MMS: Hardly Your Fathers’ Simple Spinner – Systems Challenges Designing, Building, and Operating Four In-House 'Precision' Spinners

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Simple Spinner? Pete Spidaliere's First Day on MMS.

"All they think I can do is a simple spinner. *(expletive deleted),* I've really *(expletive deleted)* coming back to Goddard."

Internal monologue, Pete Spidaliere, Oct 2005.

Introduction to Reconnection

- Throughout the universe when magnetic fields in adjacent regions have significantly different directions they often become interconnected, and plasmas move rapidly across the otherwise impenetrable boundary between the regions. This process is called magnetic reconnection.
- Magnetic reconnection is especially important because it explosively converts magnetic energy to heat and kinetic energy of charged particles, producing many intense phenomena from brilliant auroras to dangerous high-energy cosmic rays.
- The best laboratory for studying reconnection is the Earth’s magnetosphere. In fact, this is the only place where the reconnection process can be probed directly in space.
- Because reconnection is a 3-D process involving the rapid inflow and outflow of charged particles, a cluster of four spacecraft with carefully selected separations and instruments will be needed for a definitive experiment.

A Fundamental Universal Process

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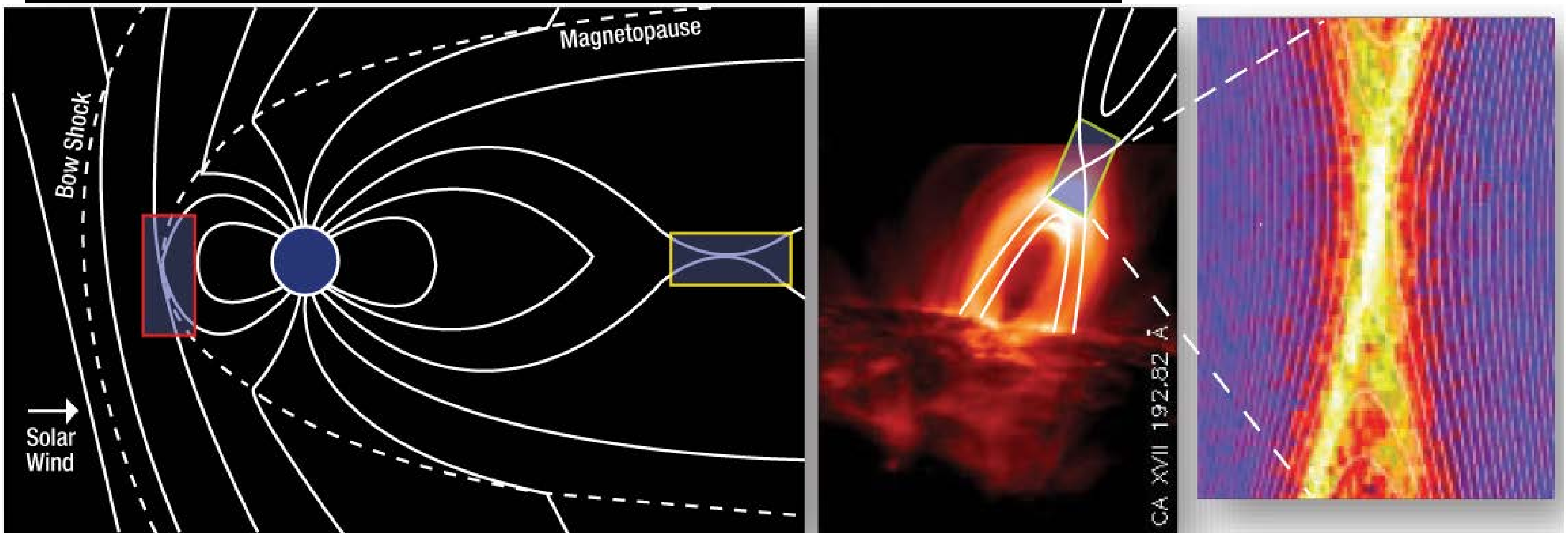

Magnetic reconnection is important in the (a) Earth's magnetosphere, (b) in the solar corona (solar flares and CMEs) and throughout the universe (high energy particle acceleration). Simulations (c) are used to guide experiments.

