Electronics for Satellite Experiments

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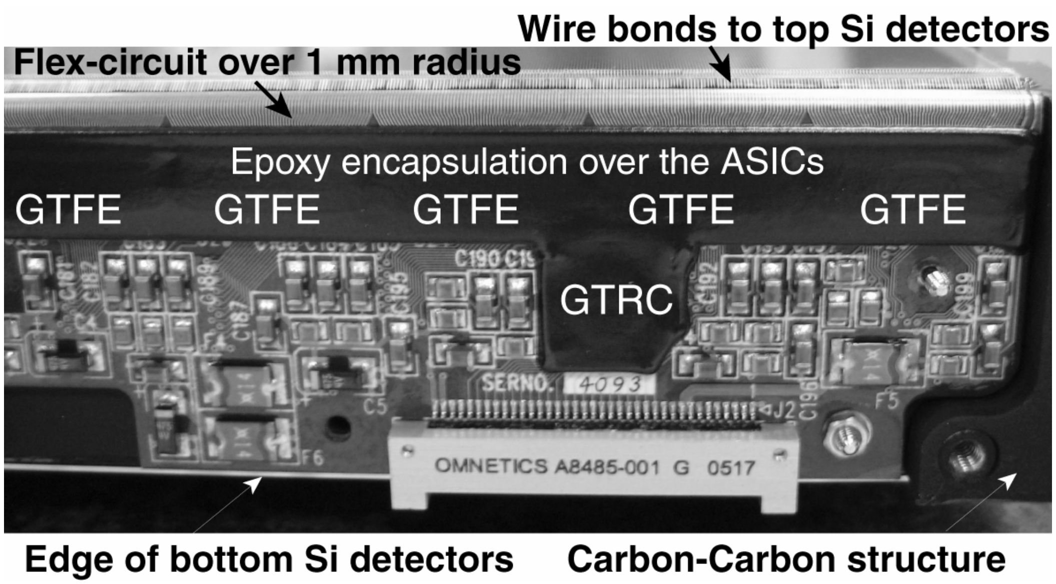
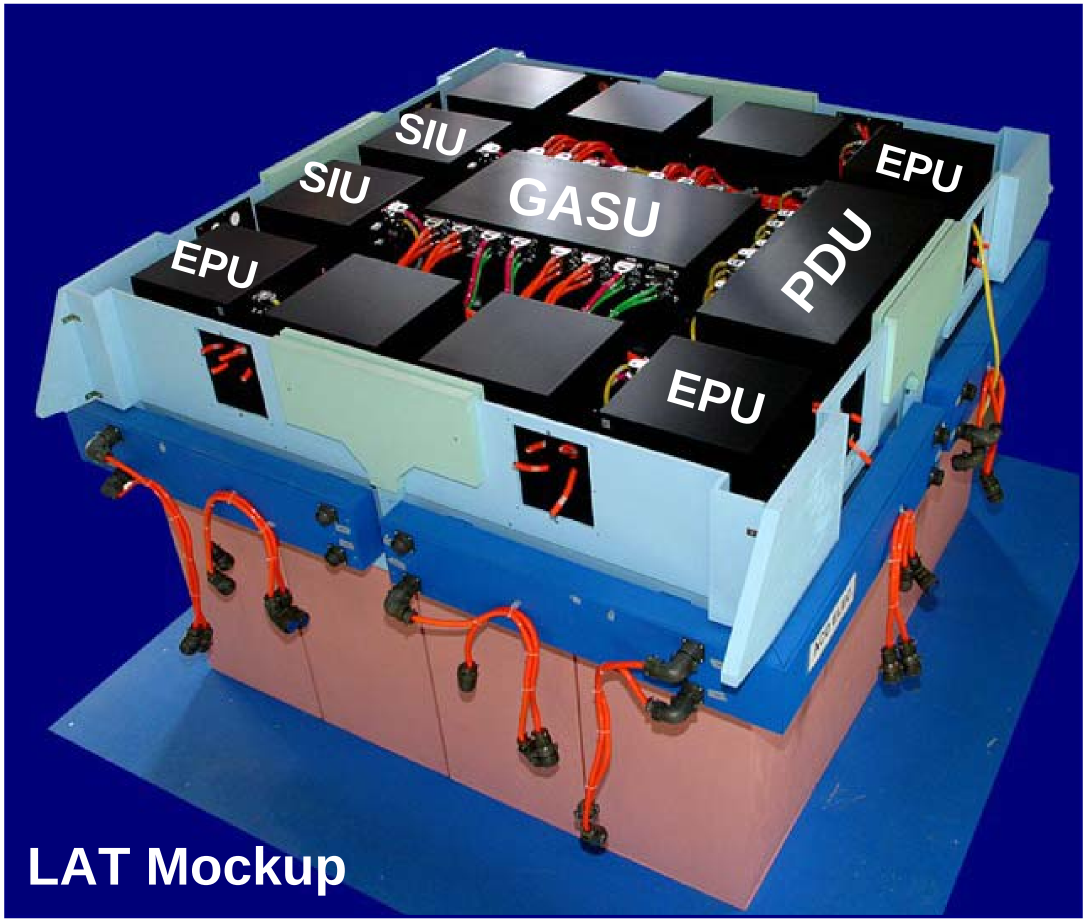
Introduction

