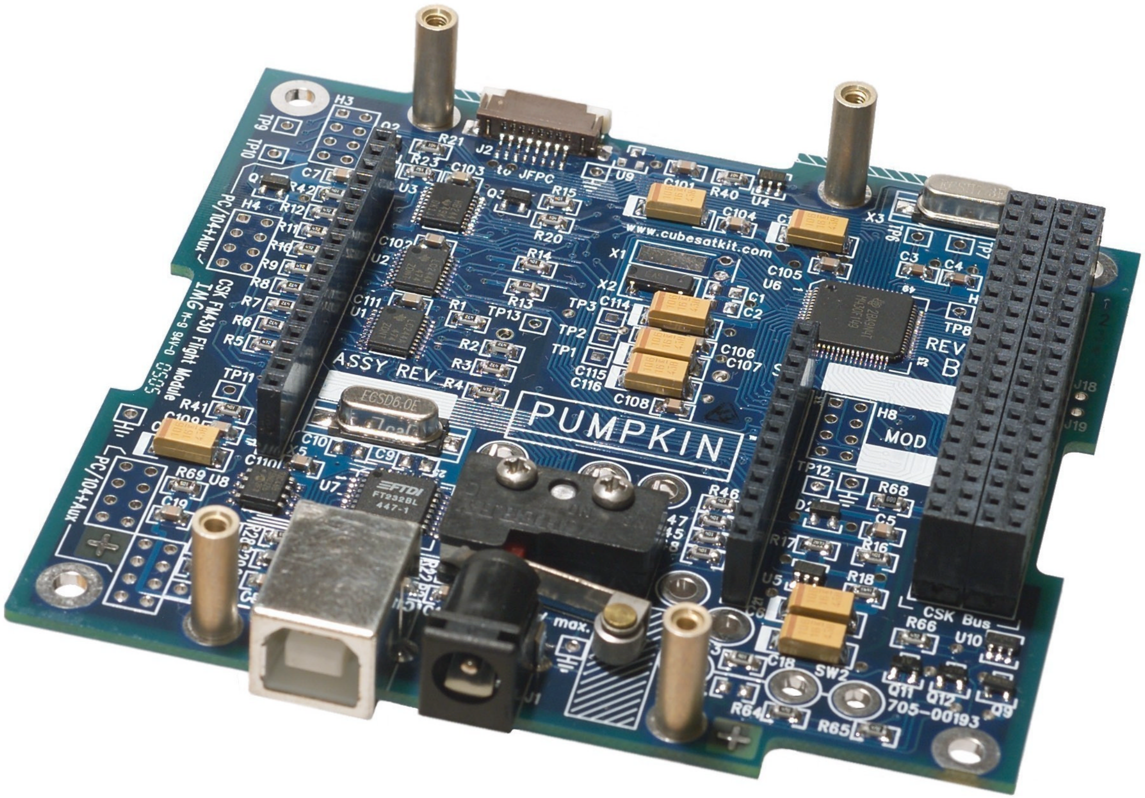


Figure 4: FM430 Flight Module Rev B

# Part VI: The CubeSat Kit's Structure

- The CubeSat's mechanical structure is constrained by exterior dimensions, defined access area and other requirements in the CubeSat specification. We chose an Aluminum sheet-metal design for strength, light weight, low cost, maximal internal volume and design flexibility.
- A module bussing scheme patterned after the PC/104 standard was chosen for interconnecting modules and connector reliability.
- ½U, 1U, 1½U, 2U and 3U sizes differ only by a single part – the chassis walls assembly.
- A 1U CubeSat Kit has over 30% of its mass and 40% of its internal volume available for a user payload.