Generalized Ohm's Law

- **Electron momentum equation (Newton's second law for electrons) is often written in terms of the E-field as:**

$$E + v \times B = \frac{m_e}{e}\frac{dv_e}{dt} - \frac{\nabla \cdot \overleftrightarrow{P}_e}{en} + \frac{J \times B}{en} + \eta J$$

- **Ok, ok, so what's the long and the short of what instruments we need?**
  - E-Field Instruments: electric field probes
  - B-Field Instruments: DC and AC magnetometers
  - Electron Spectrometers: electron number, direction, energy
  - Ion Spectrometers: ion number, direction, energy
  - Composition analyzers: distinguish the species of ions
  - Plasma contactor: controls spacecraft potential

MMS Instrument Suite Components

(view looking from the bottom of the IS Deck)

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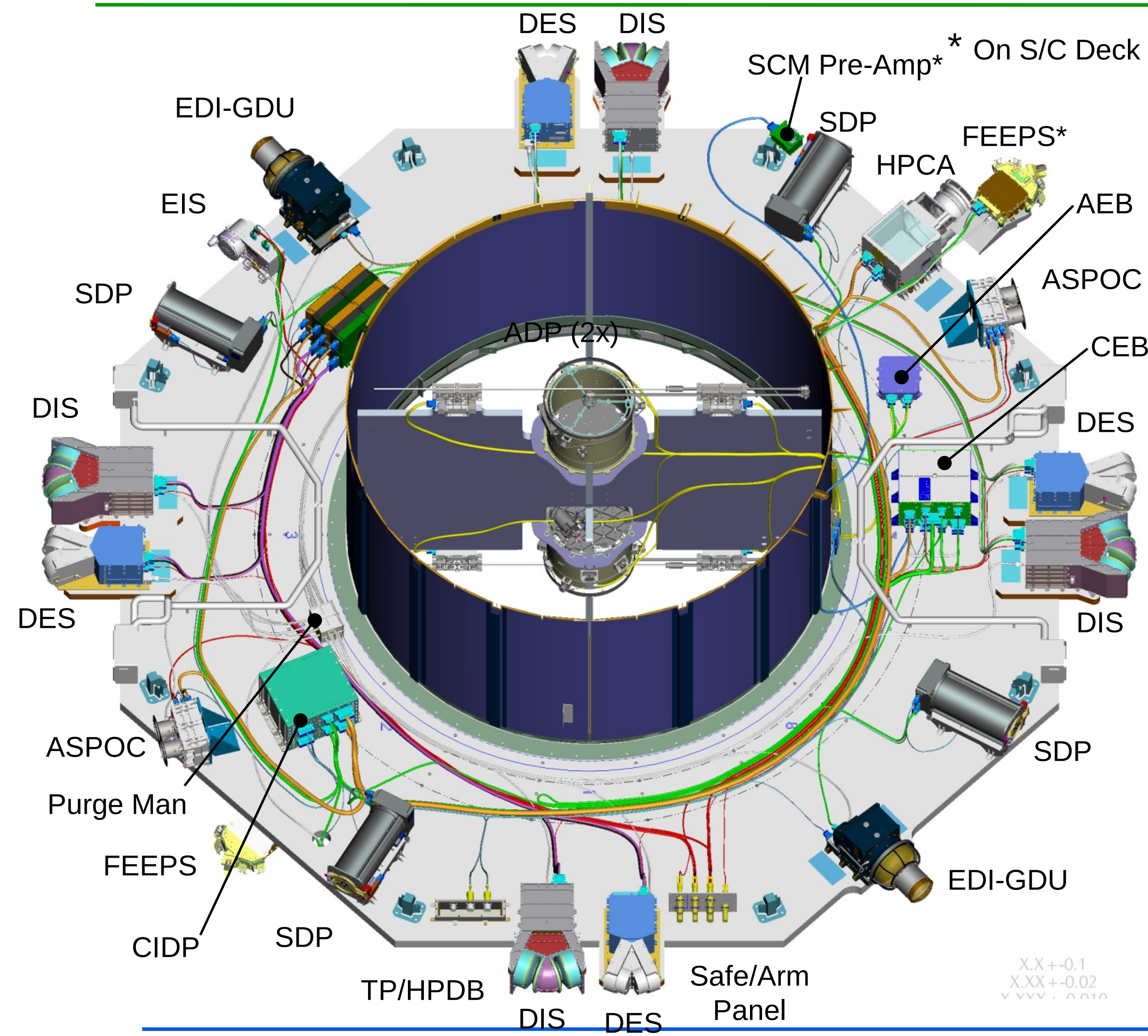
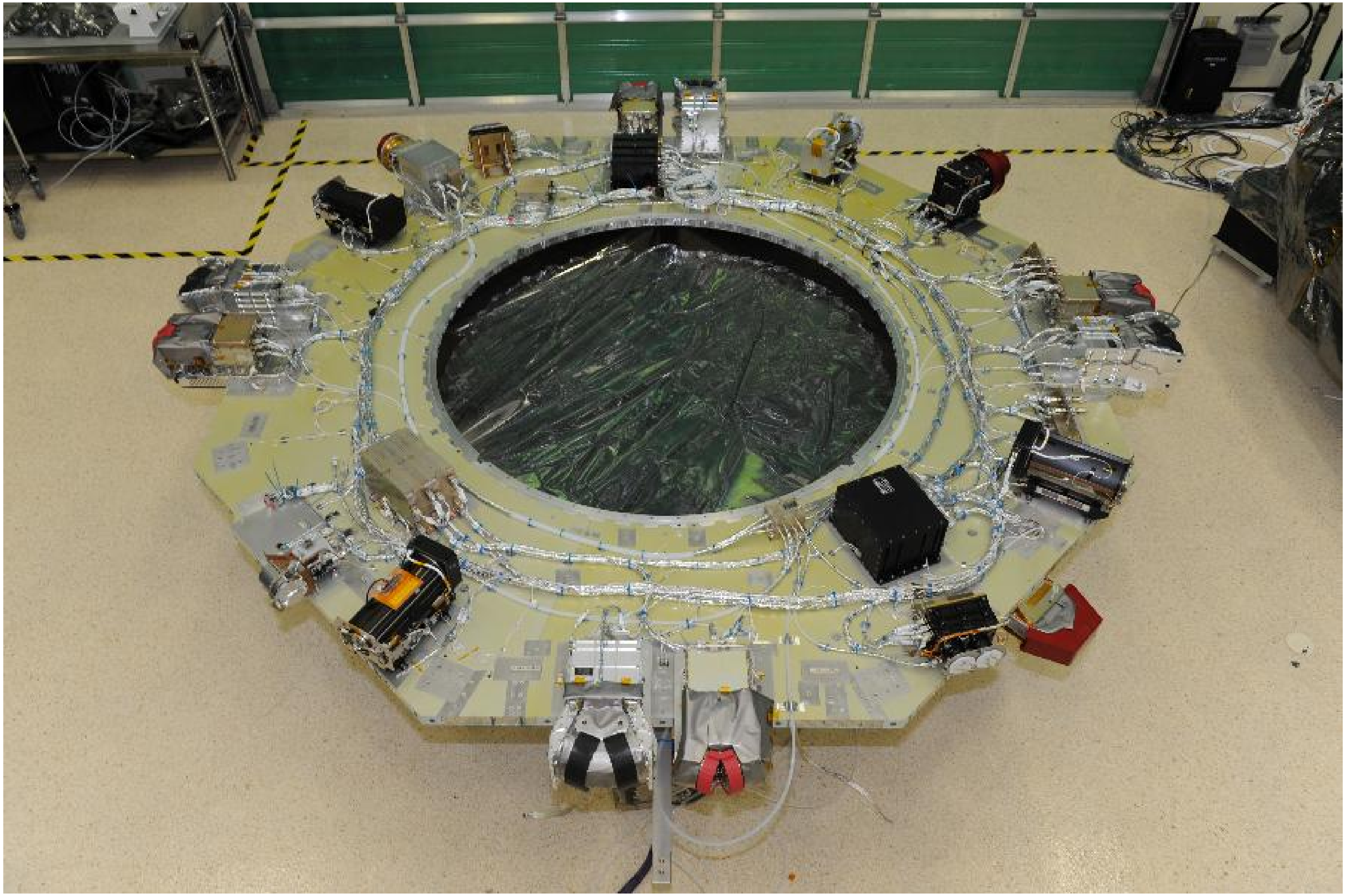


