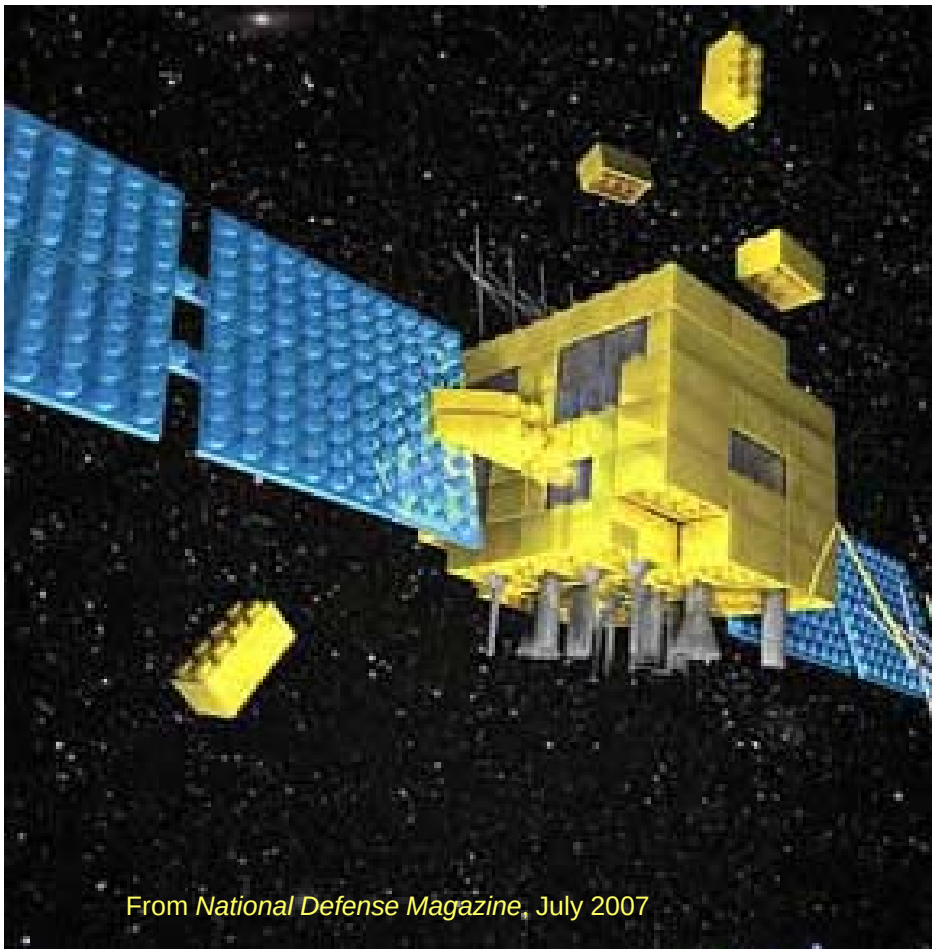
The Six-Day Spacecraft: Creating a Plug-and-play approach for aerospace systems


From *National Defense Magazine*, July 2007

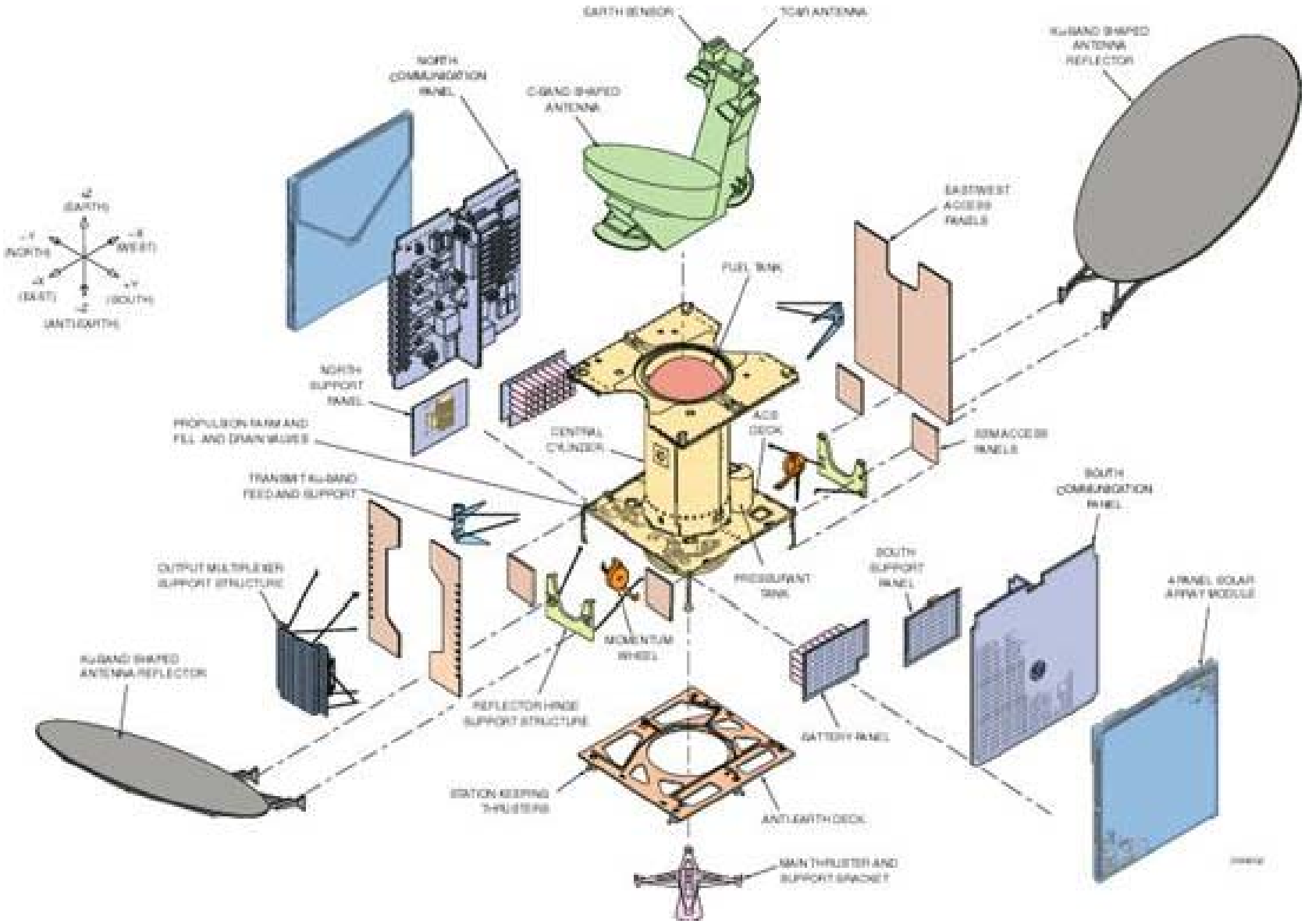
James Lyke
Air Force Research Laboratory
23 September 2008

Problem Formulation

- **Create a spacecraft in less than one week**

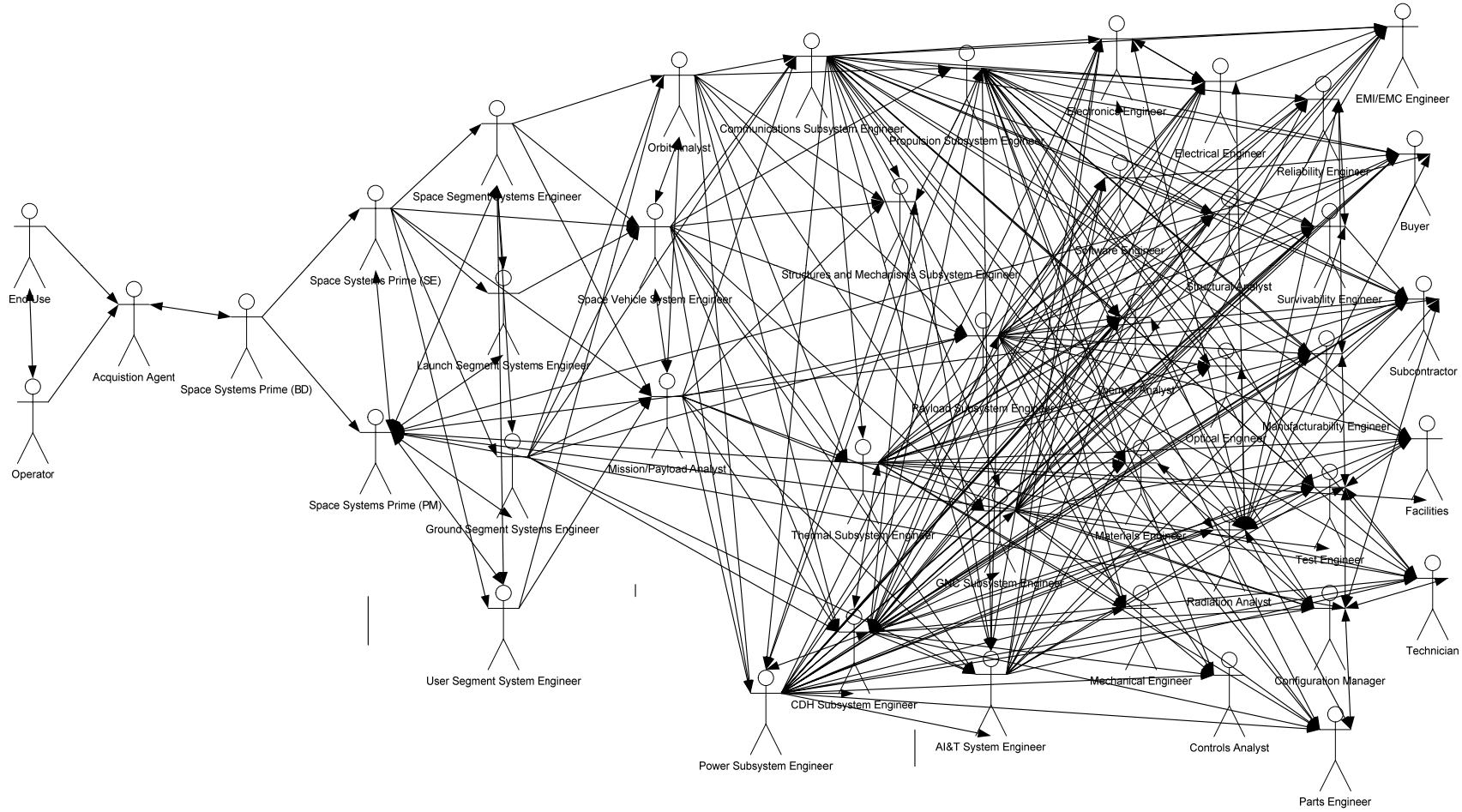
Days Instead of Years….

- Cannot be achieved by “tweaking” existing processes
- Requires fundamentally new approaches
- Standards are not enough



Source: http://www.ssloral.com/html/products/satint.html

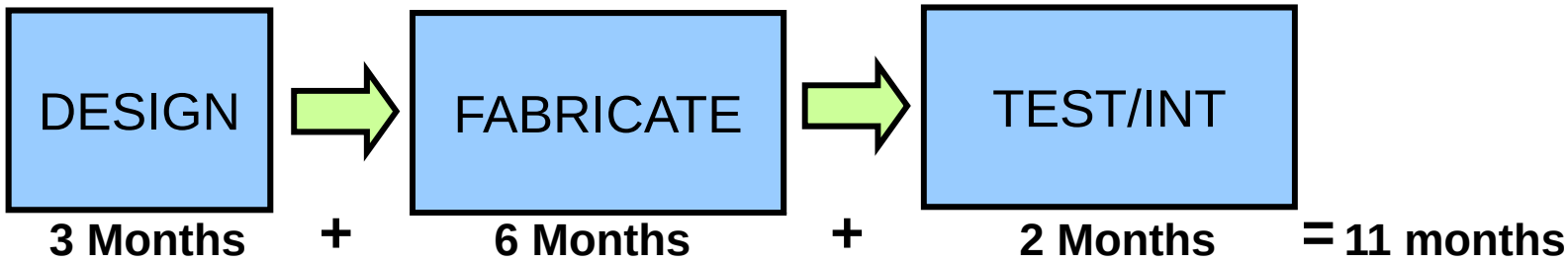
The “Marching Army”



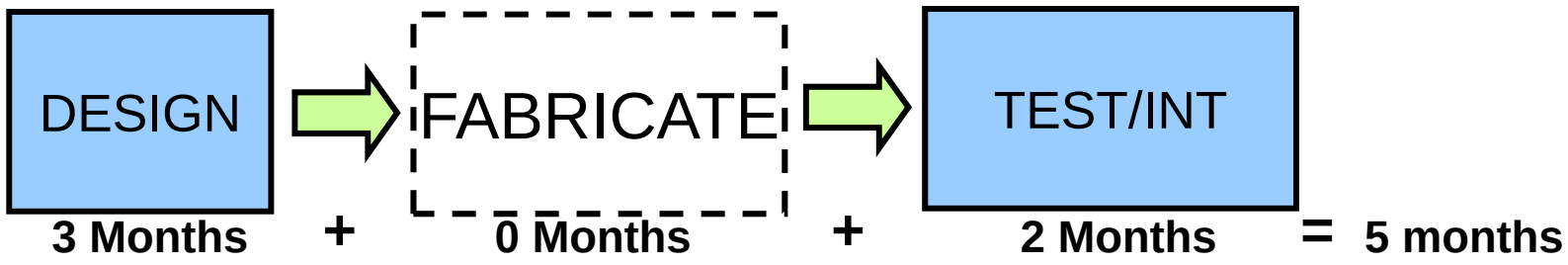
Courtesy of Michael Enoch, LM

Beating time delay – an example

Integrated Circuit (IC)



Field Programmable Gate Array (FPGA)



Convert one type of time delay into another kind you can deal with!

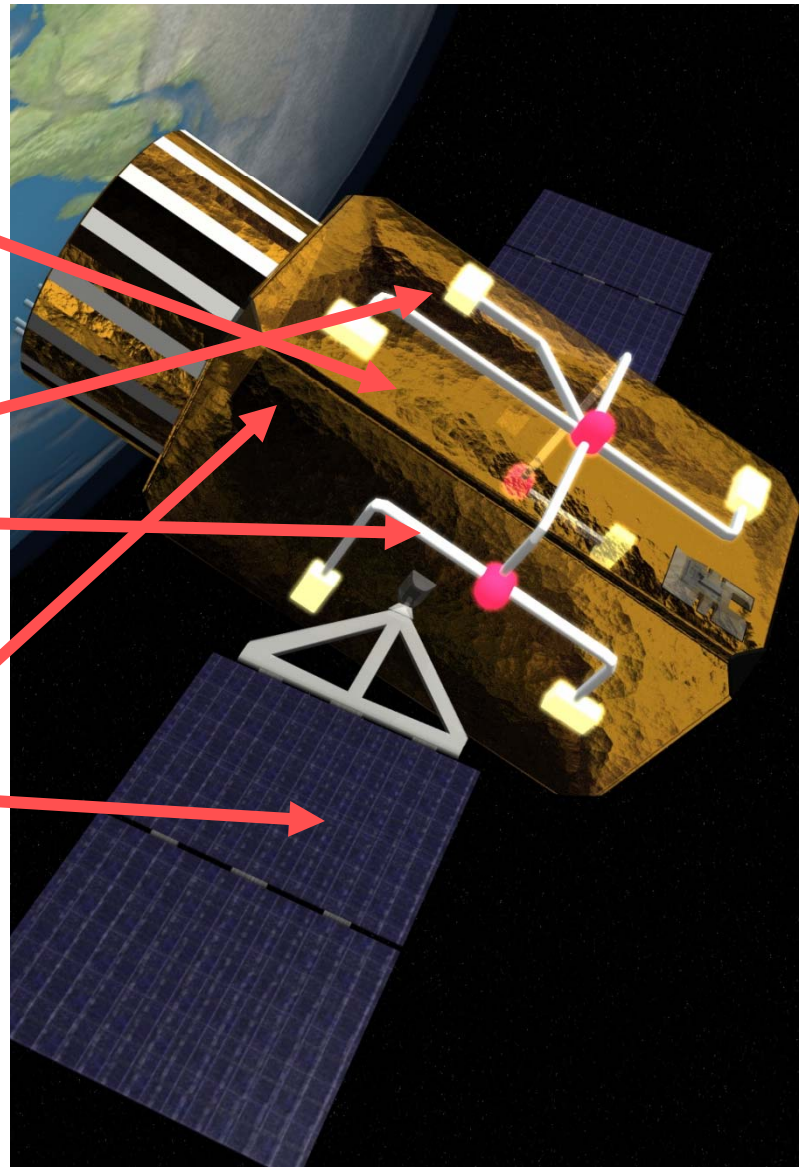
Field-Programmable Satellite Made with Field-Programmable Parts?