- My personal experience in this field is in designing, fabricating, and testing the GLAST LAT Tracker front-end electronics.
  - 576 chip-on-board circuit boards, each with 26 ASICs
    - Non-standard right-angle interconnect, employing a flexible circuit bonded to a radius milled into the circuit board
    - 884,736 amplifier channels
  - Long (~1 meter) 4-layer flexible-circuit cables
  - Two-layer flexible bias circuit



Introduction

- I have also sought input from engineers in the SLAC electronics group who have been heavily involved in the design and fabrication of all of the LAT electronics.



Design Constraints

- Power:
  - Total instrument power the order of 1 kW or less (650 W for LAT).
  - Plan to use 20% to 30% for power conditioning!
    - Space power supplies tend to be behind the technology curve; for example they still usually don't use synchronous rectification.
- Cooling:
  - No fans!
  - Use passive cooling paths. Need solid, reliable joints.
  - Do the mechanical engineering well up front, not an afterthought!
- Environments:
  - Thermal-vacuum cycles, vibration and acoustics, EMI/EMC.
- Reliability:
  - Plan on no maintenance once a system is delivered to "Integration and Test."
  - Redundancy is desired, but it can quickly become expensive and complicated.
    - Be sure that the redundant hardware can be turned on or reconfigured after the primary fails!

High Technology

- NASA seems to be generally very conservative about use of new technologies
  - Using items with "flight heritage" is by far the easy route, so if there is no compelling reason to use the latest high-tech widget, don't do it.
  - But, it appears that this inertia has resulted in many space technologies looking primitive by commercial or military standards.
- Even where modern technology may have been used in some instances of space flight, you may still find that there is no NASA-accepted standard ready for general use.
  - For example, there is no modern network standard available for space applications, compared with many choices in the commercial world.
  - MIL-STD-1553, developed in the 1970s, still seems to be the standard.
- The best space-qualified computer will have performance far inferior to that of your personal notebook computer, but the price tag of a mainframe ($250,000 for each LAT computer).
- *Nevertheless, if a specific new technology is what makes your science possible, then NASA will work with you to qualify it.*

Low Power Design

- GLAST relies heavily on ASICs to achieve low power
  - FPGAs will use more power, as well as require more space
- The LAT Tracker front-end readout design evolved from the BaBar SVT electronics
  - LAT: 180 microWatts per channel, including all digital activity
  - SVT: ~4000 microWatts per channel
- But this achievement did not involve any new technology or special tricks.
  - Requirements of lower clock rate (20 MHz), longer shaping time helped, and relatively low radiation levels helped.
  - Making the SSDs thicker (400 microns instead of 300) helped relax the requirements on noise performance.
  - But major reductions were also achieved through simplification:
    - Only 2 stages in the amplifier (simple RC/CR) shaping.
    - Simple discriminator on each channel. Time-over-threshold only on the OR of all channels in a layer.
    - Commercial non-rad-hard 3.3 V CMOS process (run at 2.65 V)