# Part VI: (cont'd)

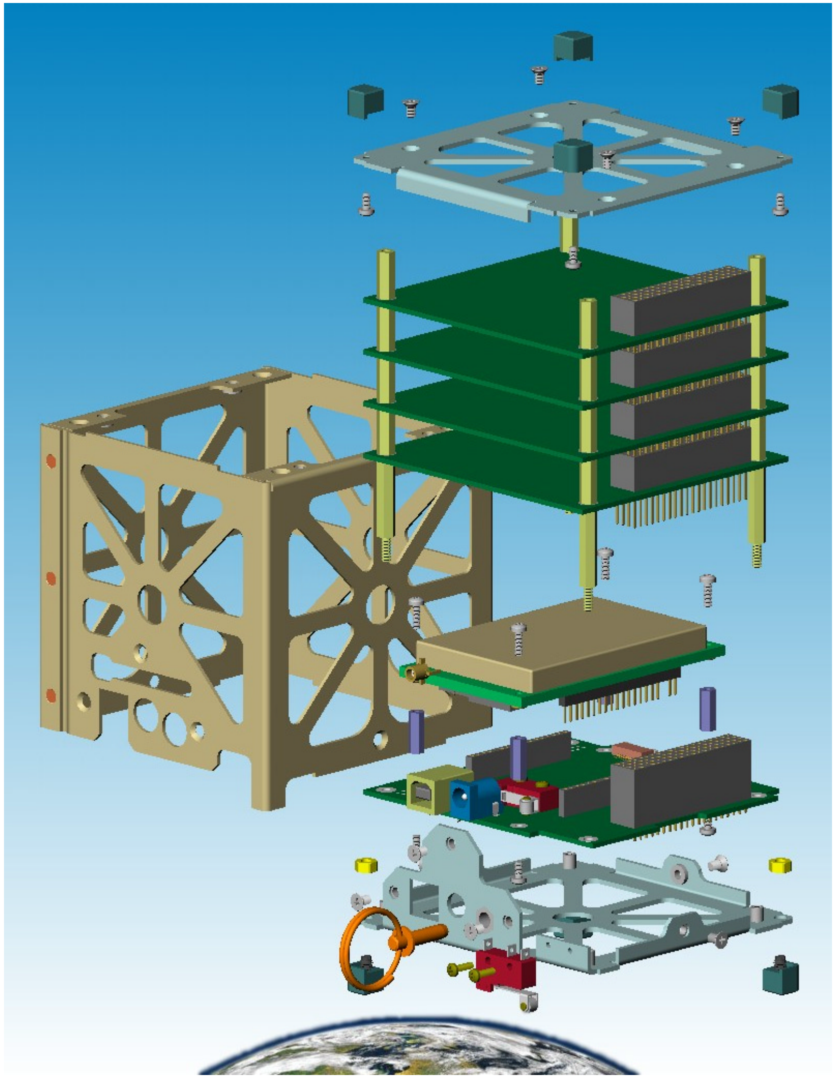

Figure 5: Exploded View of a 1U CubeSat Kit.

Clockwise from center left: Chassis Walls Assembly, Cover Plate, User Module Stack, High-Frequency Transceiver, FM430 Flight Module, Base Plate.