Eliminate wiring harnesses with pre-built programmable wiring

Integrate plug-and-play components into sockets of pre-built panels

Modularize power system components, add “smart combiners”

Programmable communications with software radio technology



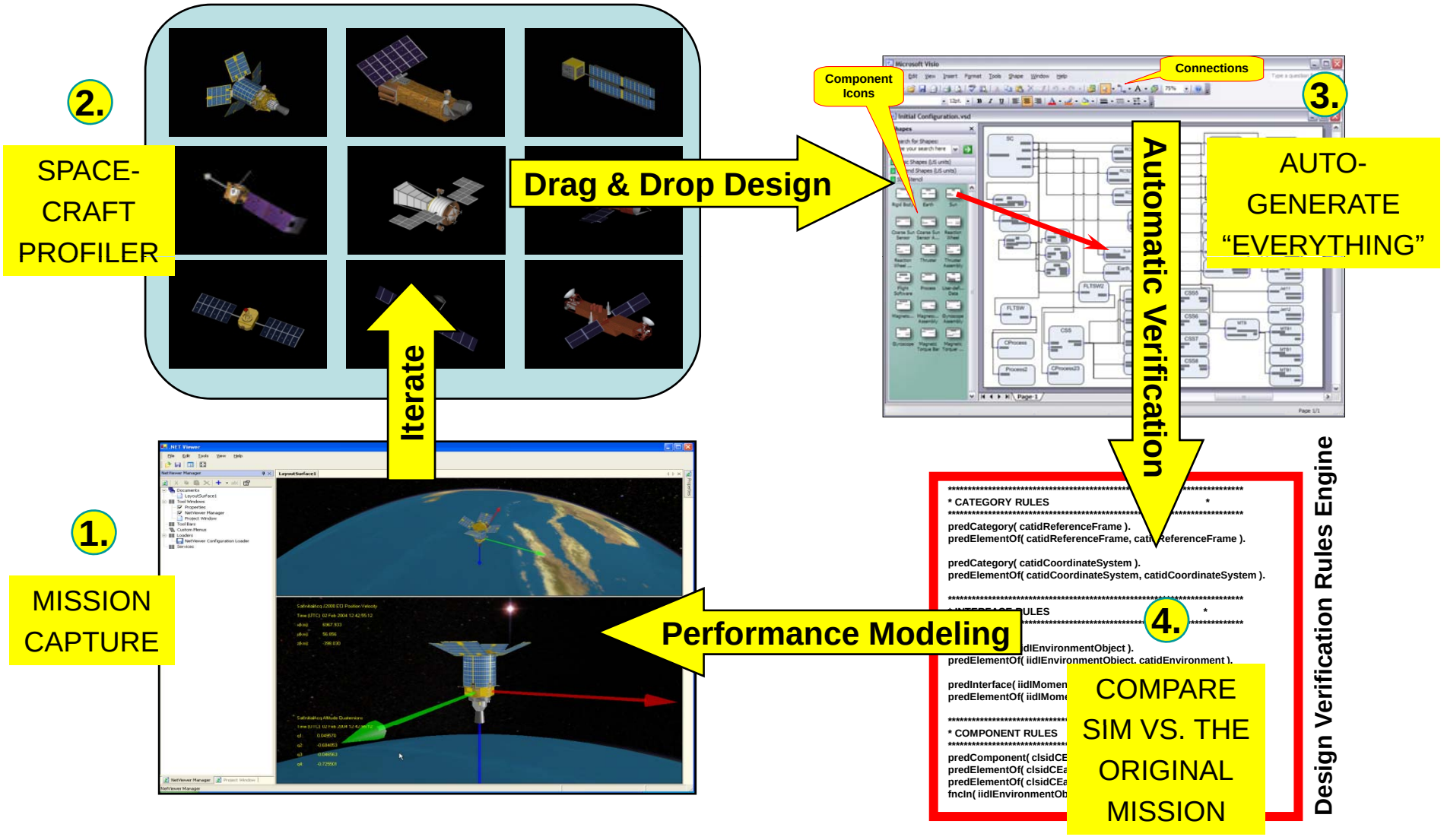
A Scalable Technology for Plug-and-play Systems

- Satellite Design Automation (SDA)
  - The metaphor of the “push-button toolflow”
- Space Plug-and-play Avionics (SPA) components / technologies
  - Interfaces (SPA-U and SPA-S)
  - Appliqué sensor interface module
  - XTEDS
  - Satellite data model
  - Test bypass

Ultra-Rapid Upfront Specification Generation: Mission Driven Tools

Mission Goals and Requirements

Component Capabilities



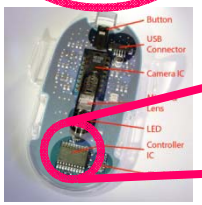
What is Plug-and-play

- **Plug-and-play is centrally based on smart components**
  - Every contains built-in electronic datasheet = xTEDS (XML-based electronic datasheet)
- **Components network into a self-organized system**

This approach is called "Space Plug-and-play Avionics"

Plug-and-Play Components
Black-Box Objects

“platform”

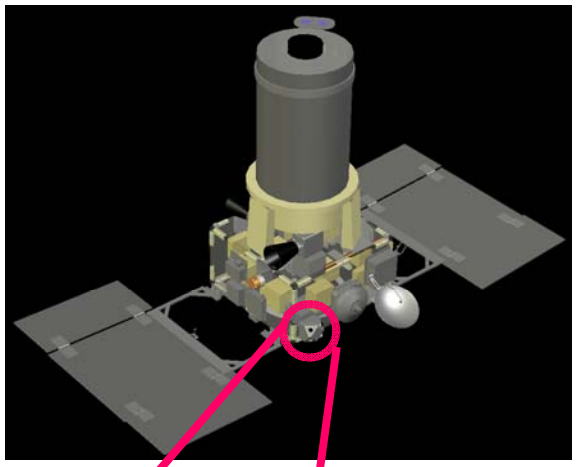


plug-and-play component

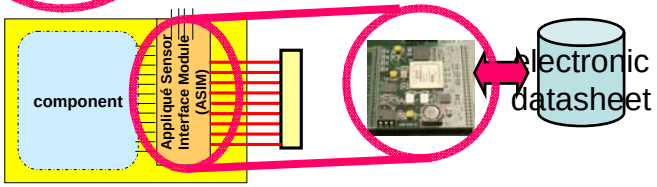
driver

USB interface chip

“platform”

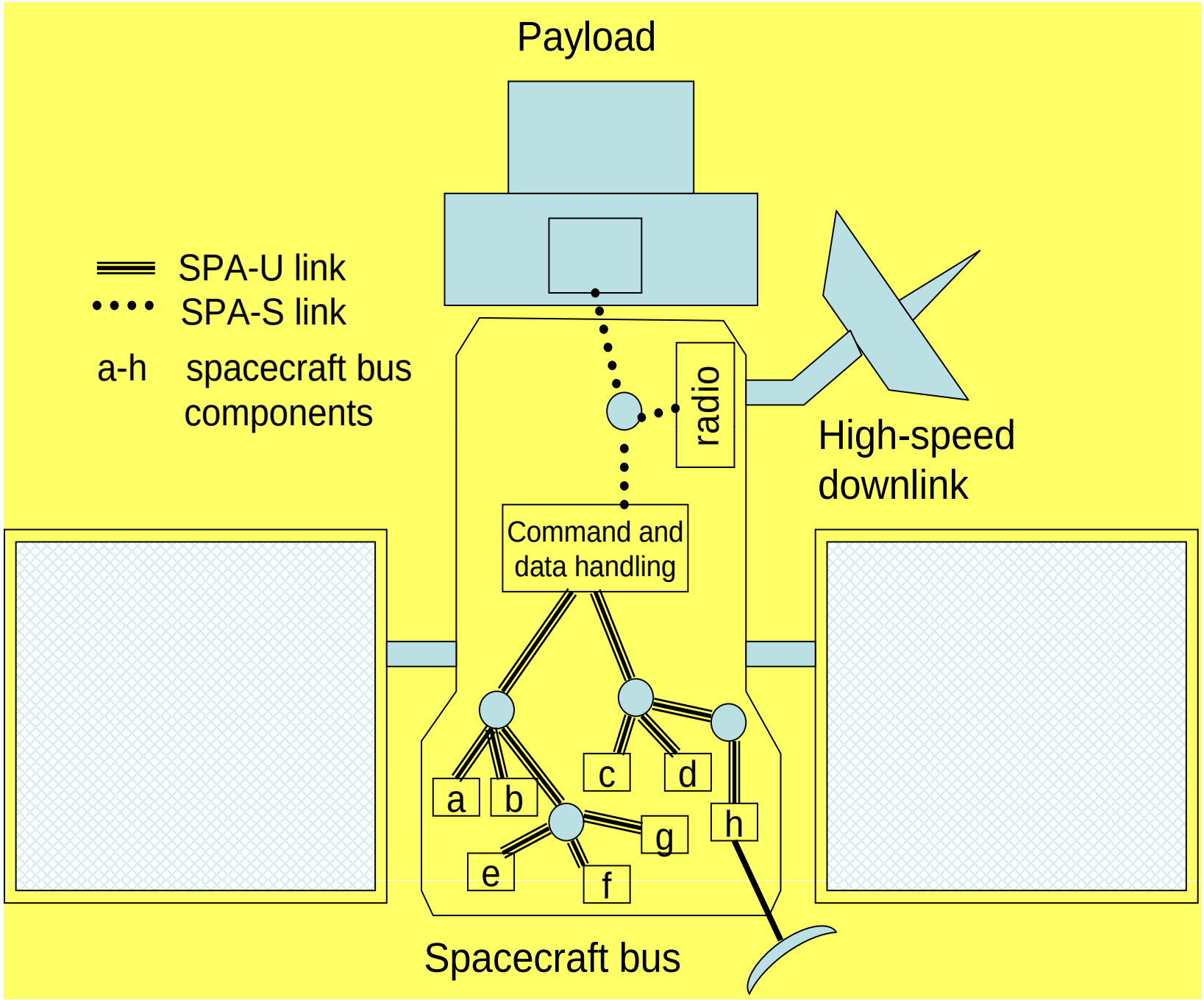


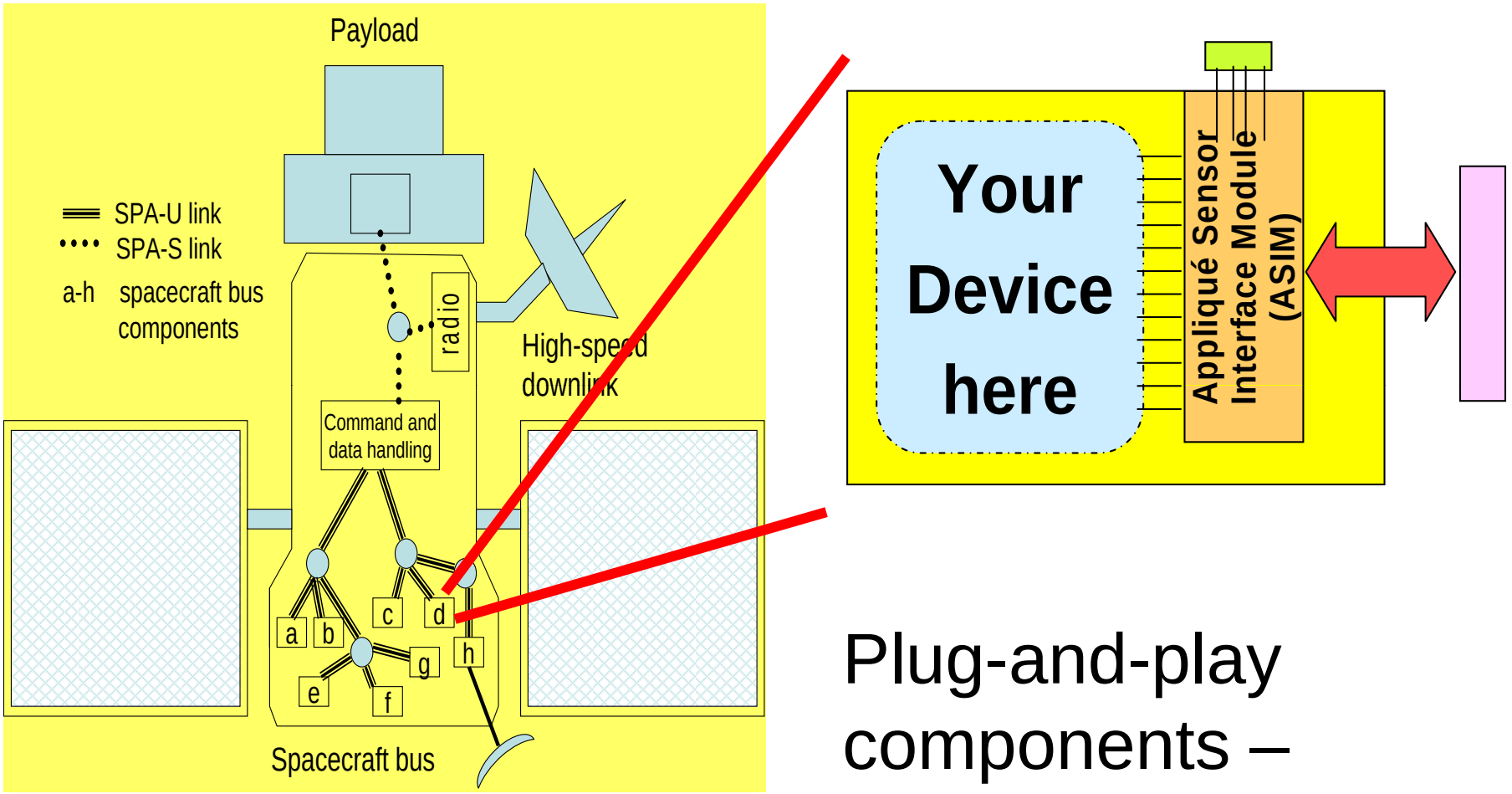
plug-and-play component



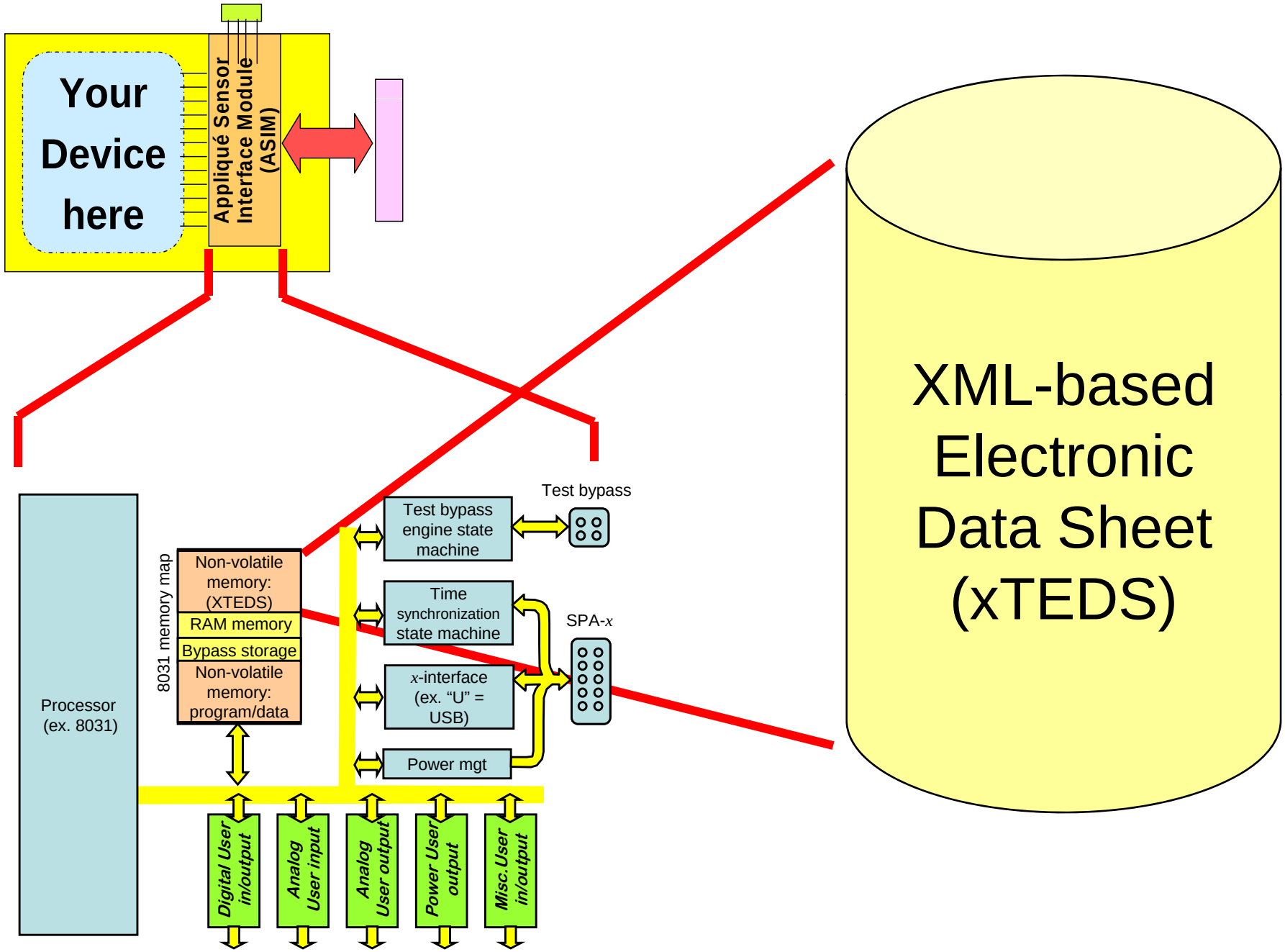
electronic datasheet

interface module

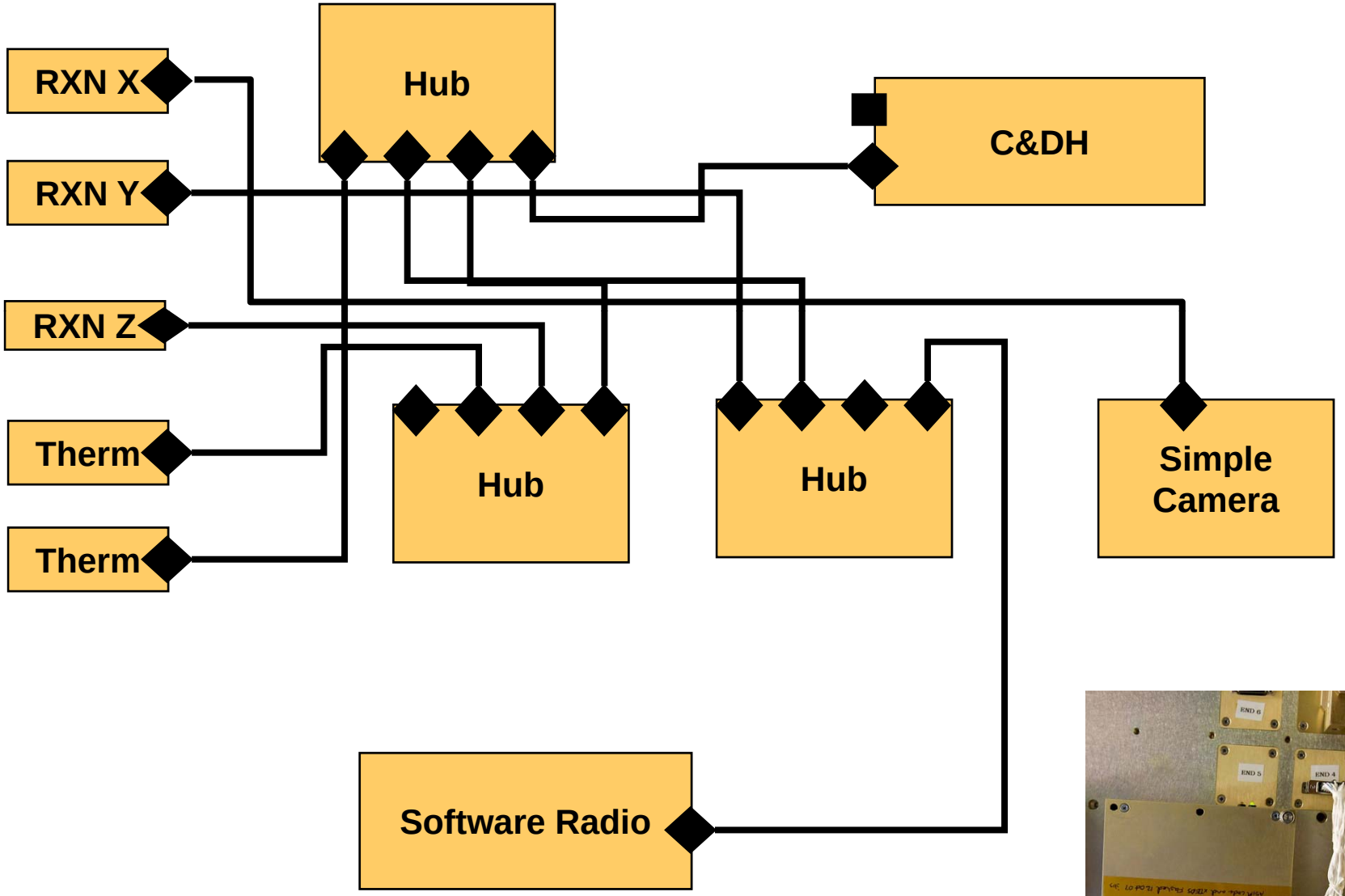

Payload
SPA-U link
SPA-S link
a-h spacecraft bus components
radio
High-speed downlink
Command and data handling
a
b
c
d
e
f
g
h
Spacecraft bus