Parts and Materials

- Don't assume at proposal time that your instrument can use non-qualified parts!
  - The LAT Tracker front-end boards number 576, and a loss of any one of them has a small impact on the mission.
  - Nevertheless, in the end NASA Code-300 (Mission Assurance) made sure that we built them with expensive parts.
- Limited choice of already qualified parts
  - See http://nepp.nasa.gov/npsl/ and http://www.dscc.dla.mil/
  - Good choice of R and C (SOA is particularly good quality)
    - NASA overstress requirements likely will mean that you get less C in a given package size than you are accustomed to.
    - Package sizes are unusual (e.g. SMT 0505 chip resistors).
    - Keep this in mind when you prototype with cheap commercial parts!
  - The list of qualified microcircuits is relatively new, very small, and a very far cry from what you may be used to in the commercial world.

Parts and Materials

- Qualified parts are expensive!
  - 100-Ohm 1% 0505 SMT QML/QPL resistor: $0.78
  - 100-Ohm 1% 0805 SMT commercial resistor: <$0.02
- Plan on a lead time of 12 to 26 weeks for qualified parts!
- Don't assume that "Space Qualified" parts are necessarily the highest intrinsic quality!
  - Modern commercial parts can have extremely high quality, due to a philosophy of engineering high reliability into a high-tech commercial mass manufacturing process.
    - Cost is paramount in commerce, but high quality parts can be essential for maintaining low production cost.
  - But NASA tradition relies more on part-by-part inspections, screening, and traceable records, usually for very low-volume production.
  - The large-volume commercial manufacturers generally don't want to be bothered with that.
  - *In any case, the main thing is to do whatever testing is needed to make **you** sure that the part is going to perform and survive in **your** application and environment!*

Parts and Materials

- Qualifying a commercial part yourself can be done, especially if the manufacturer is cooperative.
  - We did this in the LAT Tracker for the Tycho-Raechem poly-switches.
    - Great cooperation from Raechem. They provided extra screening and thermal cycles, the parts were of excellent quality, and they were the cheapest parts in the Tracker!
    - Not sure Raechem would do the same again, however.
  - Probably we should have done it for the HV caps:
    - Instead we found a manufacturer willing to do it, at high cost.
    - But the manufacturing was crude and quality low compared with what we probably could have obtained from larger manufacturers who were not willing to do the qualification.
  - But count on an FTE for several months for each part!
- Prohibited materials: cadmium, zinc, or pure tin plating.
  - Whisker growth.

FPGAs

- Huge cost/performance price for SEU hardened FPGAs
  - LAT Actel FPGAs: $4k to $5k for 2k flip flops (up to about 10k flip flops now available).
    - Built-in triplication in every flip-flop to avoid upsets.
    - Configuration is hard burned into the device (got to get it right 1st time!).
  - Commercial SOA: $1k to $2k for 50k flip flops plus embedded processor and built-in fast serial I/O channels.
- NASA reviewers focus particularly on two design areas:
  - Power-on resets: are they guaranteed to work in all conditions?
  - Clocking: they strongly prefer use of alternate-edge clocking in registers and between registers
    - Quickly chews up the few gates available in these devices and lowers performance. (LAT programs just barely fit, with little margin.)
    - (In fact, in the LAT FPGAs, only 1 of the 3 global clocks available is good enough quality to use for shift registers without alternate-edge clocking.)
- Alternate approach: use semi-rad-hard, higher-performance parts and use special software to implement triplication.
  - This still leaves an issue that the configuration program loaded into SRAM is vulnerable. Solve by reloading it frequently.

ASICs

- The LAT ASICs caused some heartburn for NASA.
  - Just the Tracker alone has 14,976 chips installed (and functional!), which is *unprecedented for space flight*.
  - But in retrospect this was probably the most trouble-free part of the Tracker electronics manufacturing.
  - MOSIS/Agilent provided excellent quality, but MOSIS will not provide any special QA documentation and certificates beyond what they provide with every shipment to every customer.
    - In the end NASA accepted a written procurement specification that detailed exactly what MOSIS does, without insisting on any modification to MOSIS' normal procedures.
    - And in the end NASA did not insist on any source inspections of Agilent facilities, which almost certainly would have been impossible.
- The LAT became responsible for qualification tests.
  - Qualification environmental testing for Tracker ASICs was done only at the module level. (*Really no issue for bare chips*.)
  - NASA is very cautious about PEMs (plastic encapsulation), but more and more there is no alternative. *Must test thoroughly.*
  - Radiation testing for total dose (~10 kRad) and for single-event latchup (never observed) and upset.