# Part VI: (cont'd)

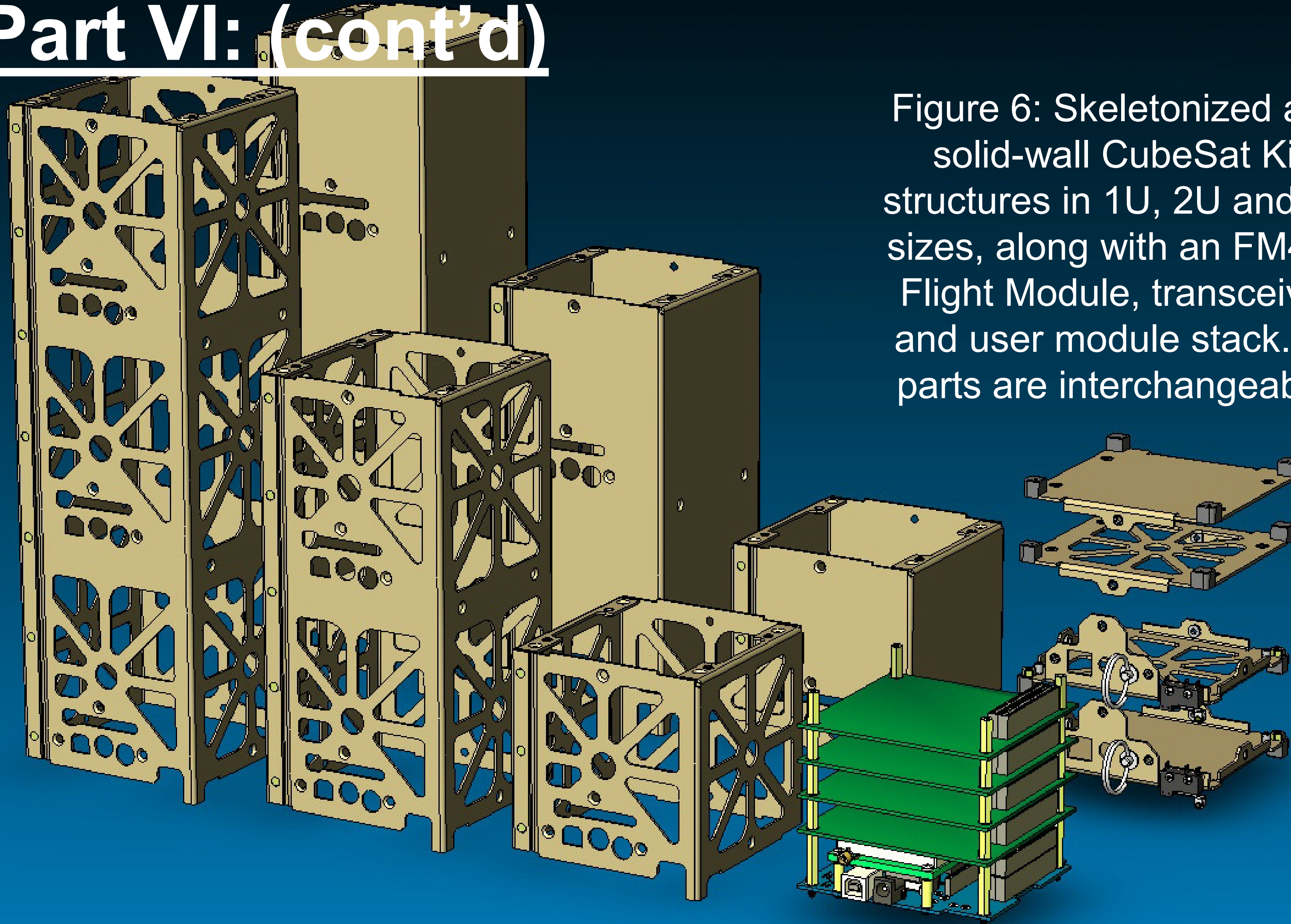

Figure 6: Skeletonized and solid-wall CubeSat Kit structures in 1U, 2U and 3U sizes, along with an FM430 Flight Module, transceiver and user module stack. All parts are interchangeable.