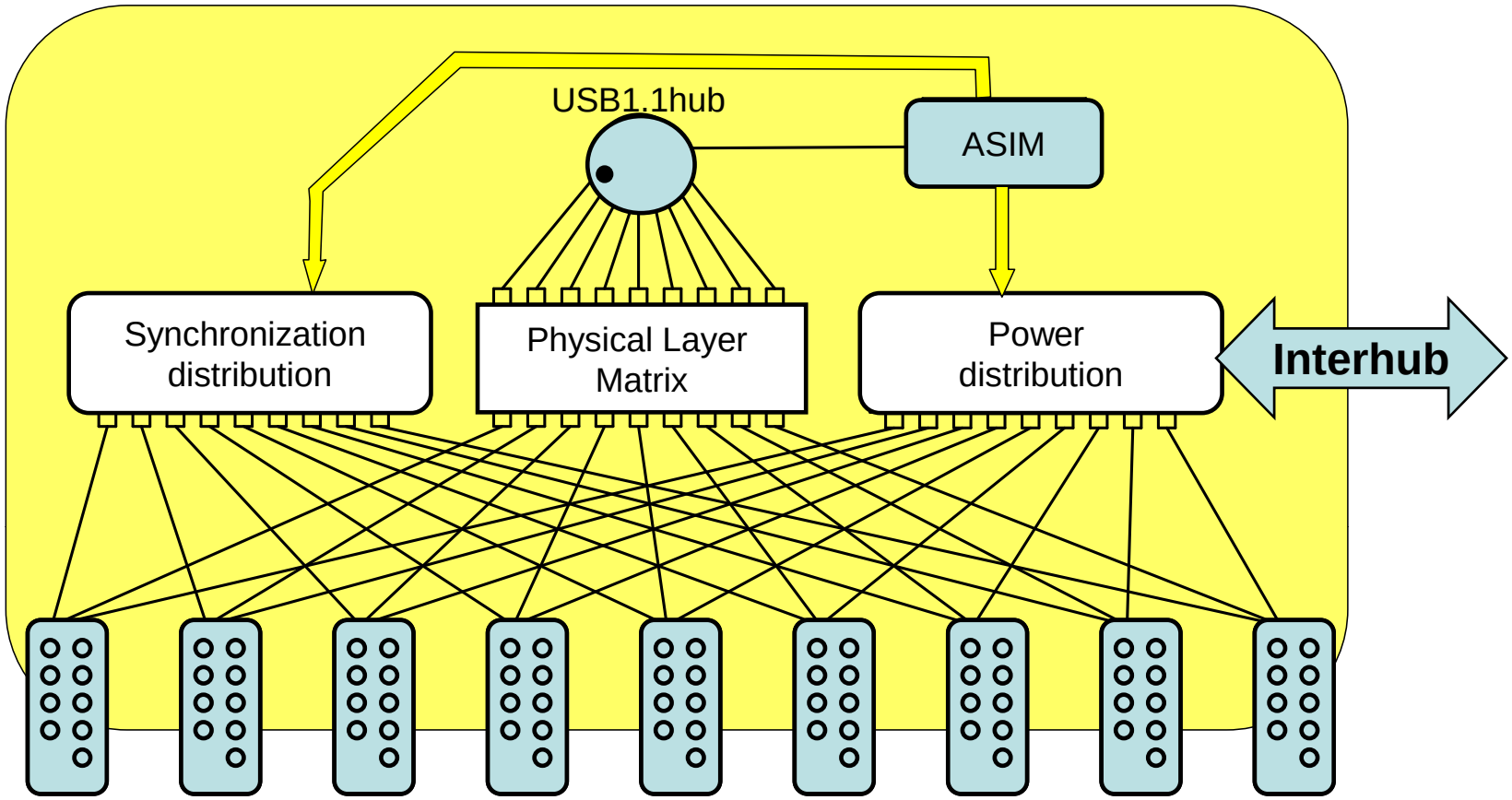


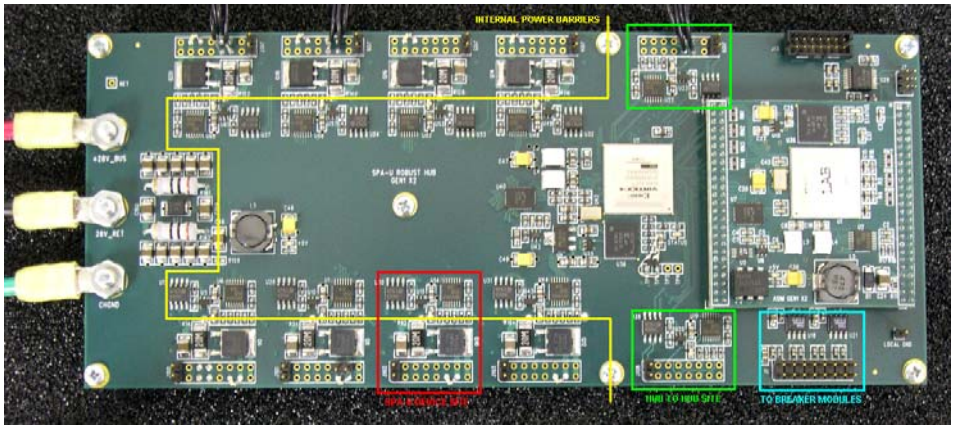
Plug-and-play components – black-box objects


Your Device here
Appliqué Sensor Interface Module (ASIM)
XML-based Electronic Data Sheet (xTEDS)
Processor (ex. 8031)
8031 memory map
Non-volatile memory: (XTEDS)
RAM memory
Bypass storage
Non-volatile memory: program/data
Test bypass
Test bypass engine state machine
Time synchronization state machine
x-interface (ex. "U" = USB)
Power mgt
SPA-x
Digital User in/output
Analog User input
Analog User output
Power User output
Misc. User in/output

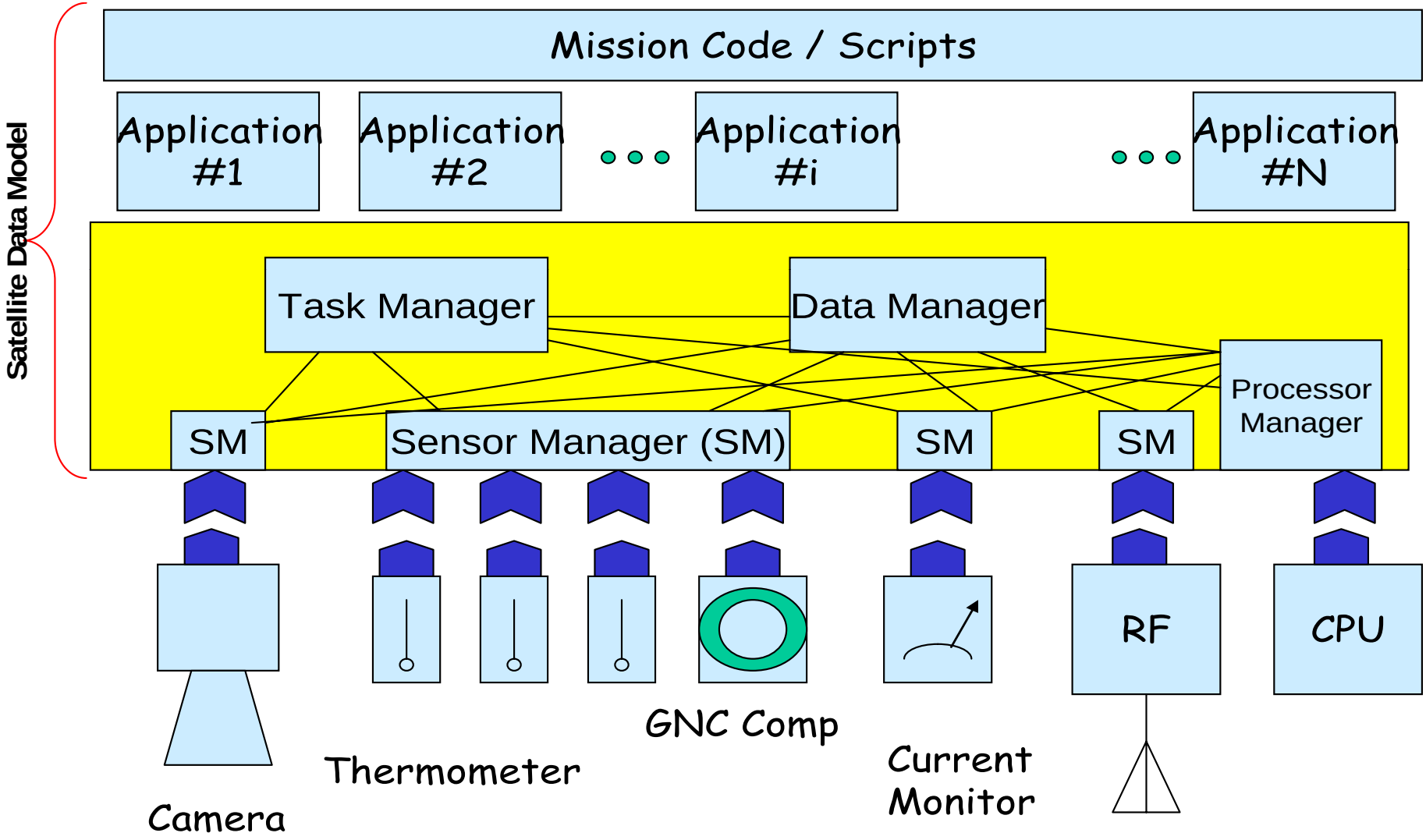
SPA Networking with SPA devices / hubs




USB1.1hub
ASIM
Synchronization distribution
Physical Layer Matrix
Power distribution
Interhub

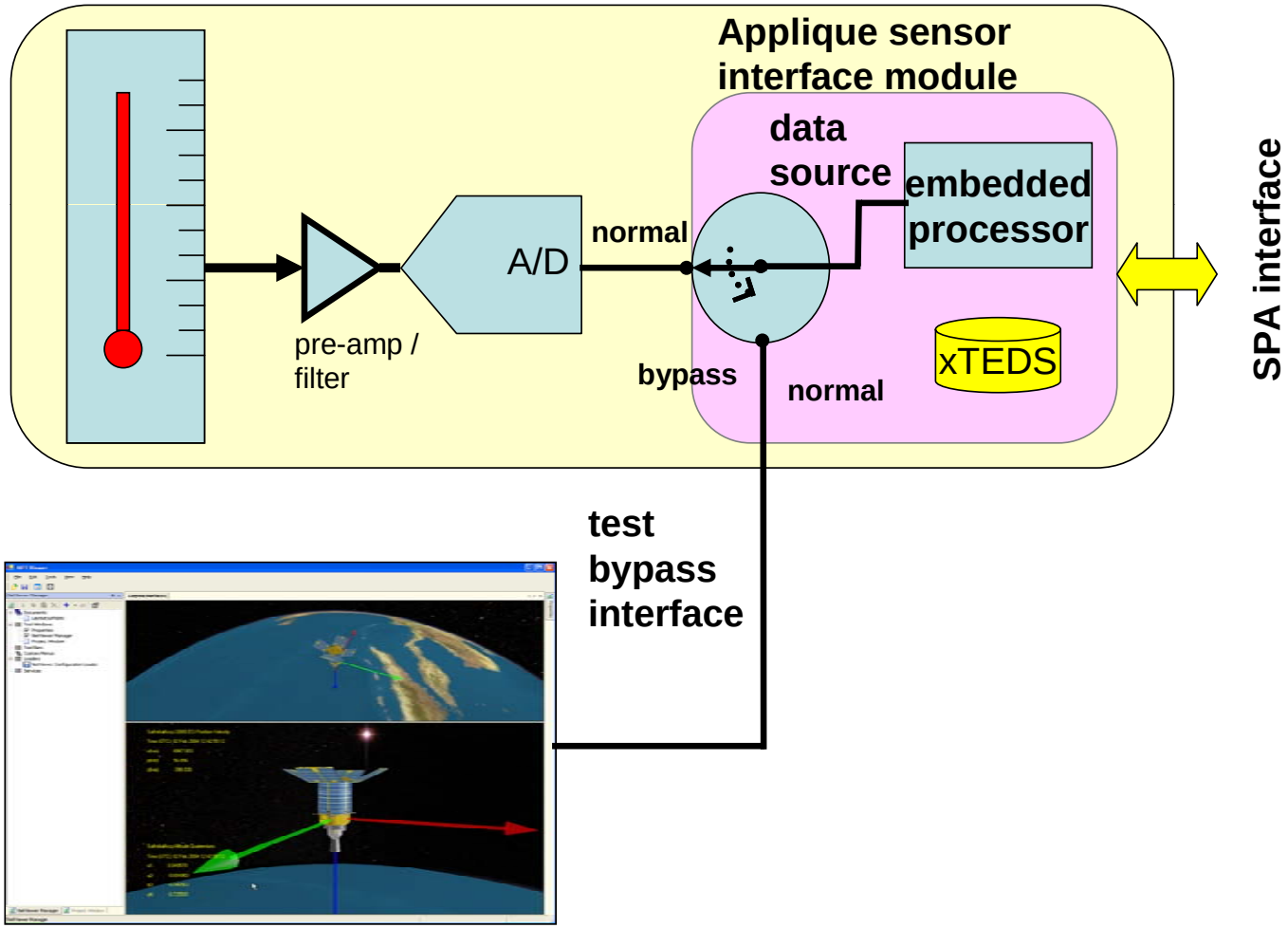

INTERNAL POWER BARRIERS
TO BREAKER MODULES

The Satellite Data Model (SDM) – Building Awareness into Plug-and-play



To simplify the testing of complex systems, a “test bypass” feature is integrated in the SPA plug-and-play interfaces. Test bypass allows an external control (simulation) to provide substituted values during test, similar to the test/debug methods used in developing software. Test bypass is particular useful in cases where an actual test involving a device’s native sensors and actuators is impractical.

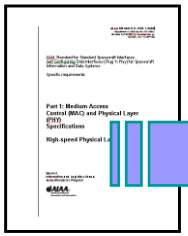
SPA (plug-and-play) thermometer



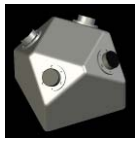
Maturation / Flight Projects

- Ground validation – Responsive Space Testbed
- Current flight projects
  - RESE (sounding rocket) (completed)
  - SAE (part of TacSat 3)
  - PnPSat
- Prospective
  - TacSat V
  - PnP Nanosatellite

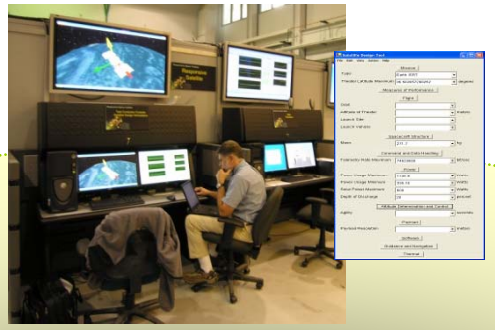
Responsive Space Testbed



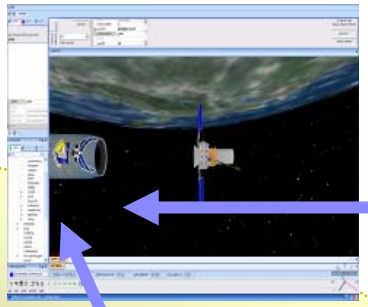
Approved SPA Interface Standards



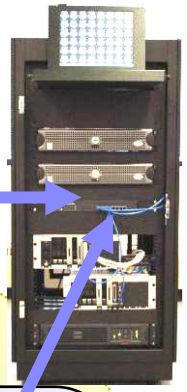
Plug-and-play space components



Automated Mission & S/c Design



Hardware in-the-loop

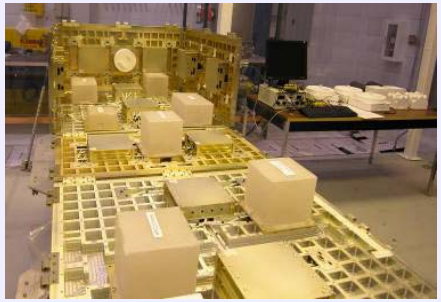


Adaptive Wiring Manifold

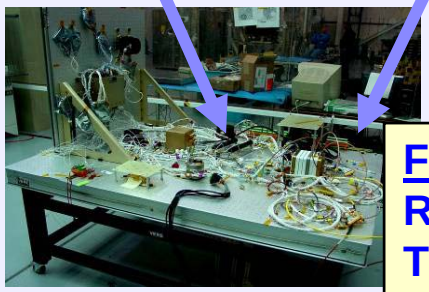
SPA-U Hub

Appliqué Sensor Interface Module (ASIM)

Technology Cell

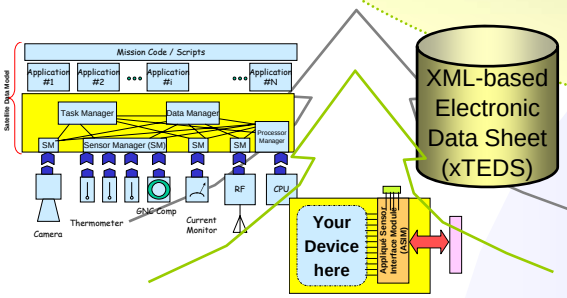


Rapid Satellite Cell



"Flat-Sat" Cell

Flt Demos
RESE-1
TS-3 SAE
PnPSat

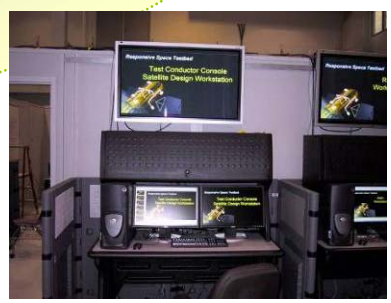


XML-based Electronic Data Sheet (xTEDS)