Circuit Boards

- Coupon testing is heavily relied upon. NASA likely will insist on doing coupon tests themselves, in parallel with the manufacturer tests.
  - Many boards passed by our GLAST manufacturers were rejected by NASA. They have very stringent requirements on plating of vias and will not budge from them.
    - Minimum 2-mil annular rings around the entire circumference.
    - 100% connection of the barrel plating to the internal plane; no voids!
  - We got into trouble in the Tracker with both rigid and, especially, flexible boards by making designs that were aggressive on space, making it very difficult for even good manufacturers to meet the NASA requirements.
- NASA is especially leery of flexible circuits.
  - Early on we considered their fears to be behind the times, but…
  - We dug a deep hole with the Tracker cable design that was very expensive to climb out of, and just barely in time!
- NASA will require the boards and/or coupons to go through a battery of thermal and humidity tests to be qualified.

Connectors and Cables

- Don't procrastinate on the cable and interconnect design, as it can be the most troublesome.
  - A full-fidelity cabling mockup is highly recommended.
- Expect to use more rugged and more expensive connectors than you would normally see in HEP.
  - $100 or more for each mated pair.
  - You can probably count on $2k to $4k per cable.
  - Circular connectors are the best, if you have the space.
- Mate-demates
  - Every mate/demate of flight hardware must be logged.
  - Safe-to-mate tests are mandatory for flight hardware.
  - Despite common myths that we've heard, in fact there is no hard NASA limit on the number of mate/demates allowed.
    - Nevertheless, connector savers are recommended.

Manufacturing

- Make sure your design is manufacturable to NASA standards early in the game, especially if you need volume production!
  - Be sure that your prototype is not manufactured in a manner that won't be practical for the larger volume.
  - Make sure that your prototype gets subjected to all the quality controls that the flight production will see. This extra early expense will pay off later.
- Get a good manufacturing engineer with space-flight experience involved early on in the project.
  - The LAT Tracker suffered from going too far with the design and prototyping before having such an engineer involved.
  - The Tracker probably could have made good use of such an engineer 100% time for a year or two, but we had to share with the entire project.
- Get a good EEE parts engineer involved early on in the project.
  - The LAT probably could have benefited from having such an engineer at SLAC, instead of on the East Coast.

Assembly

- Even aerospace vendors tend to want to work to IPC specs, not NASA specs.
  - You'll have to supplement the IPC specs with a few more stringent requirements that NASA insists on and then get NASA buy-in.
- Don't relax just because the vendor has experience with space or military hardware! That is no guarantee that they will adhere to NASA requirements or deliver quality to you.
  - NASA will want their QA people to survey the vendor, and this can be useful if you make the best of it.
    - NASA quality engineers are acutely aware of many details that have burned them before (such as silicone adhesive on masking tape, to take a painful example from LAT Tracker experience).
  - Keep an engineer or physicist at the vendor's site as much as possible, on the manufacturing floor watching every detail.
    - It is best if they have a vested interest in success of the project and always remember whom they are working for.
    - Too often, the vendor's QA people spend most of their time pushing paper, not watching what is happening on the manufacturing floor.
  - Test and inspect the assemblies 100% yourself, on site at the vendor or asap after delivery.

Conclusion

- Do take into account from the outset the increased costs necessary for parts and quality assurance.
- Do not expect to find a clear-cut, complete set of cookbook rules that you must follow in order to satisfy NASA.
- But a common-sense approach will produce good results and get you through the bureaucracy:
  - NASA is not really ISO9000, but you can win them over if you
    - Clearly document *your* requirements at the outset.
      - Don't make "goals" into "requirements"!
    - Clearly document *your* manufacturing and test plan.
    - Get their approval on the plans.
    - Keep complete records that your assemblies satisfy the documented requirements.
  - Plan for success in your official tests, because failures are likely to bring you much more "help" than you ever wanted.
  - ***You are the #1 person who must be satisfied that the circuit will be reliable, so do your best to make use of NASA to help you achieve that goal.***