# Part VI: (cont'd)

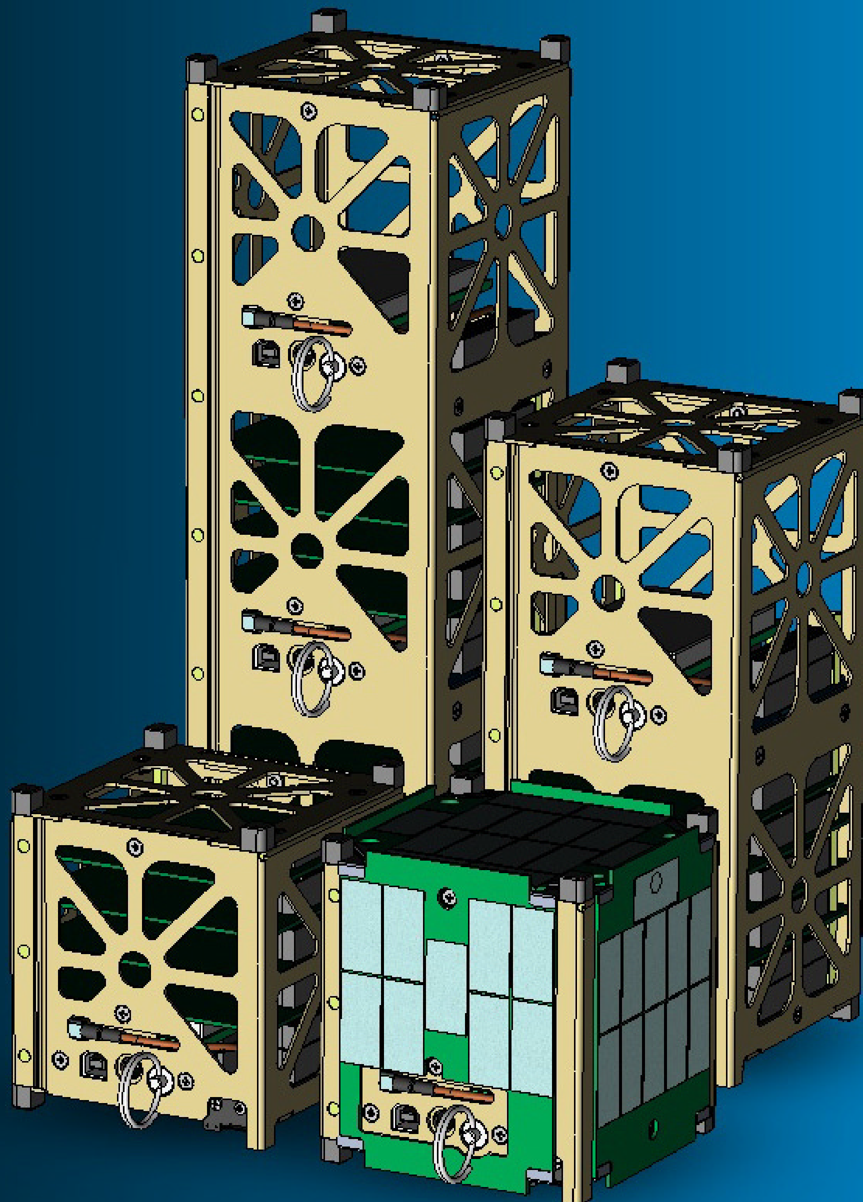

Figure 7: A Collection of 1U, 2U and 3U skeletonized CubeSat Kits with module stacks of different sizes. One is also fitted with user-supplied solar panels.

# Part VII: Real-world Experience

- Previous CubeSat mission timelines have stretched over 2-4 years. Some never launched. All designed major portions (esp. the structure) from scratch. *Larger budgets and more manpower have not necessarily meant shorter timeframes.* Student-led projects tend to slip the most.
- *"Re-use, don't re-invent"* mantra is gaining adherents. The CubeSat Kit saves 6-18 months of mission time.
- Over 25 CubeSat Kits are in customer hands. This makes the CubeSat Kit *the largest single installed base of common CubeSat hardware in the world*.
- Some CubeSat Kit customers are designing *their second CubeSat mission*, this time with the CubeSat Kit. They appreciate a la carte ordering of picosatellite components.

# Part VII: (cont'd)

- The CubeSat Kit has passed preliminary testing in customer hands. First launches are expected in 2006.
- Some CubeSat Kit customers have moved from 1U to 3U structures as the scope of their project has grown.
- Various third parties are now developing CubeSat components specifically for the CubeSat Kit.
- Several multinational and multi-organizational projects have CubeSat missions based on the CubeSat Kit.
- Launch opportunities are still somewhat limited. Launch costs have remained at $ 30-40K / kg.
- Sharing amongst CubeSat Kit customers is still in its infancy.

# Part VIII: Summary

- Like the PC, *picosatellites will develop rapidly* in the next few decades because of their short lifespans, low cost, and designs based on commodity technologies.
- Your mission and payload are already unique – the rest of your picosatellite need not be. *Focus your efforts on the unique aspects of your mission.*
- Modest mission goals will help ensure success. Budget constraints are a reality. *Avoid complexity* wherever possible. You must make your launch date on-time.
- *Use available hardware and standardized software* wherever possible. The CubeSat Kit will help.
- Reach out to other picosatellite developers to share information, experiences, hardware and software as part of a *global picosatellite community*.

