Enhanced Power Systems for CubeSats

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CubeSat Power

- Important components and driving forces:
    - Power collection (solar panels)
    - Power conversion (EPS)
    - Energy storage (batteries)
    - Power distribution (unregulated & regulated busses)
    - Topologies (battery chemistry, solar cells, electronics)

Solar Panels

- Space industry at the forefront of improving solar cell efficiency … 28% rigid TJ cells the norm in CubeSats
- CubeSats limited by available surface area
- Only a few COTS solar cell form factors are suitable for use in CubeSats
  - Cells that are too big simply don't fit (short of cutting them down to size – not recommended)
  - Cells that are small enough to fit incur additional assembly costs, reliability concerns and mass and area-coverage penalties
- No trivial way to combine multiple, dissimilar solar cell strings into a single array on a CubeSat because:
  - Strings in different orientations will have different power outputs
  - Diode ORing strings requires them to be voltage-matched
  - Each cell's strings must be closely current-matched

Batteries

- CubeSats flocked to Li-Ion battery chemistry (3.7V nom.)
  - Advantages:
    - High specific energy, energy density & specific power
    - Traditional CC / CV charging algorithm
    - Low price
    - Low self-discharge
    - Ubiquitous
  - Disadvantages:
    - Narrow operating temperature range (e.g., needs heaters to charge below 0C)
    - Requires OC, OV and UV protection against fire and other hazards
  - Usable over a range of 4.2V down to 3.5V or even 3V
  - Other issues
    - Li-Po (flat, prismatic, bag) vs. Li-Ion (cylindrical, case)
    - Leverage consumer protection strategies or develop “space-grade?”

Operating Voltages

- Initial (ca. 2000) concepts were 5V-centric
    - Assumed 5V SBCs & PC/104 would be popular (e.g. QuakeSat)
    - 5V microcontrollers were still reasonably common
    - Many peripherals, radios & sensors had +5Vdc supplies

    ∴ a 5V power bus became a core component of many CubeSats
- But 3.3V was also quite popular …
    - Microcontrollers were overwhelmingly moving to 3.3V operation
    - Logic families, too … (supported wide operating ranges)
    - Not a panacea. E.g. not well-suited to e.g. radio Tx stages

    ∴ 3.3V components became increasingly common in CubeSats
- Higher voltages?
    - Solar panels: theoretically available as source, but practically only used to charge batteries
    - HV generated locally via step-up converters, etc.
    - No simple integration of 28V bus

Voltage Translation

- Some devices operate only at a single voltage, e.g.
  - SD Cards: Spec requires 3.3V
  - Radios: May have logic-level I/O but high-power Tx stage
  - Simple Li battery chargers (at +5V in)
- Solution: local, point-of-load regulation + level translation
  - Low-power, low-duty-cycle devices well-suited to LDOs
  - Zero-power active translation and isolation circuitry is available. Pumpkin CubeSat Kit architecture servos all attached MB devices (e.g., USB, SD Card, radio) to PPM’s VCC over a 5.0-2.0 Vdc range.

Voltage Conversion

- Linear regulators
  - Low Dropout (LDO) Regulators at sub-0.3V dropouts
  - Simple
  - Quiet
  - The larger V_{IN} - V_{OUT}, the less efficient
- Switching dc/dc converters
  - Step-up (boost), step-down (buck) and step-up/step-down (boost/buck, SEPIC)
  - More complex – higher parts count
  - Noisy (but some can be synched together)
  - The larger V_{IN} - V_{OUT}, the more efficient
- Most devices have a sweet spot for operating, performance deteriorates when deviating from the optimum

Small-cell Solar Panels

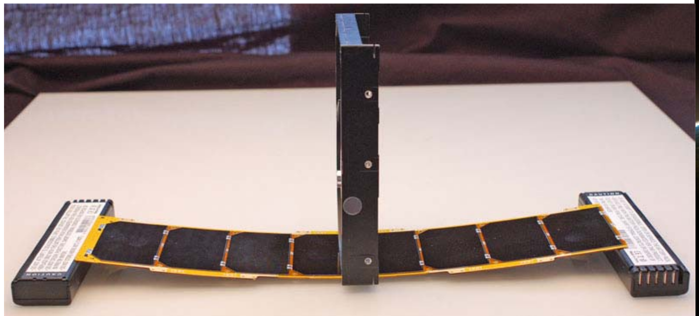
- Small, individual solar cells (e.g., TASC)
  - Low-budget approach to solar panels
  - Not provided as CIC – require glass and interconnects
  - Small size means many options for fitting on sides of CubeSats
  - 4-, 8-, 12- and maybe even 16-cell strings possible
  - Was very labor-intensive to build, now treated as SMT parts
- Examples: CINEMA, TJHS, PhoneSat 2
  - Fill Factor: 50-60 % (?)
  - Specific power: 55 W/kg (?)
  - Stowed volume efficiency: 50 kW/m^3 (?)
  - Cost: <50 \$/W *for cells only* (no I, no C, no labor & other materials)