Plug-and-play Technology

Objectives

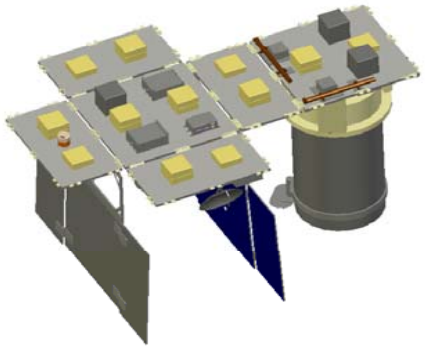
- **Drive toward 6-day spacecraft**
  - **Dissect and examine every process**
  - **Develop modular systems & automated tools**
- **Validate plug-and-play architectures**
- **Integrate analysis tools & hardware-in-loop**
- **Demonstrate fast I&T, initialization, and ops**
- **Explore prospective satellite configurations and operational concepts prior to build**

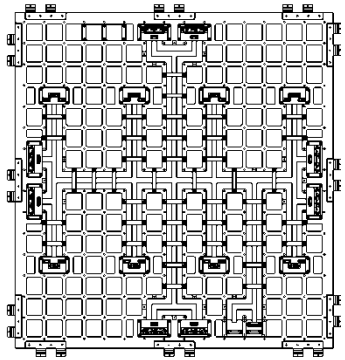


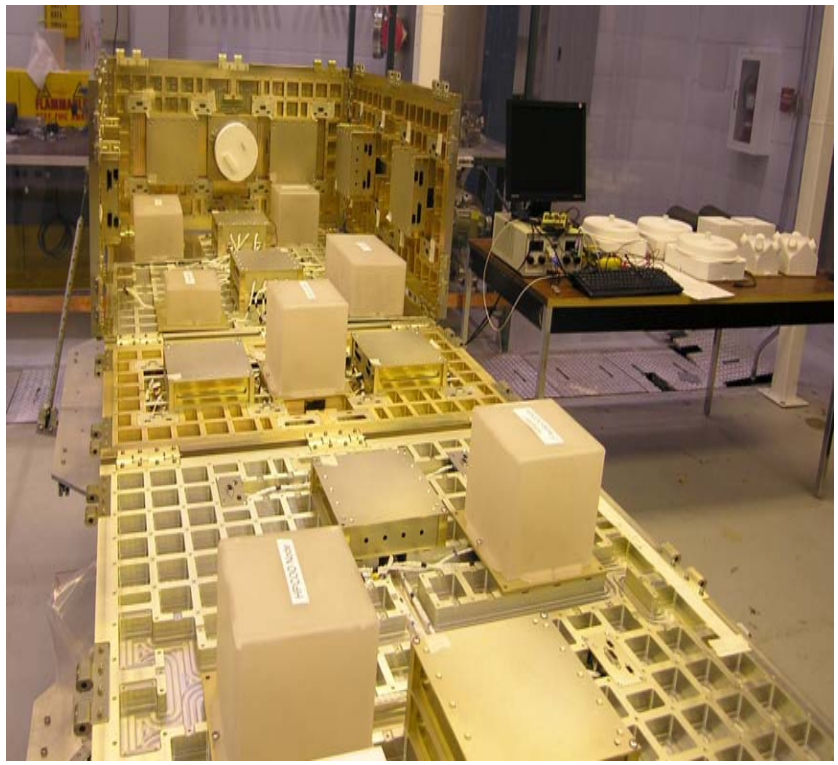
RIMS Ground Station

Modular Concept Bus

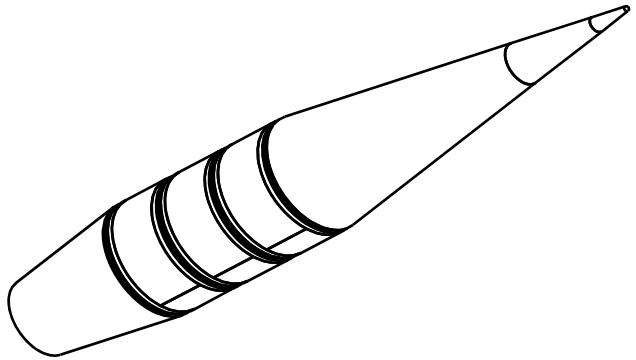
- Like the Detroit “concept car”
- Logically extends ideas of plug-and-play to the rest of the satellite







Re-Entry Structures Exp't I (RESE-1)



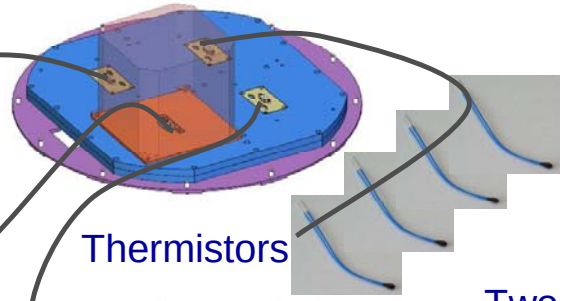
RESE-1 Suborbital Flight Experiment

- Sounding Rocket: Single stage Terrier
- Launch Site: White Sands
- Launch Date: Sept 2007
- Max Altitude: ~ 250,000 ft
- Duration above 90,000 ft: ~100 sec

RESE-1 Plug-and-Play Experiment on dedicated composite deck with 4 SPA-U spacecraft sensors:

SPA hardware integrated into controller cards and configured for space in 4 months

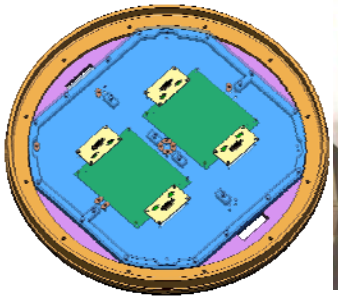
Magnetometer

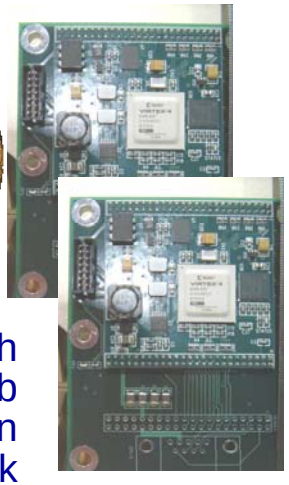


Thermistors

Tri-axial Accelerometer

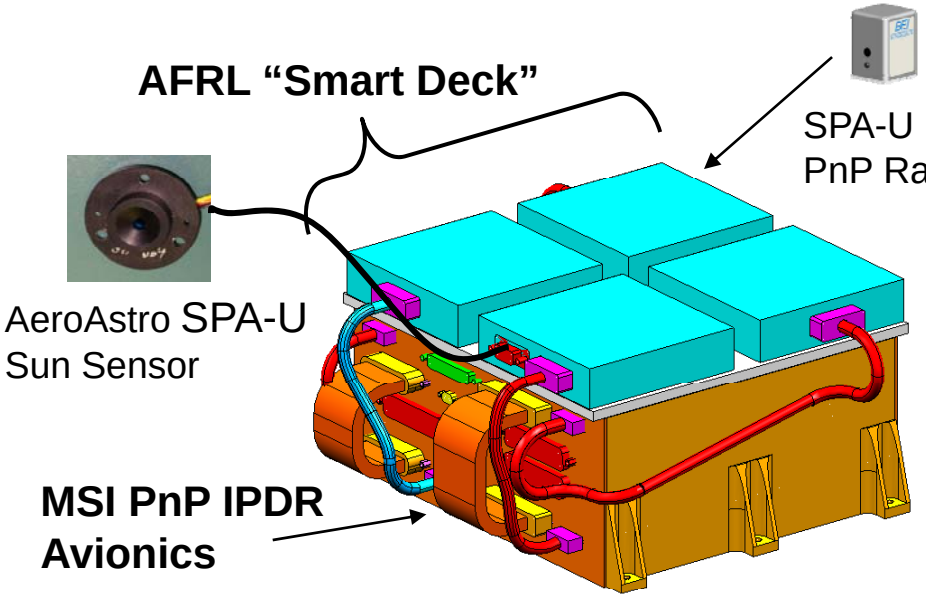
Strain Gauges





Two controller cards with integrated SPA-U hub and ASIMs integrated on bottom of composite deck

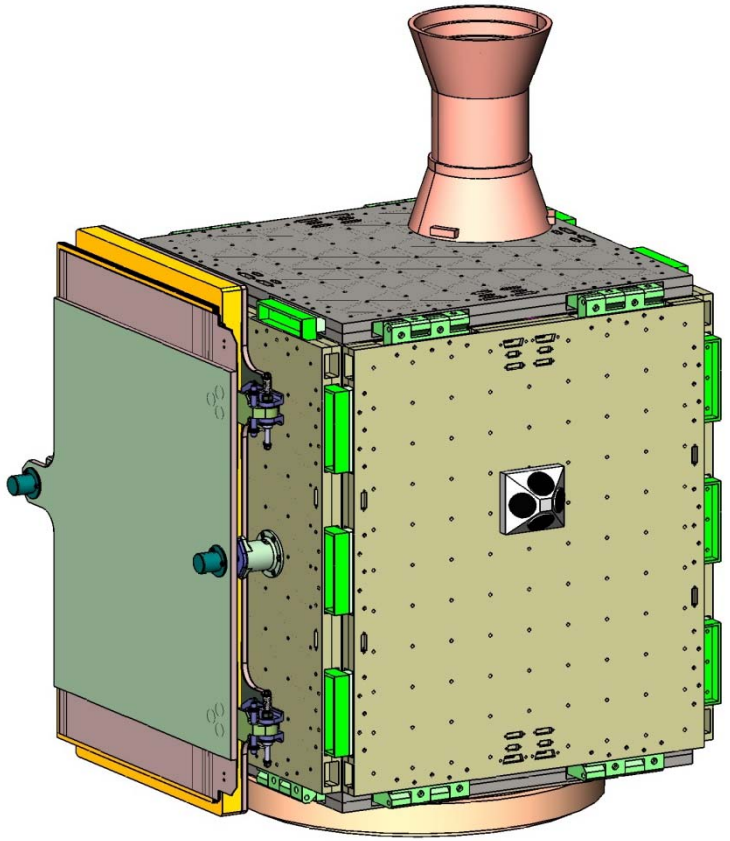
TacSat-3 Spacecraft Avionics Experiment (SAE)



- Launch on TacSat-3 in Dec 2007
- Dimensions: 9" x 9" x 5.75"
- Mass: 8 kg
- Orbital Average Power: 10W

- Smart Deck with SPA-U host, 4 SPA-U ports, and data handling system
- Parallel PnP capability using MSI's Intelligent Power & Data Ring (IPDR) with multiple processing nodes for redundancy
  - Spacewire/SPA-S link between Sensor Processor and C&DH for backup downlink capability of HSI data
- SPA-U PnP experiments
  - Reaction wheel electronics, rate sensor, memory stick data storage, AeroAstro Sun Sensor, or other (selection in progress)

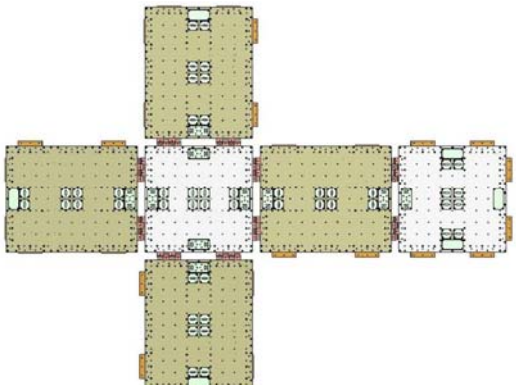
Plug-and-play Satellite (PnPSat)

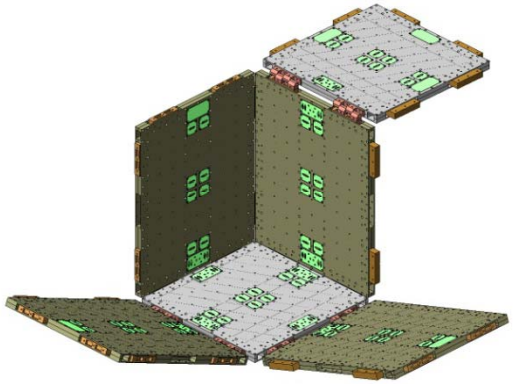


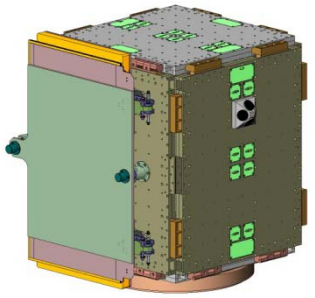
- First spacecraft ever built entirely on PnP principles
  - Decentralized, scalable computation
  - Use of satellite data model
  - All components (even panels) are SPA devices
  - up to 48 mounting sites
- Ambitious development schedule
  - Targeting flight in 2009

Configurations of PnPSat

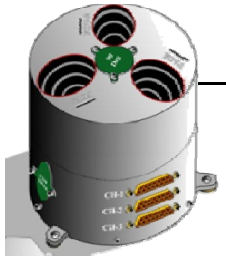
- PnPSat bus can be easily changed to various configurations to support requirements for different stages of the project
  - Flatsat configuration
  - Assembled configuration
  - Other configurations possible
- Panel-to-panel joints are pinned to allow panels to be rotated from horizontal (flat) to vertical (folded)
  - Securing hinged joints with precision pins
- Individual panels or sets of panels can be integrated and tested in parallel before final assembly







PnP Elements Enable Avionics Network



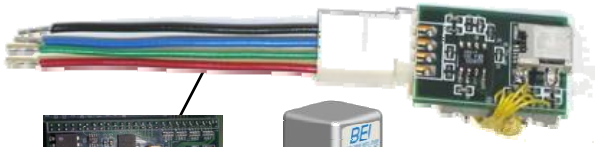
Star Tracker

ASIM

ASIM

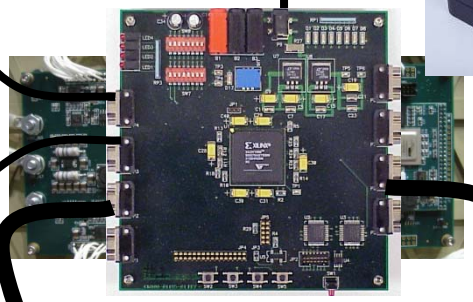
TT&C

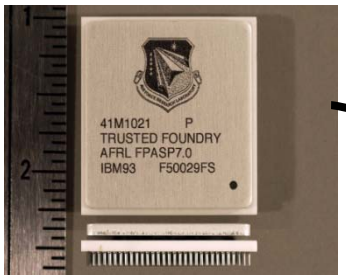
Accelerometers, thermostats, etc.