# Notice

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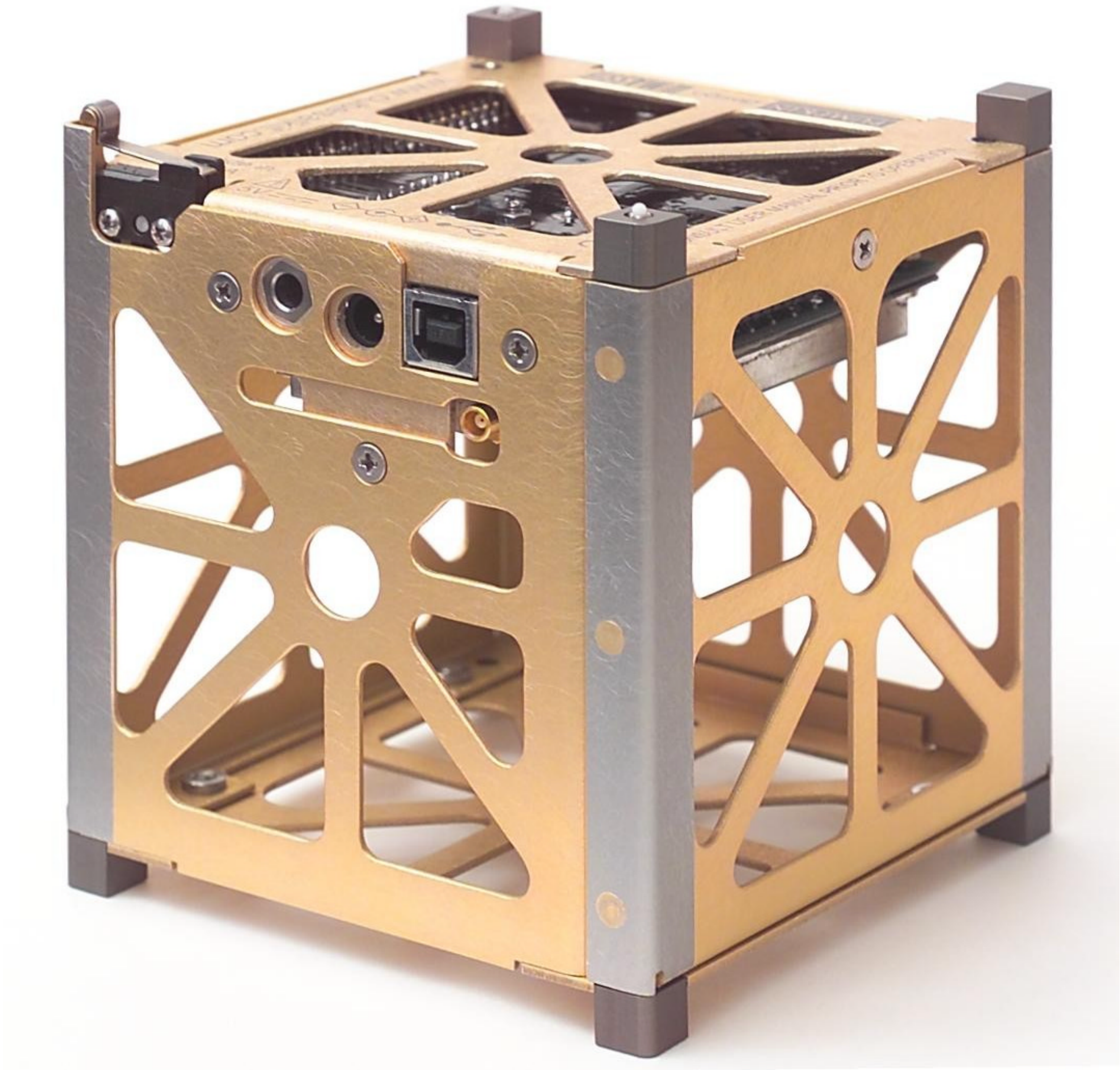

Q&A Session

Thank you for attending this Pumpkin seminar at the GNSS Workshop for the Americas 2005!

# Notes & References


1. Desktop PC prices based on PC's Limited AT 286-12 purchased by the author in 1986, and Dell Computer promotions for Dell Dimension 2400 desktop with Windows XP Home from September 23-28, 2005. In 1988 PC's Limited changed its name to Dell Computer Corporation.
2. IBM mainframe history at http://www.thocp.net/hardware/mainframe.htm.
3. Iridium program history at Wikipedia http://www.en.wikipedia.org.
4. *CubeSat Kit User Manual*, Pumpkin, Inc. 2005.
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# Appendix

- Speaker information
  - Dr. Kalman is Pumpkin's president and chief software architect. He entered the embedded programming world in the mid-1980's. After co-founding the successful Silicon Valley high-tech pro-audio startup Euphonix, Inc. he founded Pumpkin with an emphasis on software quality, performance and applicability to a wide range of microcontroller-based applications. He holds two United States patents, is a consulting professor at Stanford University and is invariably involved in a variety of hardware and software projects.
- Acknowledgements

  - Stanford Professor Bob Twiggs' continued support for the CubeSat Kit, and his input on enhancements and suggestions for future CubeSat Kit products, are greatly appreciated.

- Salvo, CubeSat Kit and CubeSat information
  - More information on the Pumpkin's Salvo RTOS and Pumpkin's CubeSat Kit can be found at http://www.pumpkininc.com/ and http://www.cubesatkit.com/, respectively.
  - More information on the open CubeSat standard and the CubeSat community can be found at http://www.cubesat.info/.
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