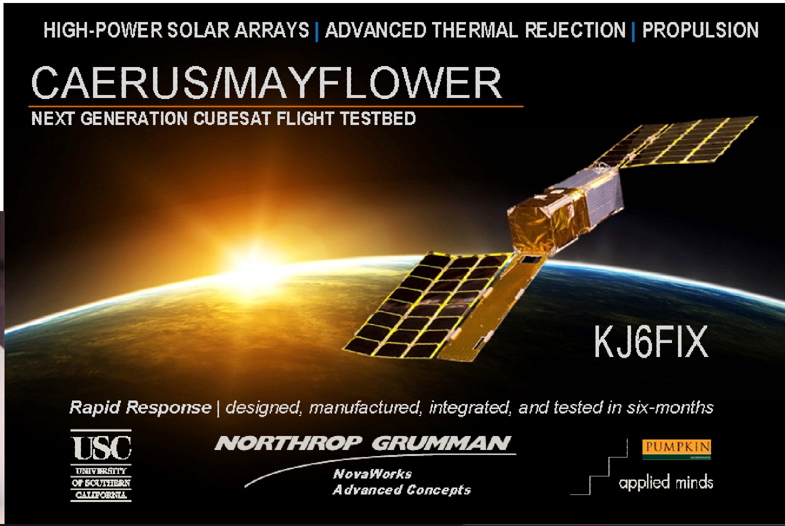
Large-cell Solar Panels

- Large (e.g., 40x70mm, 26.62cm^2, 1W BOL) individual solar cells
  - Good area coverage, minimal number of interconnects
  - Competing with the LORALs etc. for cells on open market
  - Narrow enough to fit on sides of CubeSats, leads to 2-/4-/7-cell strings on 1/2/3U CubeSats faces, respectively
  - 1U CubeSats: V_{OC} = 5V, requires boost to charge 2 Li cells
  - 2U & 3U CubeSats: V_{OC} = 10 & 17.5Vdc, requires only buck converters for 2-cell batteries when well lit, boost/buck adds some charging capability when poorly lit.
- Example: Pumpkin PMDSAS v5 7-cell panel 710-00772
  - Fill Factor: 70 %
  - Specific power: 93 W/kg ~ 10g/W
  - Cost: 800-1200 $/W

Large-cell Solar Arrays

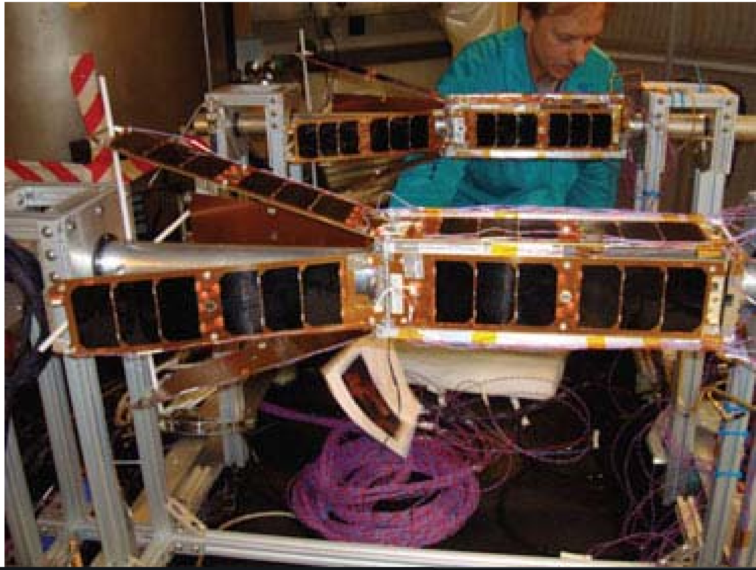
- Large (e.g., 26.62cm^2) individual solar cells
  - Good area coverage, minimal number of interconnects
  - Competing with the LORALs etc. for cells on open market
  - Can fit up to 8 cells per panel on a 3U deployed array
  - V_{OC} = 20 Vdc, good headroom over typical battery and operating voltages
- Example: Pumpkin PMDSAS v3 “Turkey Tail” array
  - Area coverage: 76 %
  - Specific power: 89 W/kg ~ 10g/W
  - Stowed volume efficiency: 142 kW/m^3
  - Cost: 1700 $/W





CubeSat Power Trends

- Early CubeSats (esp. 1Us) had little power, and so had to be as efficient as possible. Served by simple multi-channel EPS.
- In 2010 3Us really hit their stride, and demonstrated the utility of the Colony-class recipe: payloads of 1500cc volume and ca. 10W. Extension of panel-based EPS.
- Pumpkin's solar array work has raised CubeSat power past the 50W class … 70+W arrays are available now.
- Pumpkin's goal with CIC is 5g/W.



Resultant Power Topologies

- Fixed solar panels
  - Multi-channel EPS
  - Boost/buck topologies required for end panels & USB charging
  - Max. 3 converters required (+X/-X, +Y/-Y, +Z/-Z)
  - Panel topology and regulated outputs driven by battery voltages, with some flexibility
- Deployable solar panels
  - Extension of fixed-panel scheme
  - Either higher power or more channels, depending on panel orientations
- Solar Arrays
  - Simpler, high-power EPS for entire array
  - 8SNP topology demonstrates practical & efficient cell layout … $20V_{OC}$ drives downstream circuit and battery choices, offers flexibility beyond 7.4V Li-based batteries

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Q&A Session

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Appendix

- 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 several United States patents. He is a consulting professor in the Department of Aeronautics & Astronautics at Stanford University and directs the department's Space Systems Development Laboratory (SSDL). Contact Andrew at aek@pumpkininc.com.

- Acknowledgements
  - Pumpkin's Salvo, CubeSat Kit and MISC customers, whose real-world experience with our products helps us continually improve and innovate.

- CubeSat Kit information
  - More information on Pumpkin's CubeSat Kit can be found at http://www.cubesatkit.com/. Patented and Patents pending.

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