ASIM

Spacecraft Panel

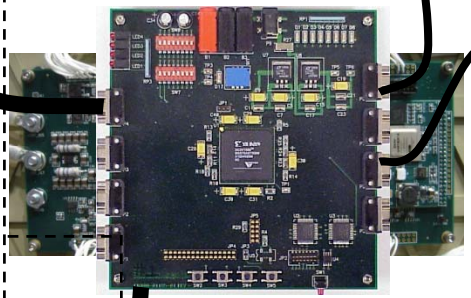


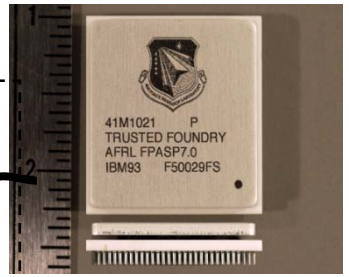


WSSP 6GFlop Processor

SPA-U/-S Network Backbone

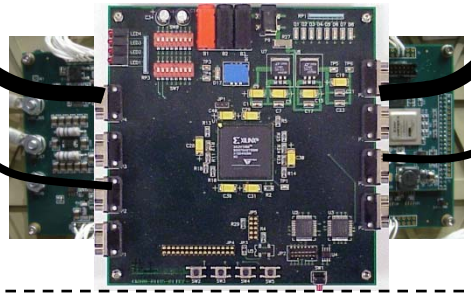
Spacecraft Panel





WSSP 6GFlop Processor

Spacecraft Panel



ASIM

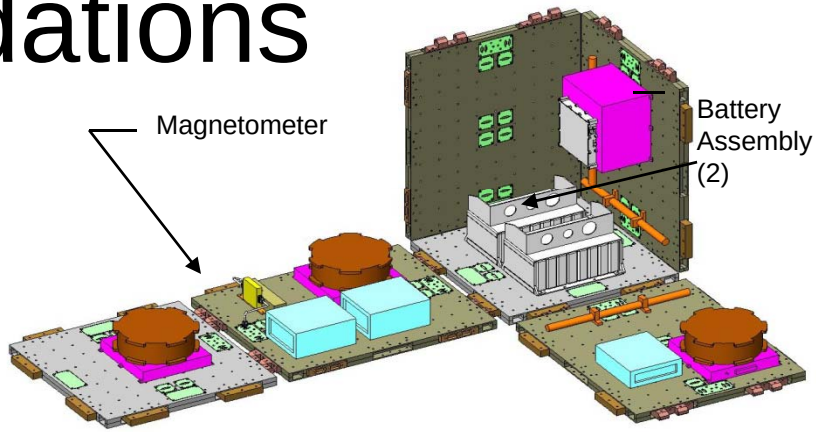
Sun Sensors

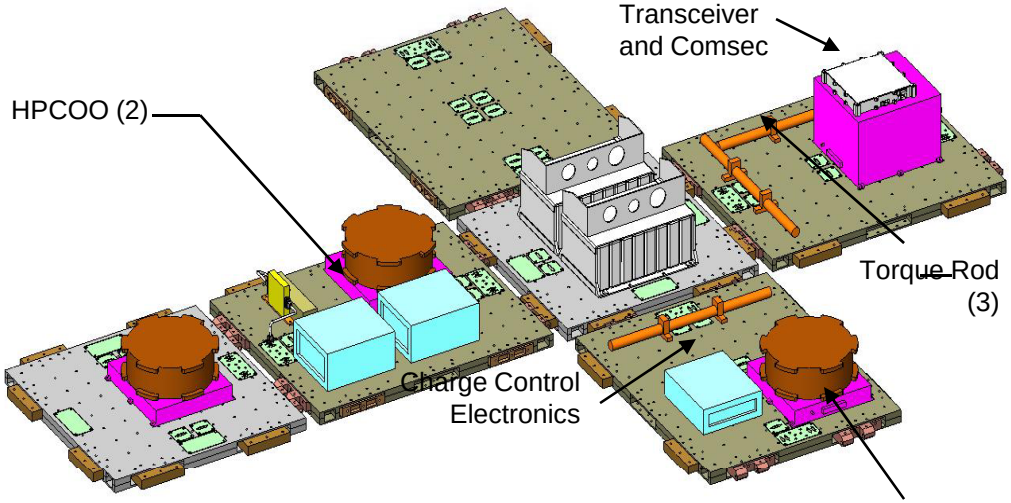
ASIM

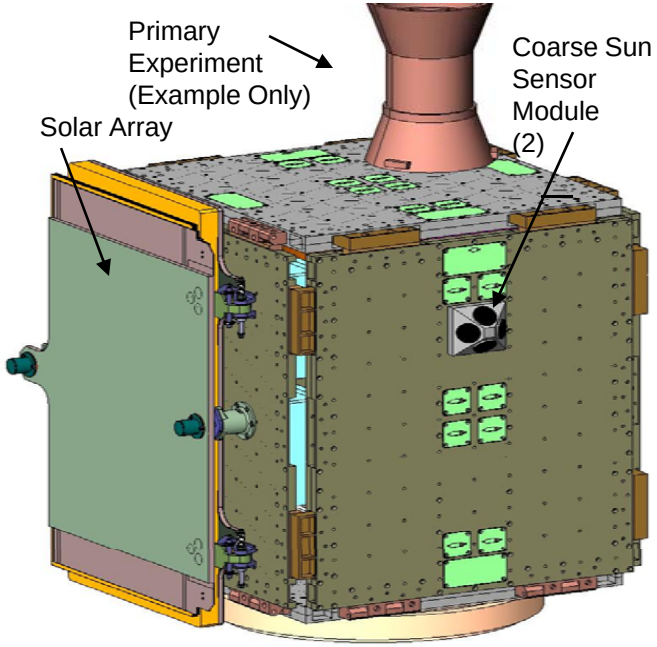
Reaction Wheels

Component and Experiment Accommodations

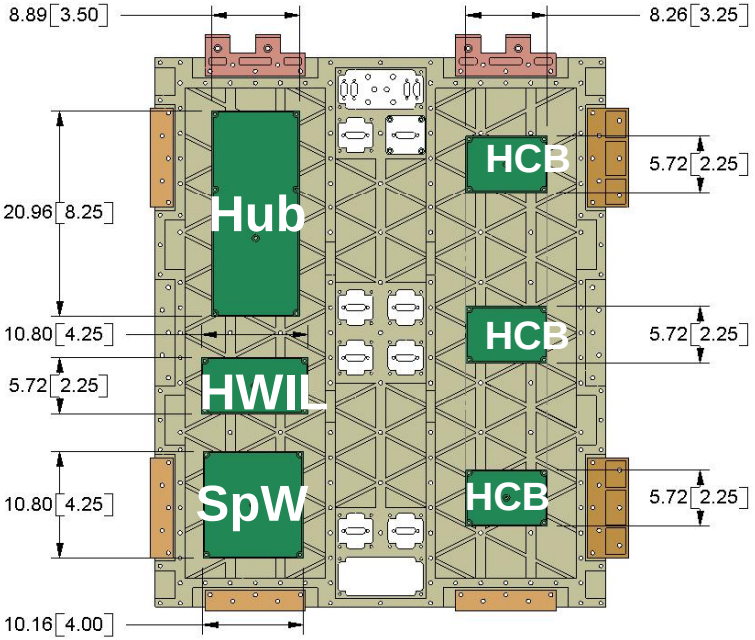
- A full complement of PnPSat components shown
  - By recessing electrical infrastructure and harnessing, we significantly increase flexibility for component and experiment mounting
  - Initial version of PnPSat may have fewer spacecraft components than the version shown



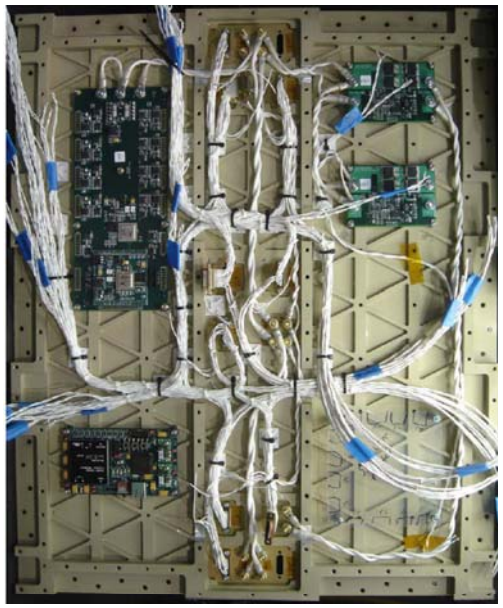




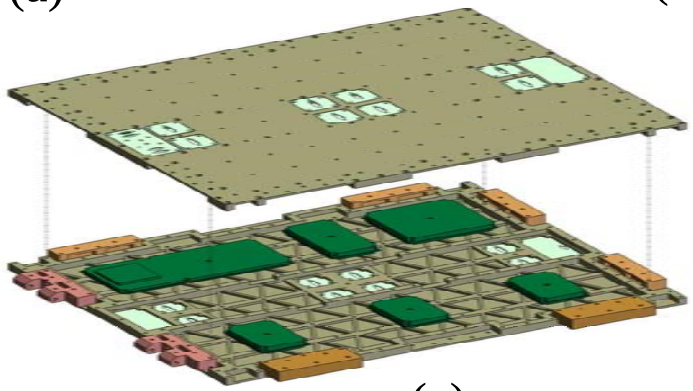
Encapsulation (complexity hiding)



(a)

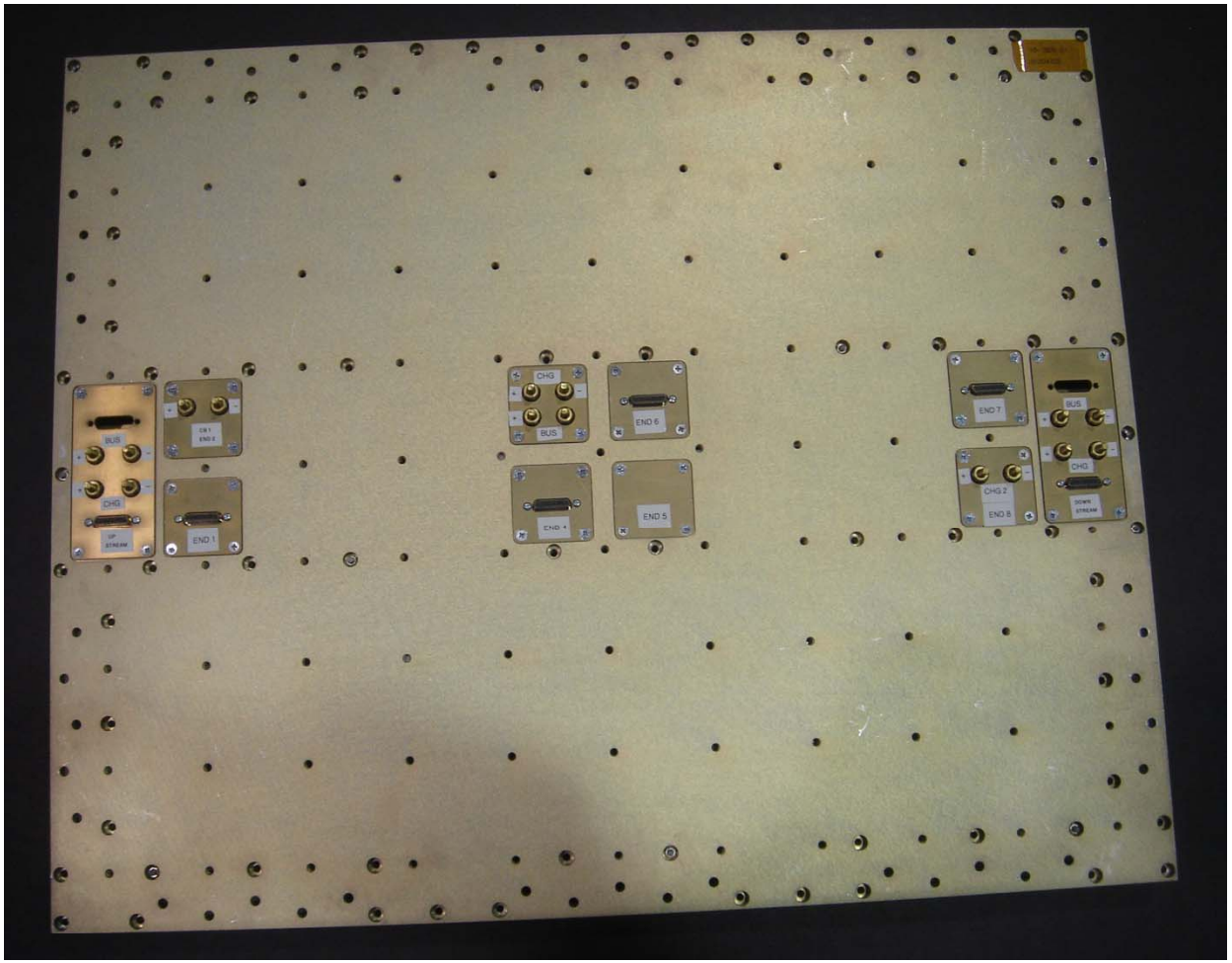


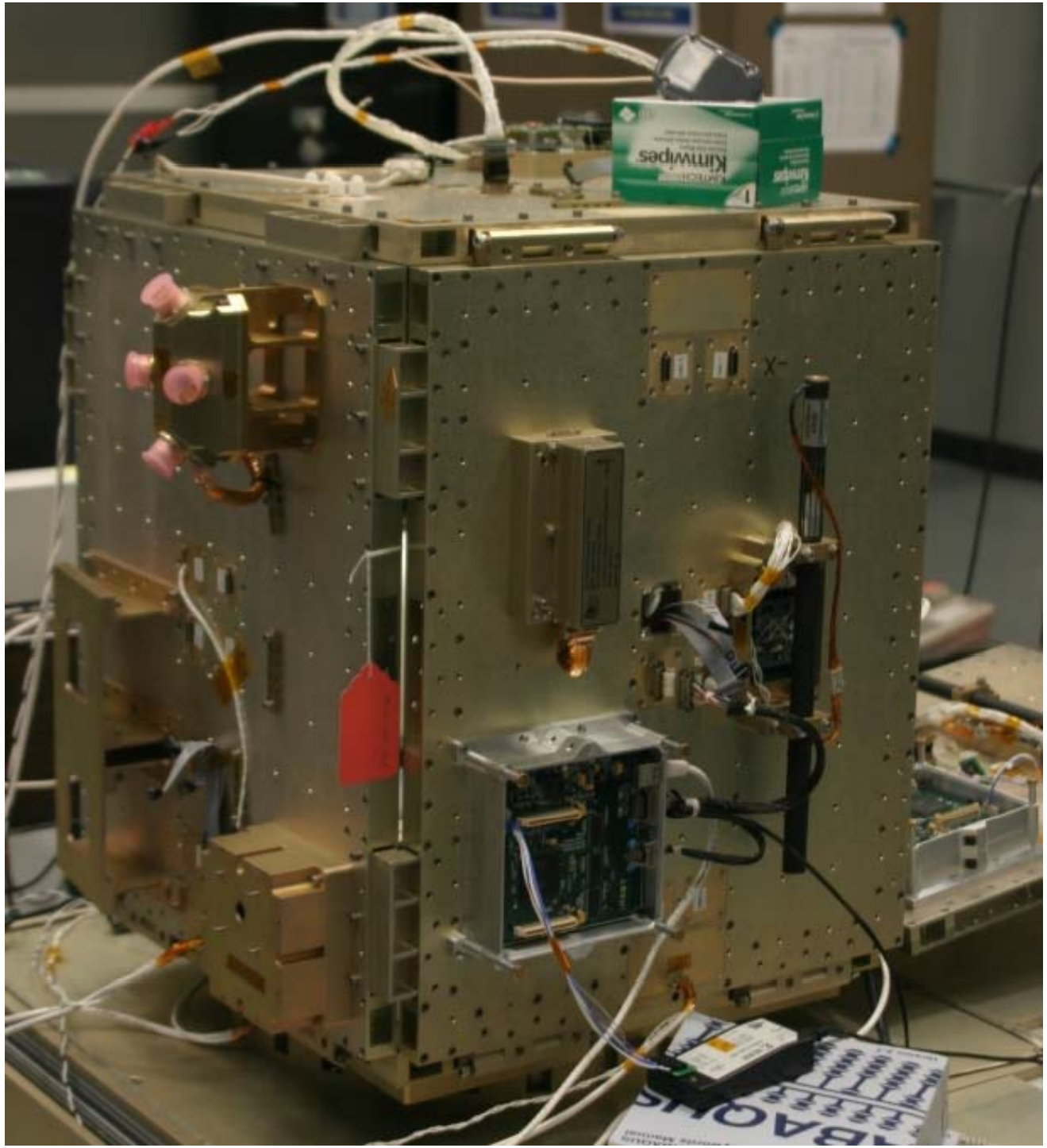
(b)



(c)

Encapsulation (complexity hiding)

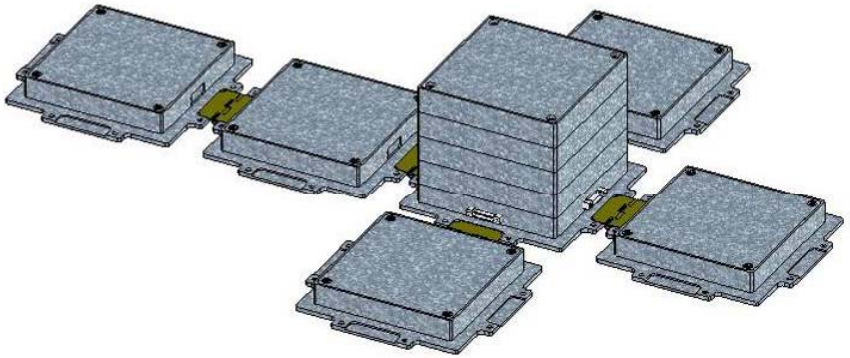


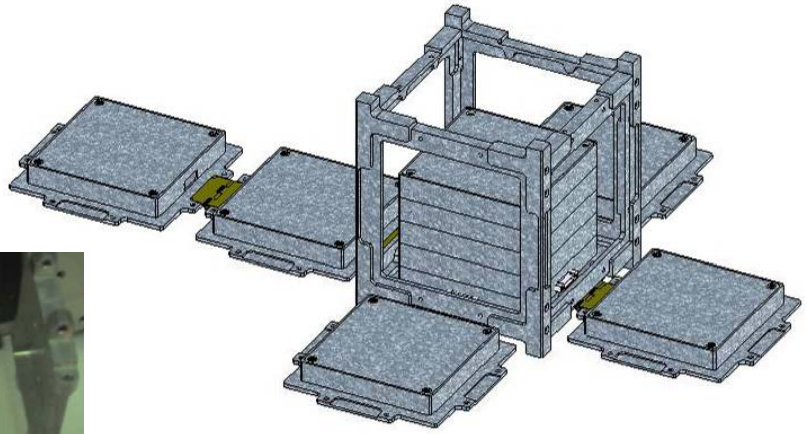

Kimwipes
X-

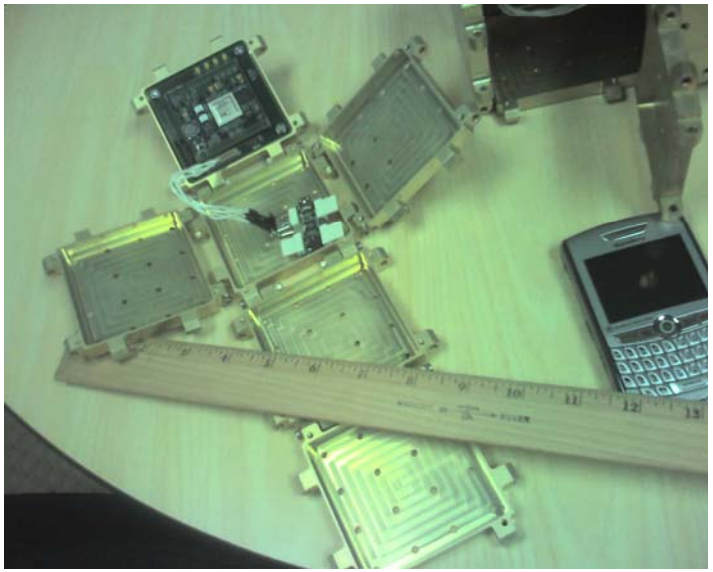
Miniaturization – the “nano”

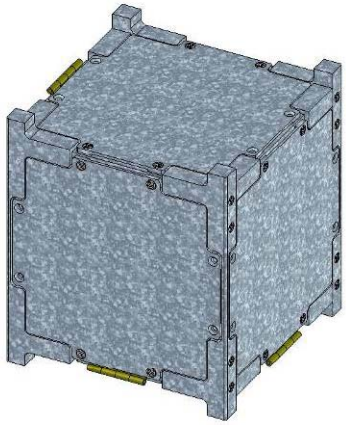
- Targeting PnP platforms as small as cubesats (100mm)
- Supports increased payload mass fraction and creation of PnP nanosatellites
- Compact nanosat modular form factor (NMF)standard (70mm x 70mmx12.5mm)

Frame and Module

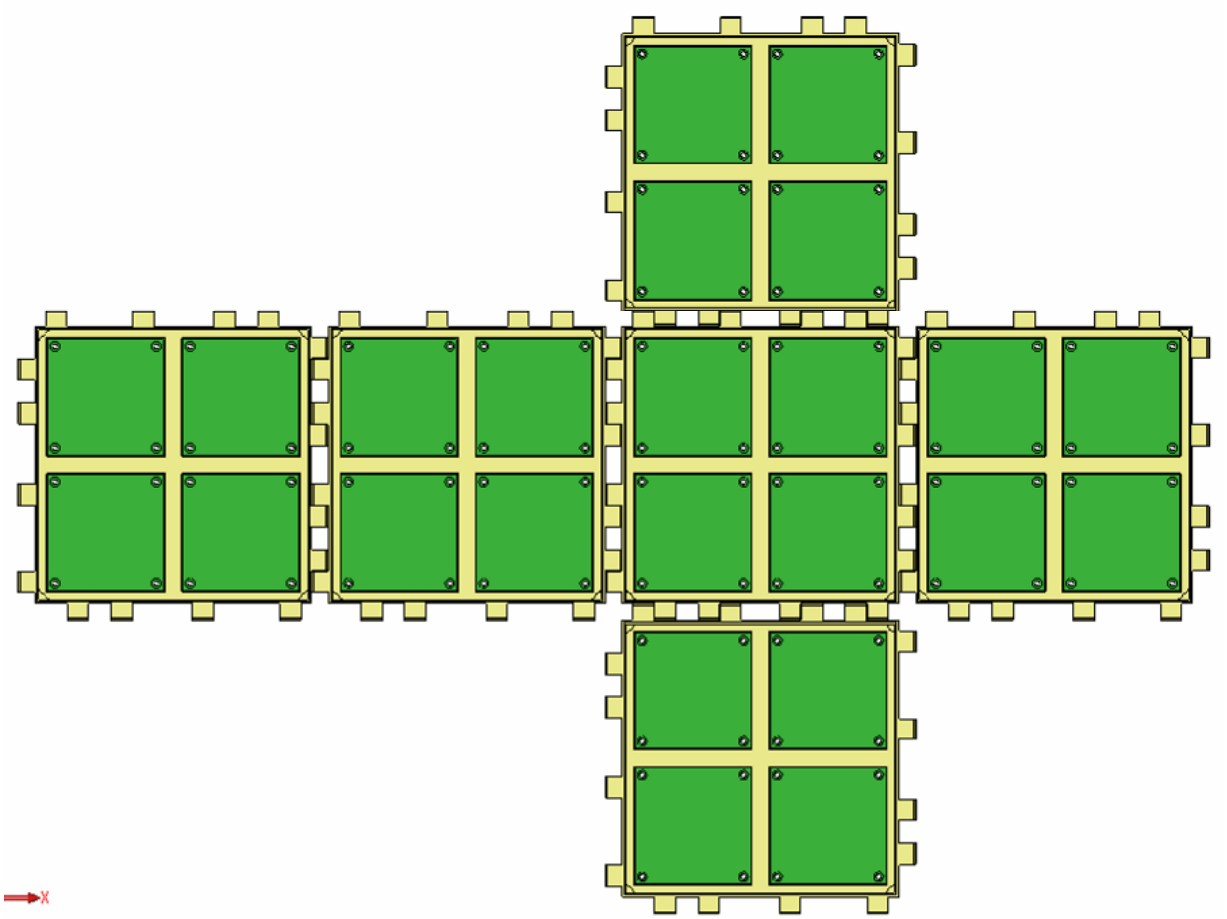


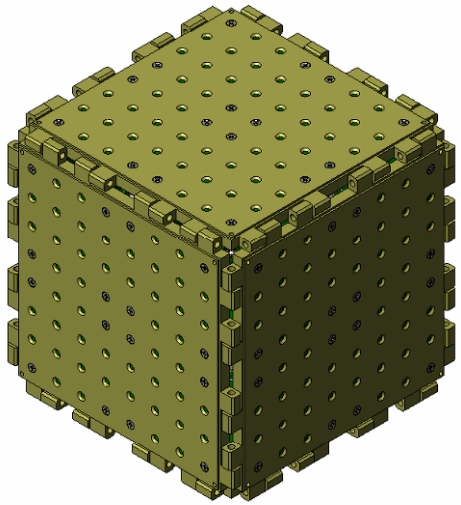




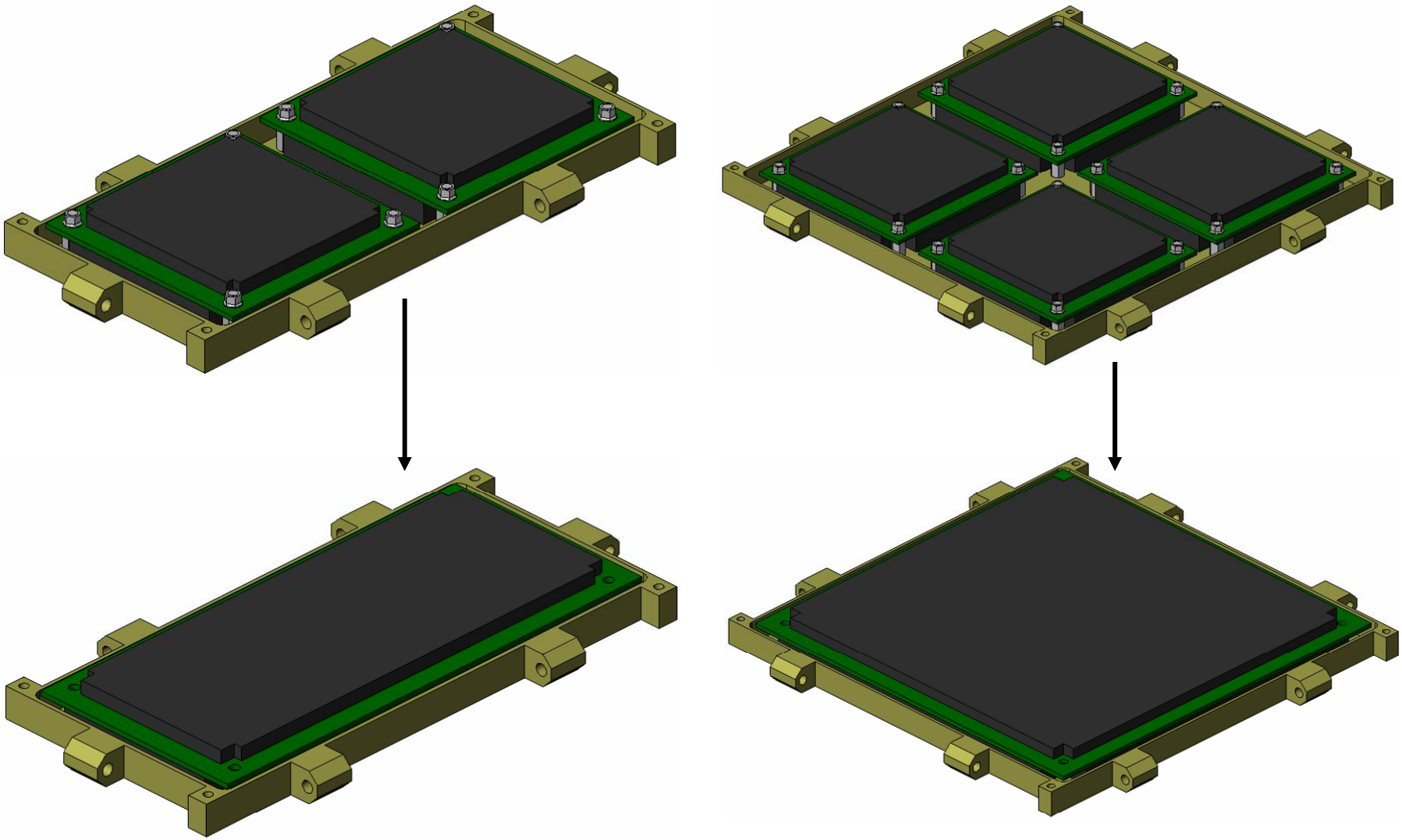


2x2x2





Larger Geometries Feature: Larger Board Envelope



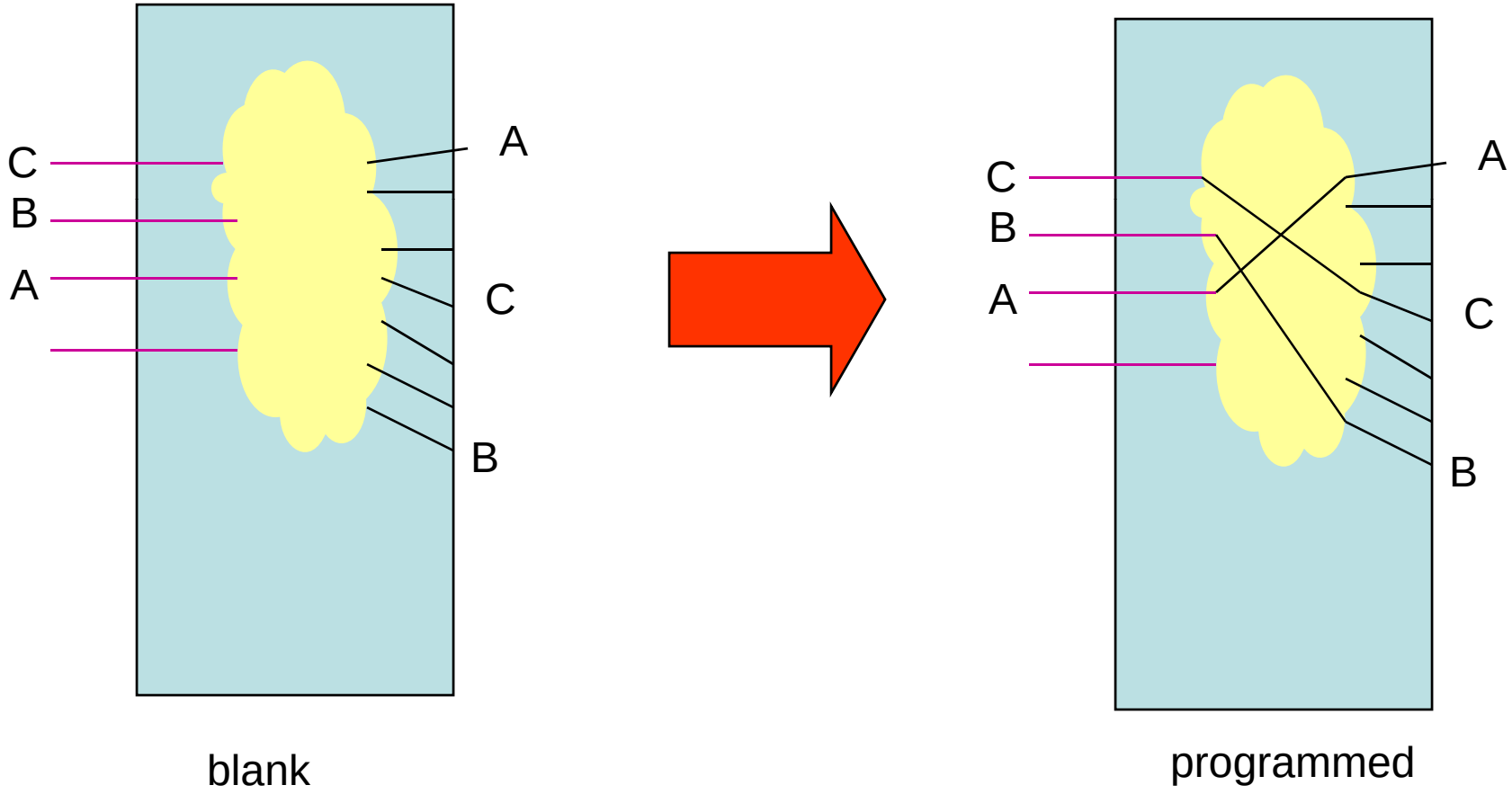
Future Directions

- SPA evolution (backward-compatible improvements)
- High Performance Computing On-Orbit
- Software-definable radios (“Modular comm”)
- Push-button toolflow (PBTF) vision
- Power systems
- Thermal systems: improved isotherms, coarse-grain configurable thermal management
- Application development
- Miniaturization

Adaptive wiring manifold

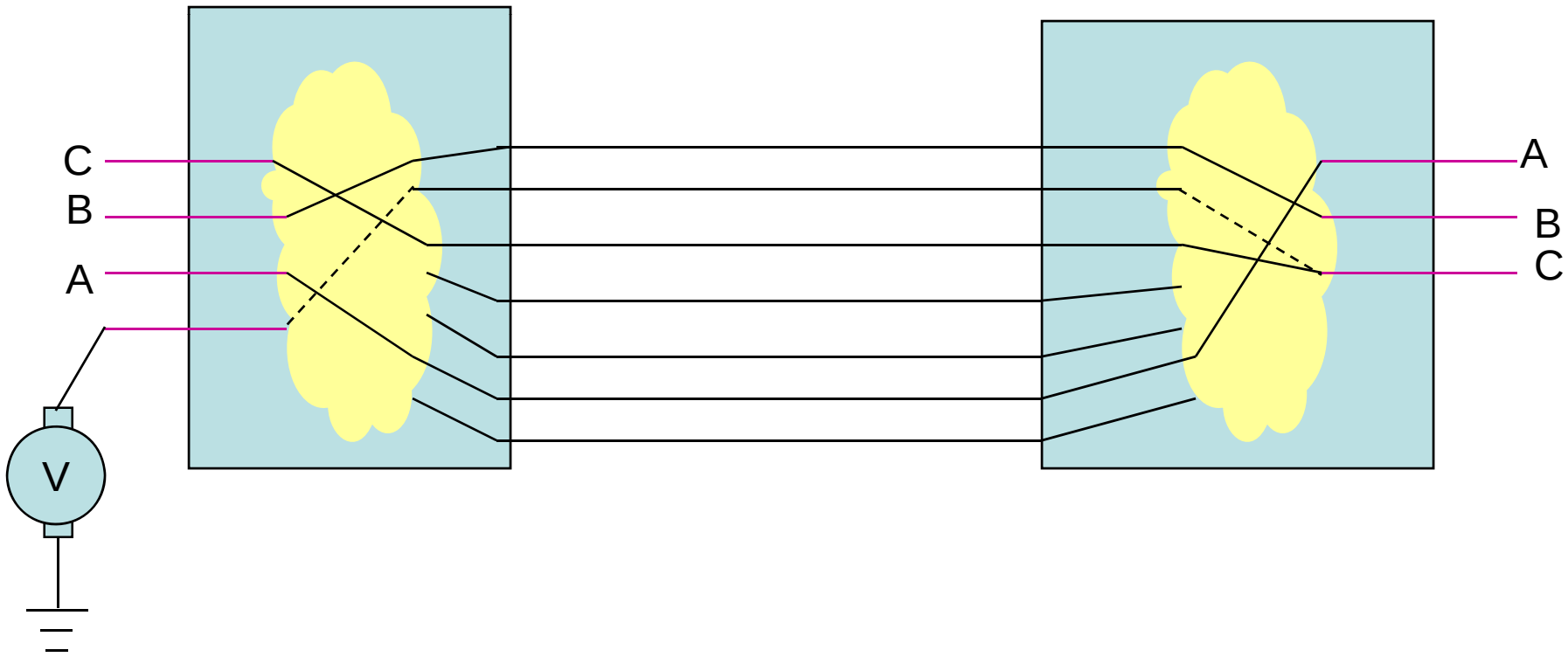
- Wiring harnesses take a long time to build
- Adaptive harnesses can be pre-build and programmed in minutes
- The adaptive wiring manifold complements and extends the utility of the SPA concept by allowing other special types of electrical connections (e.g. analog, rf) to be programmable managed in a “plug-and-play” manner

Adaptive wiring allows terminal connections to be set under software control

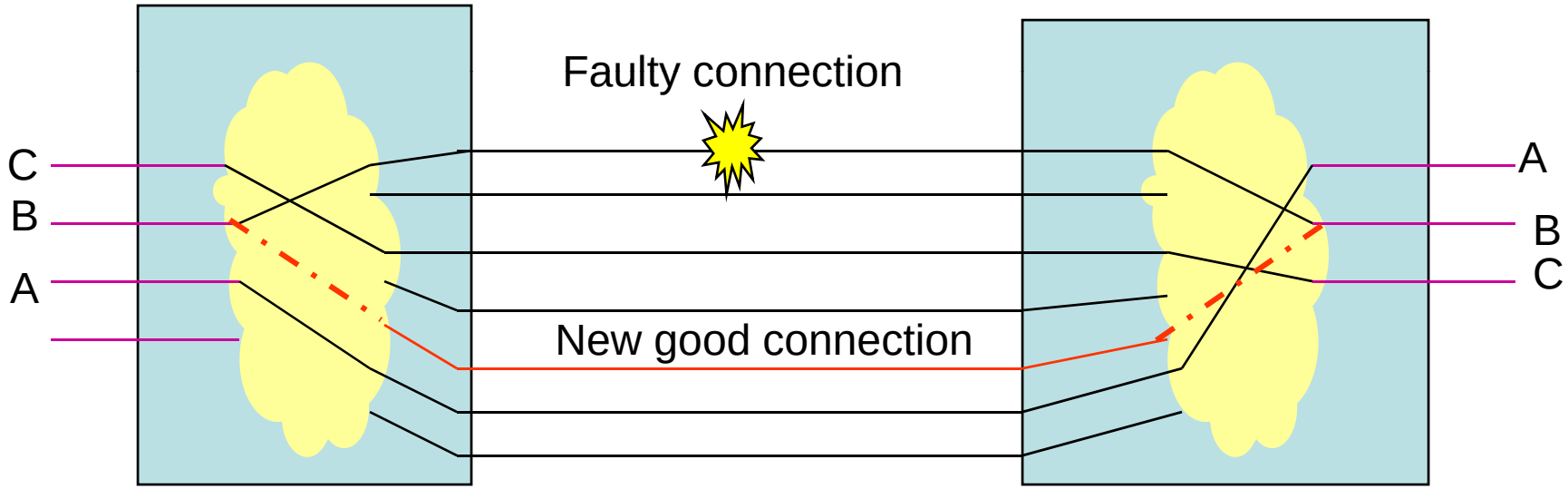


Adaptive manifolds can be built into panels or boards, which can flexibly assembled in different ways and programmed in ensemble to yield the desired connection patterns

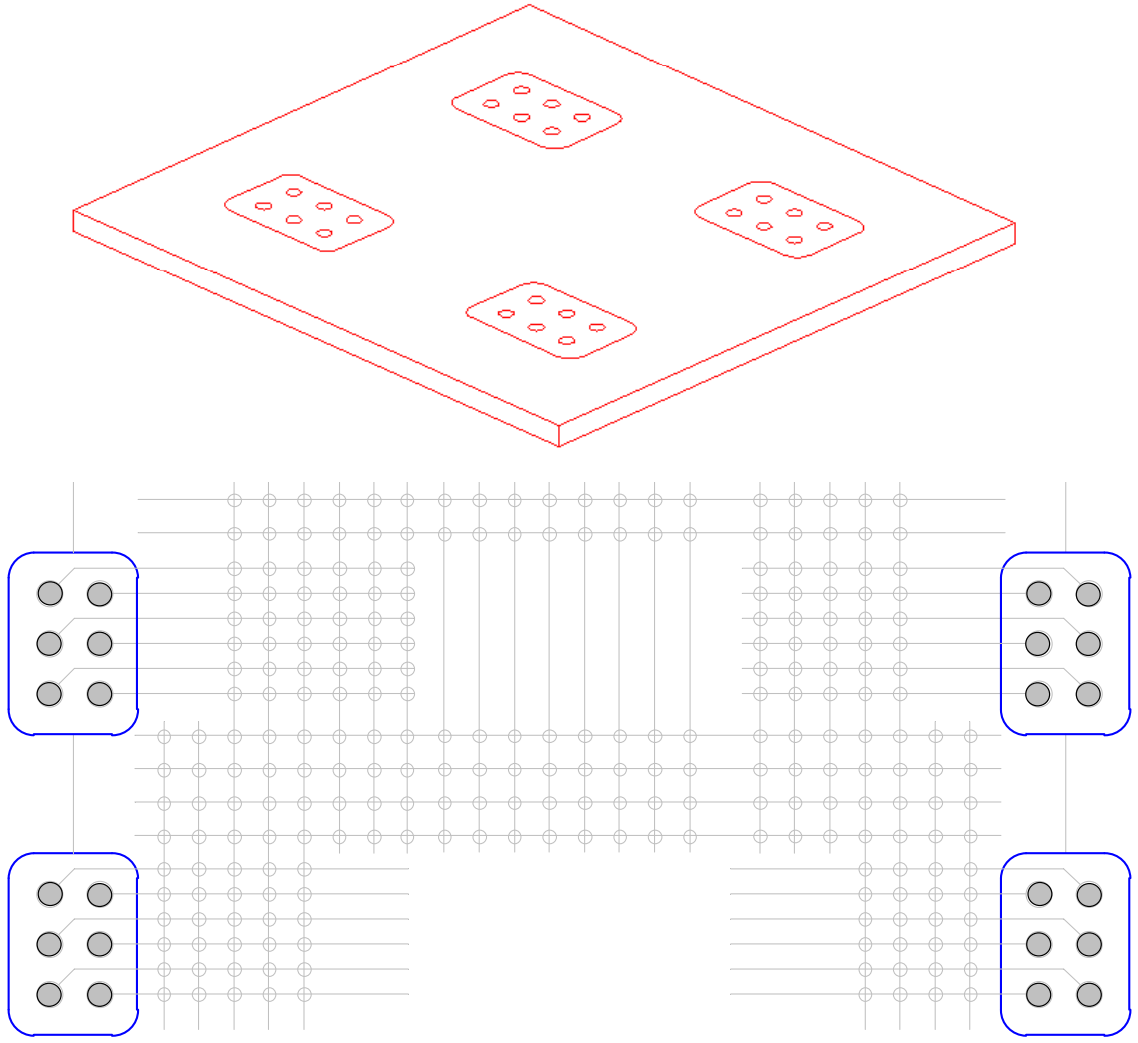
Temporary probes can be inserted and “dissolved” when no longer needed. In this case, we use the manifold to set up a temporary connection to check a possible problem with terminal C on the right panel



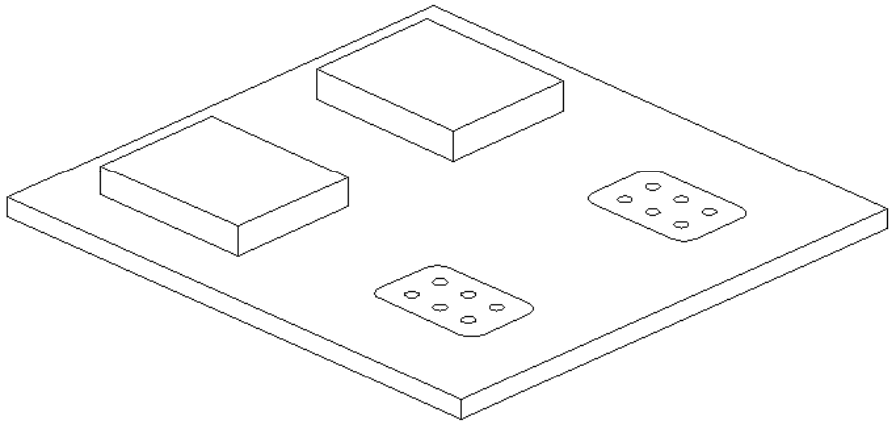
Adaptive manifolds can be reconfigured around defects or faults. In this case, we circumlocute a fault affecting “B” by reprogramming the manifolds in two panels

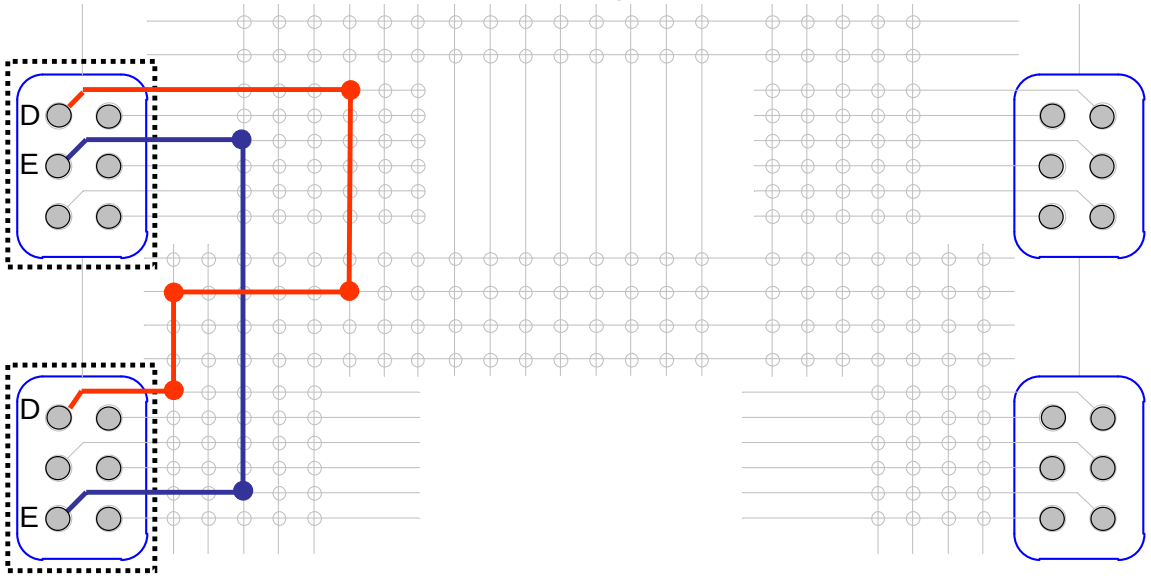


The physical embodiment of an adaptive panel could employ a number of sockets. The internal construction is at one level merely a series of wires (straight lines) and switches (hollow circles)

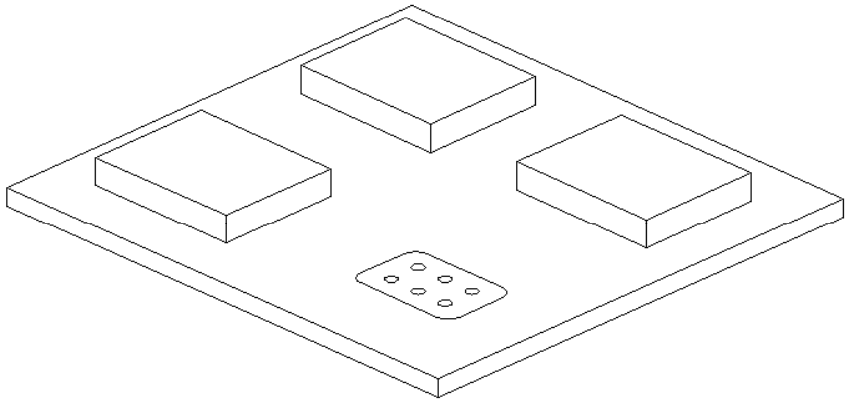


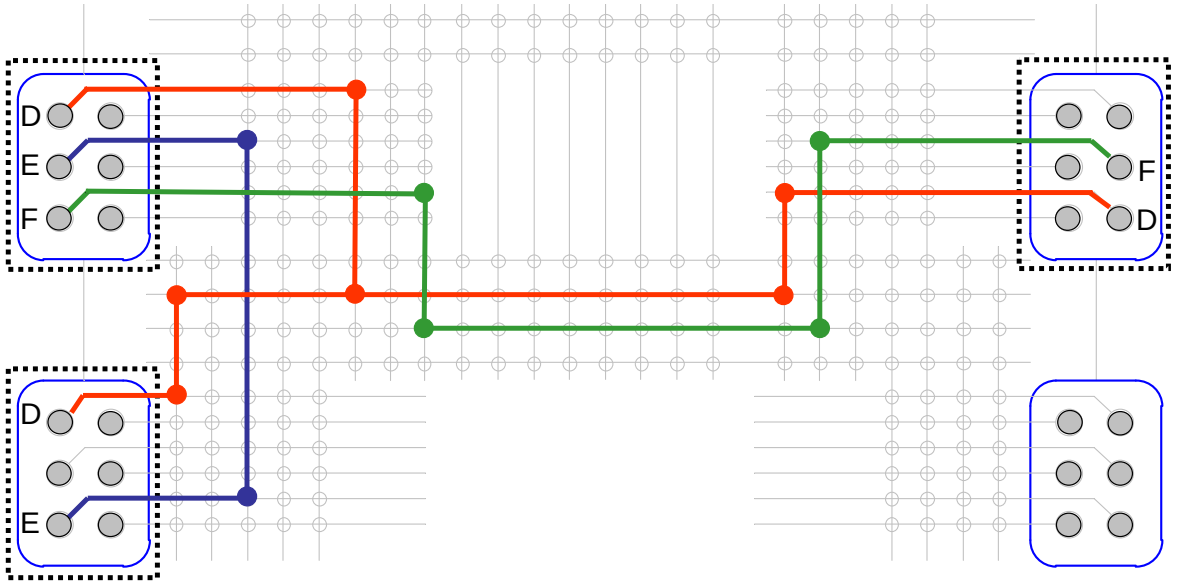
Terminals between different components plugged into the panels are formed by closing the proper switches (the paths are generally non-unique). This approach is very similar to the routing networks in FPGAs, except that the switches might be many small metal electromechanical relays or high-amperage solid state relays



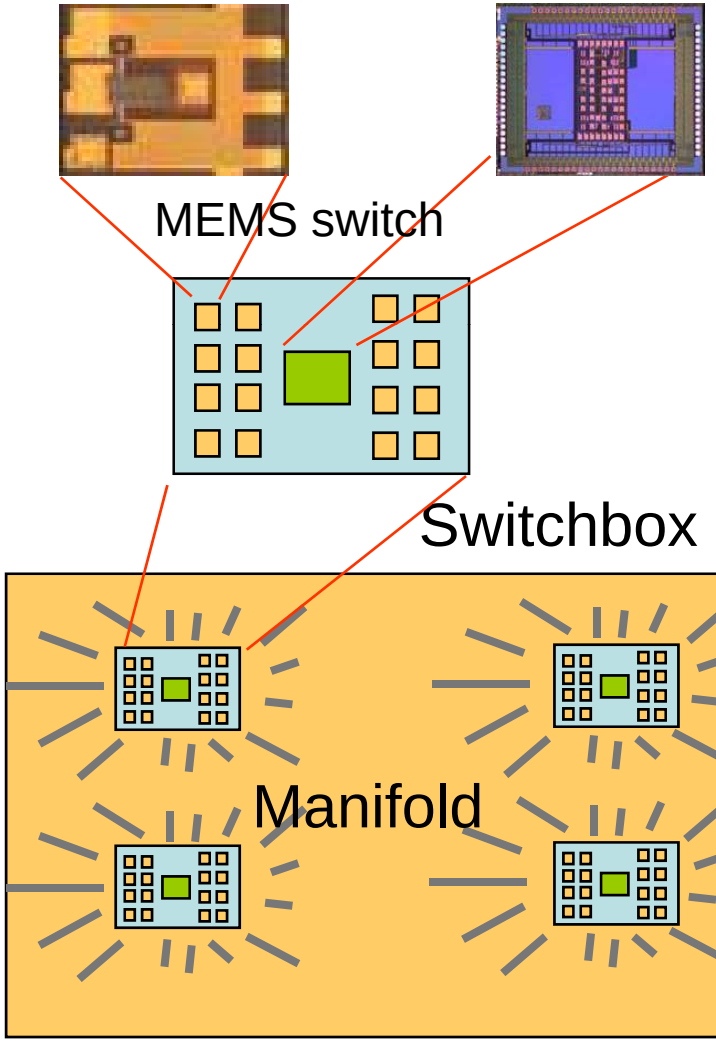


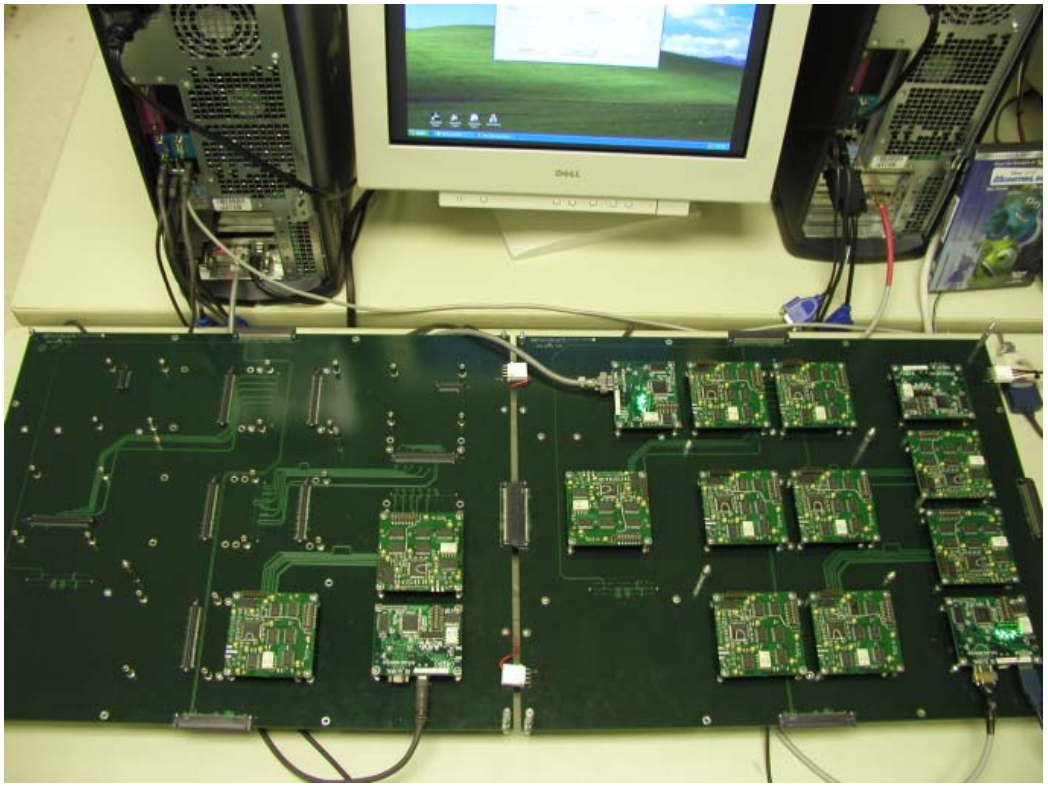
Of course, when more components are added to an adaptive panel, additional connections can be instantiated as needed



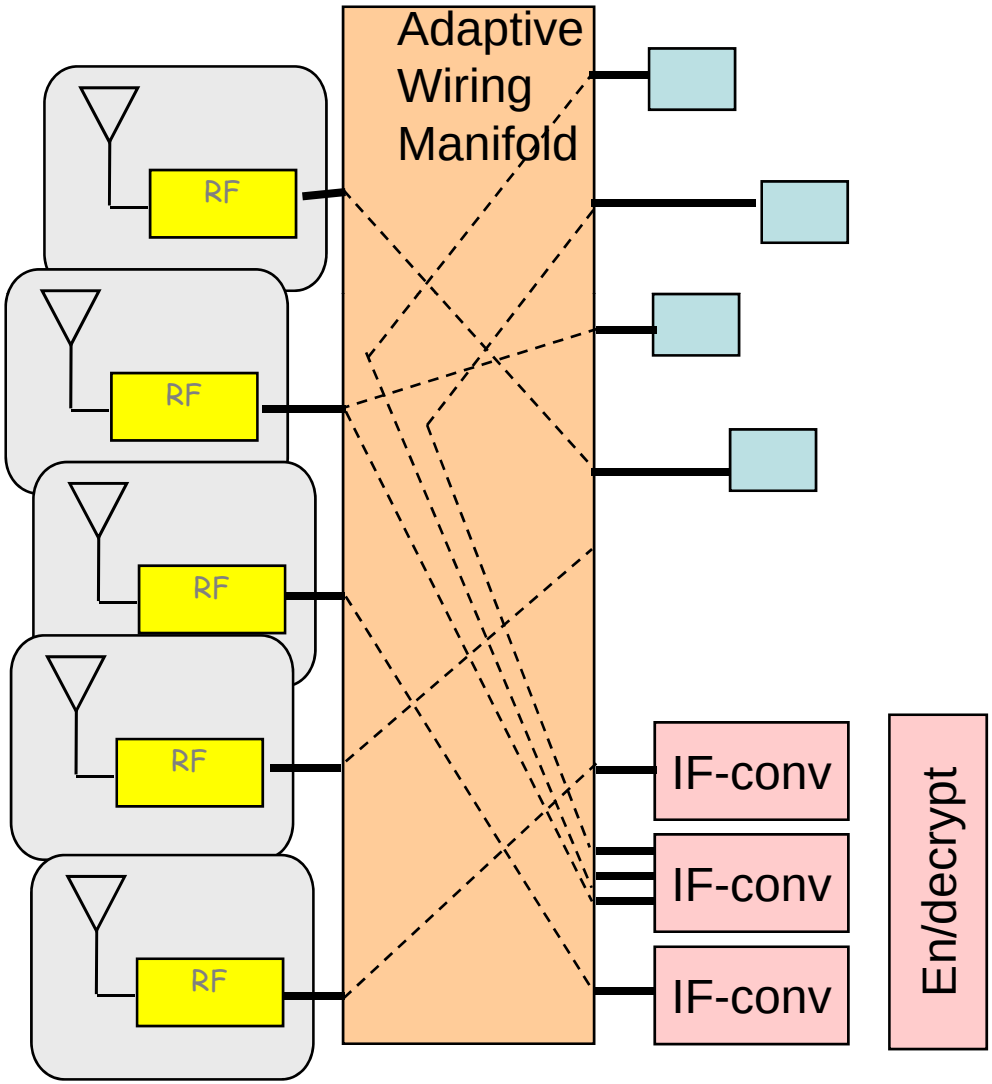


AFRL developed a simple demonstration of the adaptive wiring technology using two large “panels” and over 100 latching microelectromechanical switches,grouped into several sw. We were able to successfully move persistent (non-volatile) copper pathways from port to port

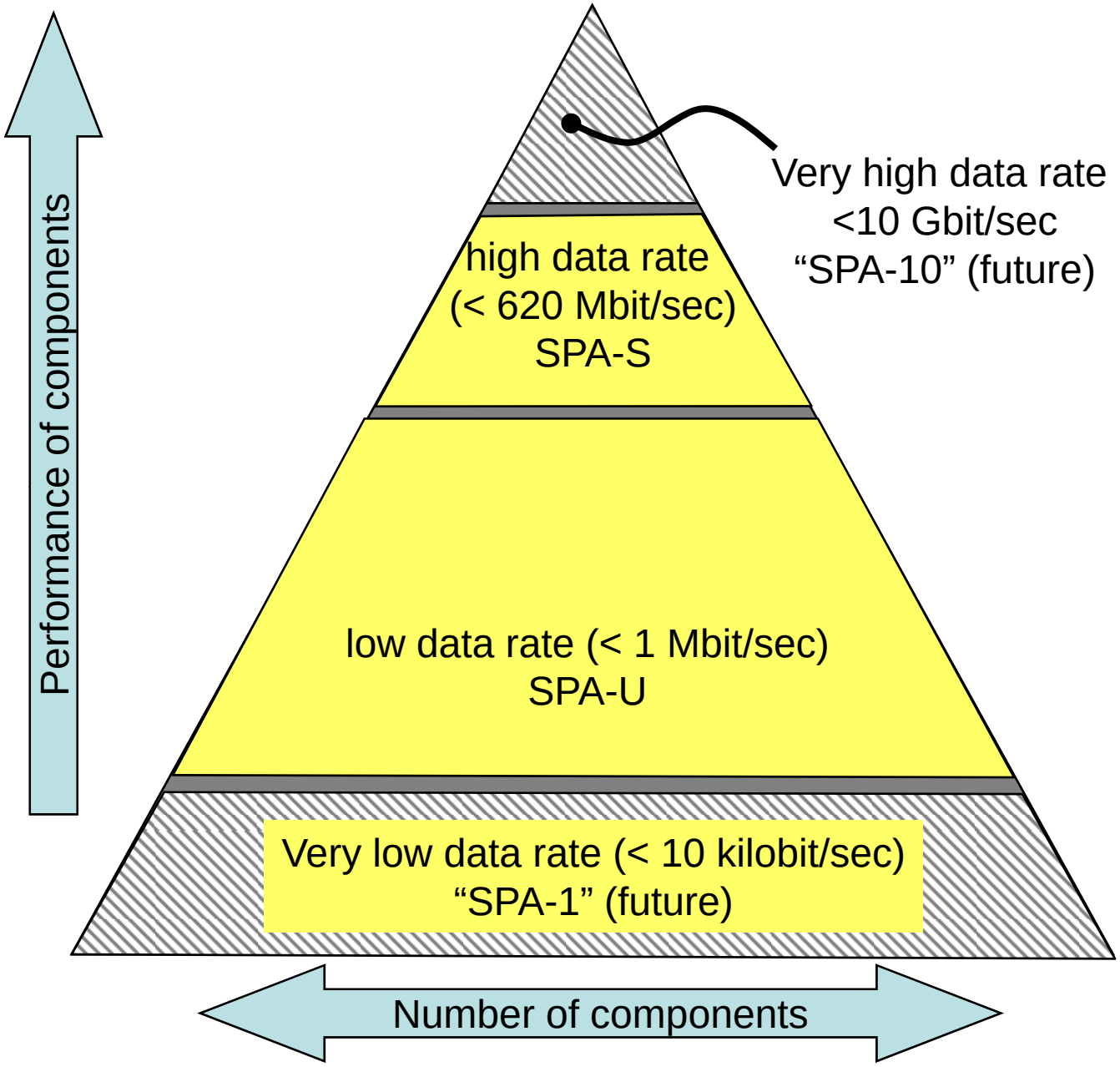




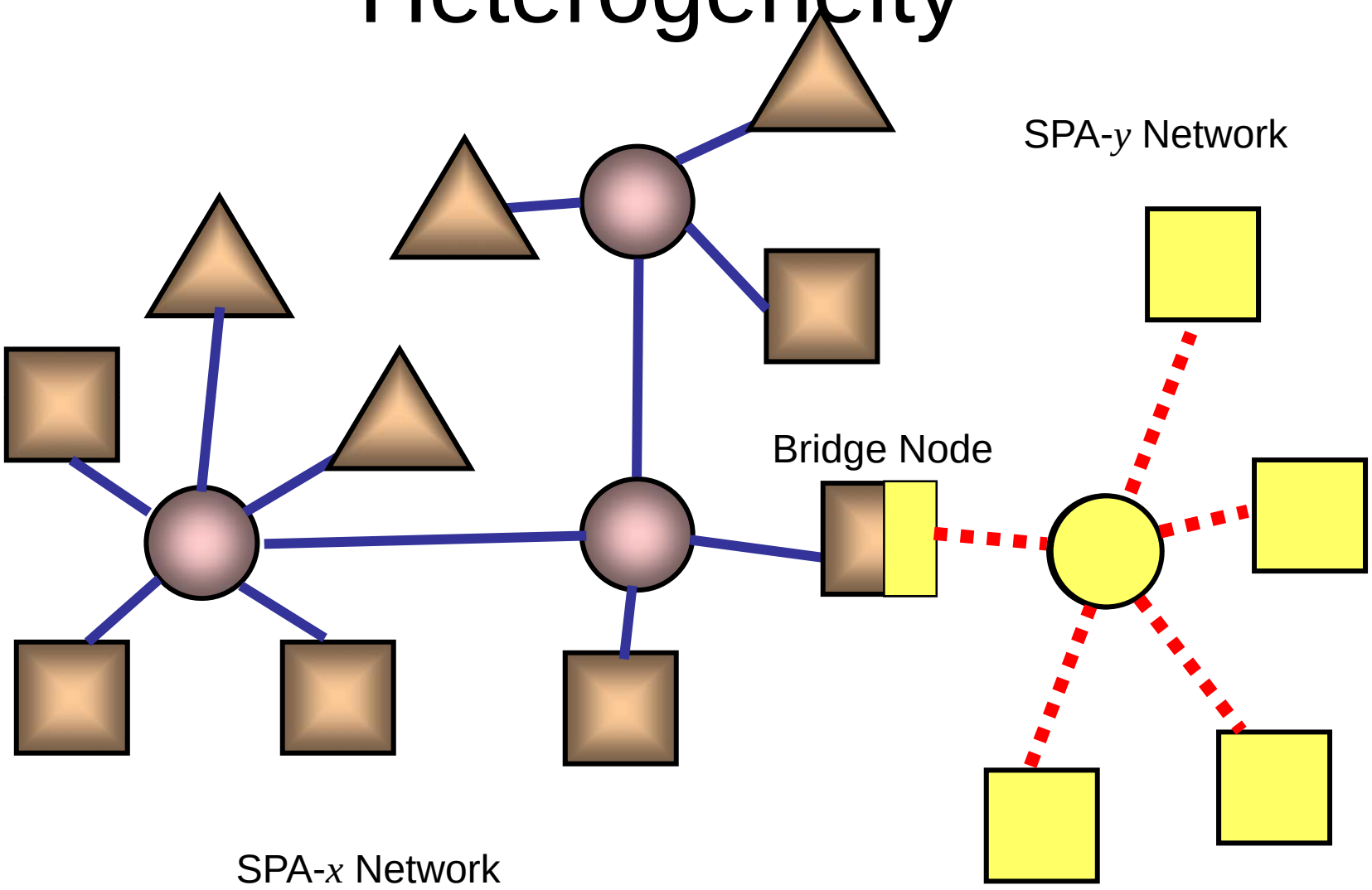
LEGO radios (Beyond “software radio”)



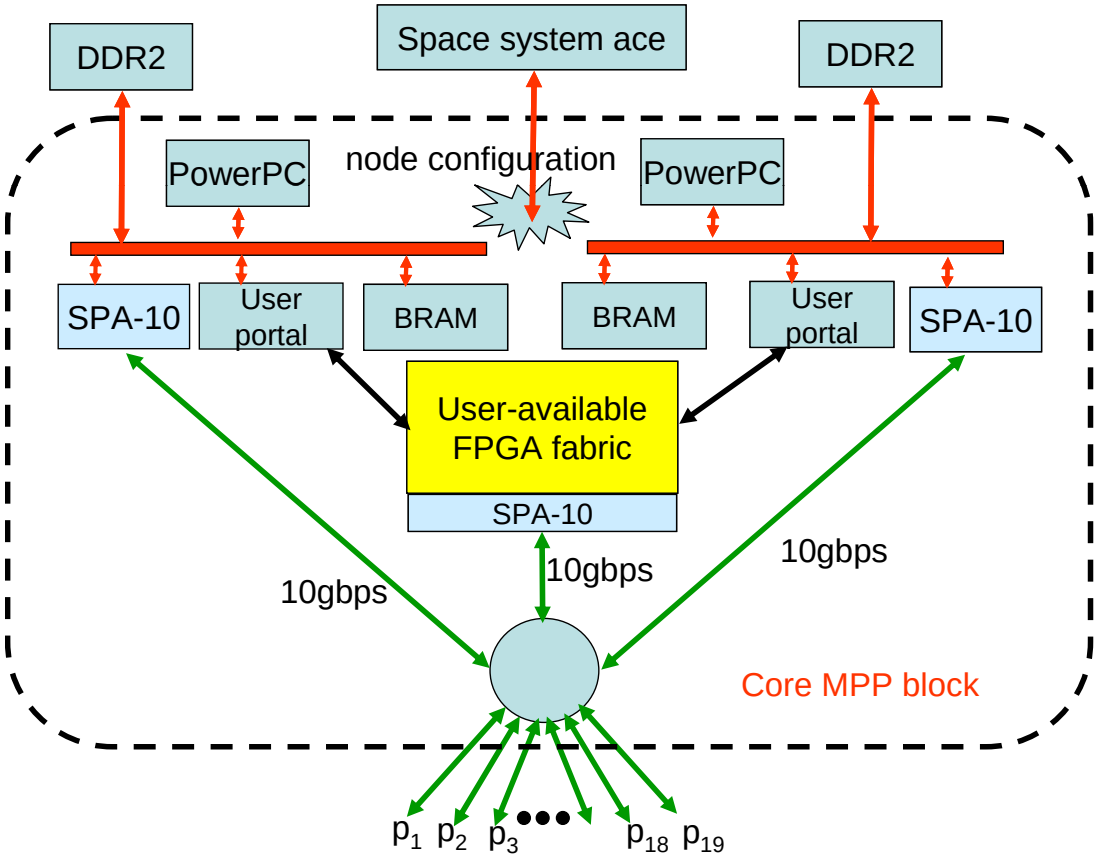
- Ability to comingle elements of a modular rf system fluidly, adaptively
- provision of more comprehensive spectrum coverage
- “Cognitive radio” (support for plug-and-play waveforms, dynamic waveforms, and adaptive configuration)


Performance of components
Very high data rate
<10 Gbit/sec
“SPA-10” (future)
high data rate
(< 620 Mbit/sec)
SPA-S
low data rate (< 1 Mbit/sec)
SPA-U
Very low data rate (< 10 kilobit/sec)
“SPA-1” (future)
Number of components

Heterogeneity

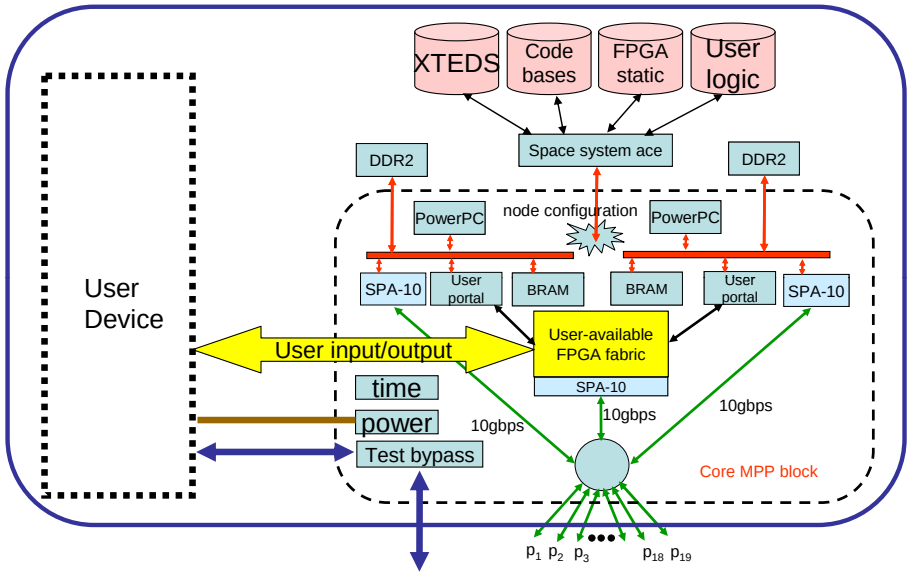


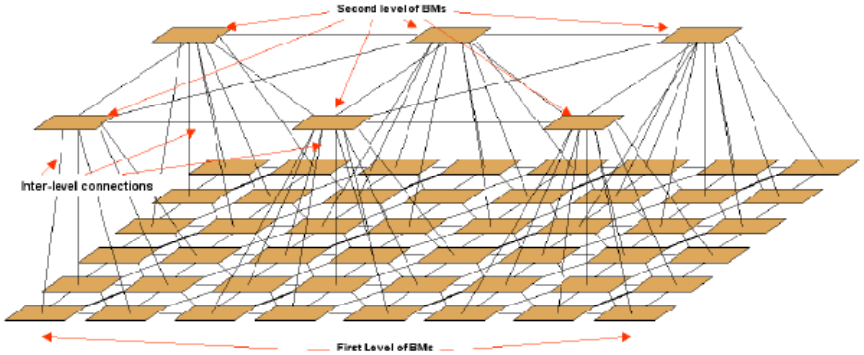
High-performance ASIM concept for 10 gbps standard



- FPGA-based ultra-scalable network
- Each node supporting up to 20 “SPA-10” ports

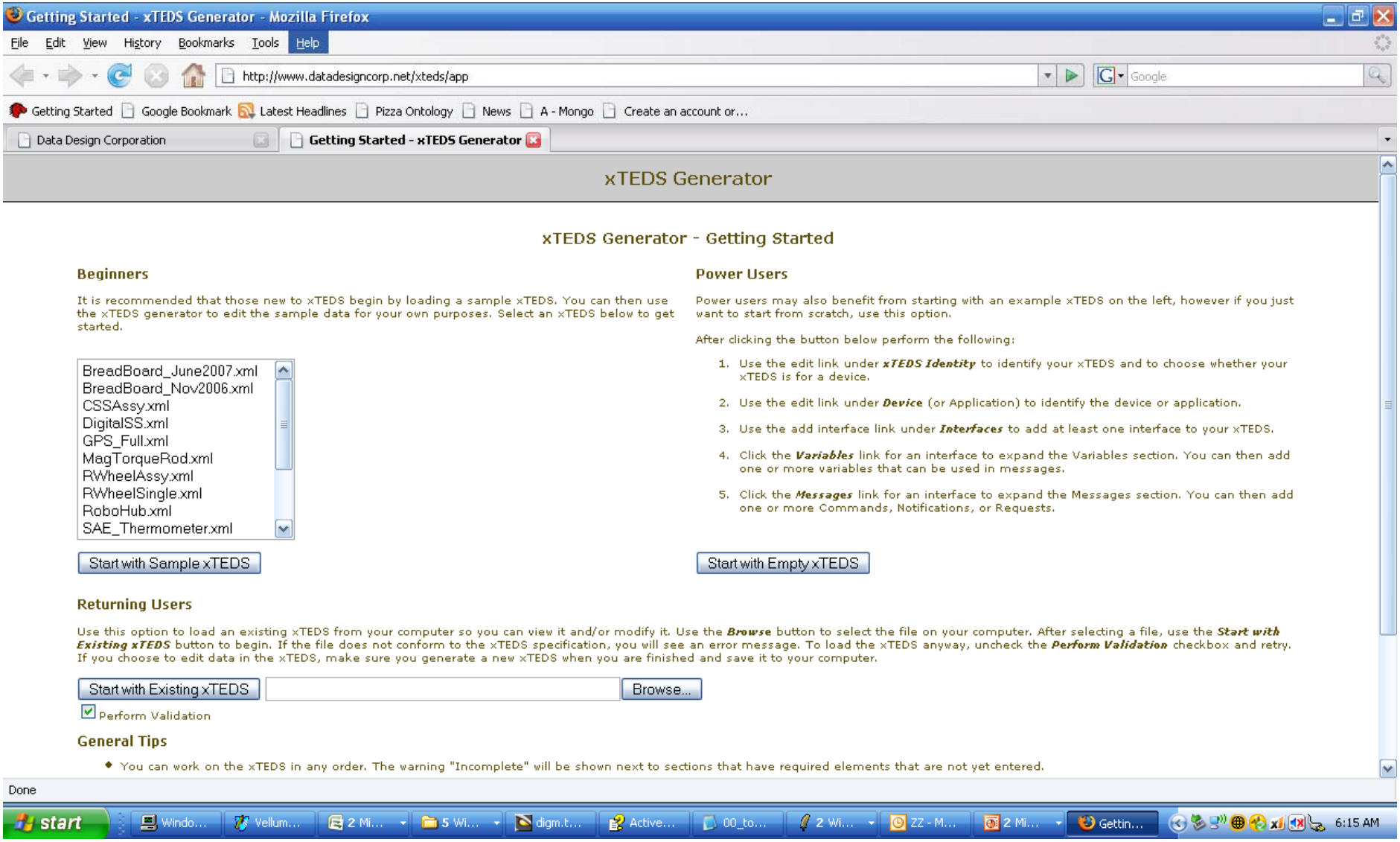
Self-scaling networks of multi-gbps endpoints





- Encapsulated high-performance nodes (up to 100Gbps bisection bandwidth)
- Scalable SPA super-computing fabric supports grid-like connection of many SPA-10 devices
- Lower-speed SPA networks connect through bridge nodes

Web-based XTEDS builder



Standards- “Help-Desk” Approach

- Let’s establish a foundation within a non-profit to serve as a go-to
- A central place for
  - Standard drafts
  - Education / training
  - Workshop coordination
  - Community indexes
  - Databases for software, component libraries, design aids
- Support needed for
  - Secretariat administrative roles for brokering the standards to a publishable form
  - Supplemental IT support to create the public and member only sections of the website and support the databases necessary
  - Manpower to create the documents, evolve to a useable form (ex. In PnP, anyone smart enough to create the document is dedicated to creating the technology – sound familiar?)

Conclusions

- Key principles of SPA as a disruptive technology
  - Smart interfaces, self-description, casual arrangement of network element, complexity hiding and encapsulation, robust software infrastructure (SDM)
  - Push-button toolflow (embodied in the Mission Sattelite Design Toolkit)
- Dramatic benefits: faster, more flexible, more robust, less expensive systems
- SPA-U/SPA-S infrastructure has advanced enough for serious prototype development
- Critical point in evolution – how do we cross the chasm (technological valley of death)?
- Promotion through standards, small business community to push technology to a critical “tipping point”

Acknowledgements

- Gifted, distributed research team
  - In-house staff
  - Small Business Innovative Research Program
- Support and commitment of AFRL management
- Those who attended our workshops and believe in us