ADP - Axial Double Probe
AFG - Analog Flux Gate Magnetometer (mounted on boom)
ASPOC - Active Spacecraft Potential Control
CEB - Central Electronics Box (Fields)
CIDP - Central Instrument Data Processor
DES - Dual Electron Spectrometer
DFG - Digital Flux Gate Magnetometer (mounted on boom)
DIS - Dual Ion Spectrometer
EDI/GDU - Electron Drift Instrument/ Gun Detector Unit
EIS - Energetic Ion Spectrometer
FEEPS - Fly's Eye Energetic Particle Sensors
HPCA - Hot Plasma Composition Analyzer
IDPU - Instrument Data Processing Unit (FPI)
SCM - Search-Coil Magnetometer (mounted on boom)
SDP - Spin-Plane Double Probe
TP/HPDB – Test Panel Heater Power Distribution Box

Instrument Suite 1



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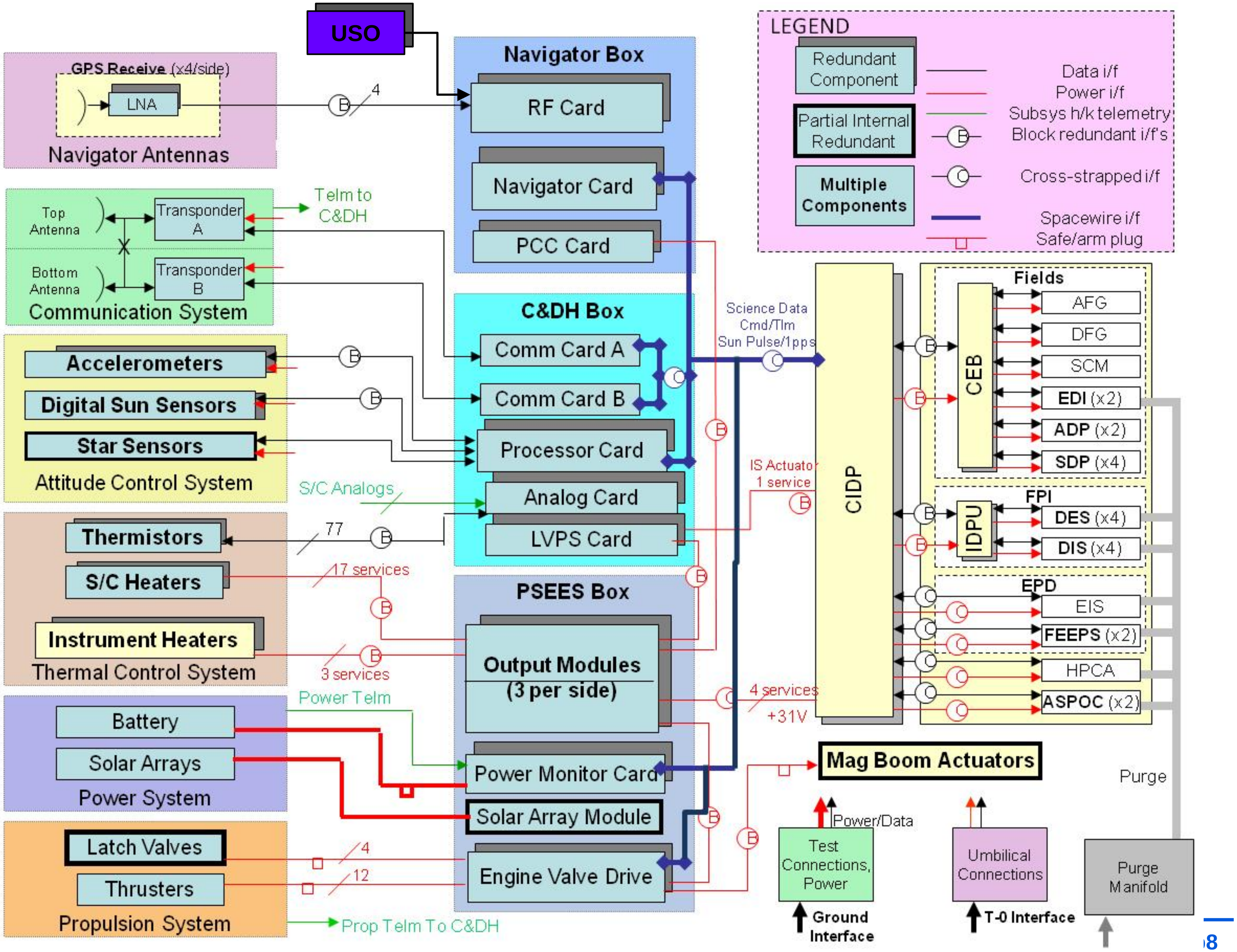
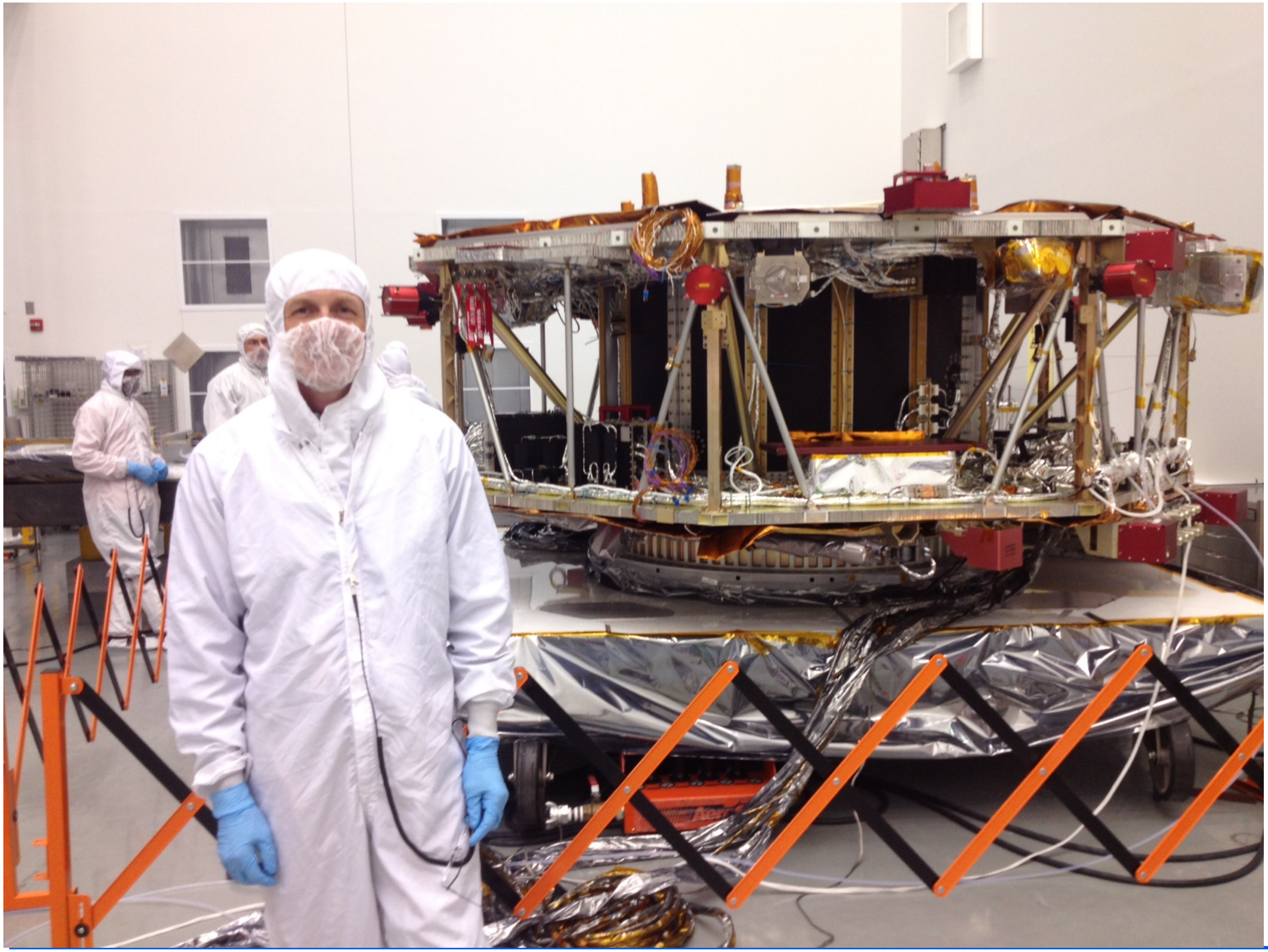
Block Diagram
Something missing? There will be a quiz.



Observatory 1 (MSE accidently let into the Cleanroom)



Observatory 2

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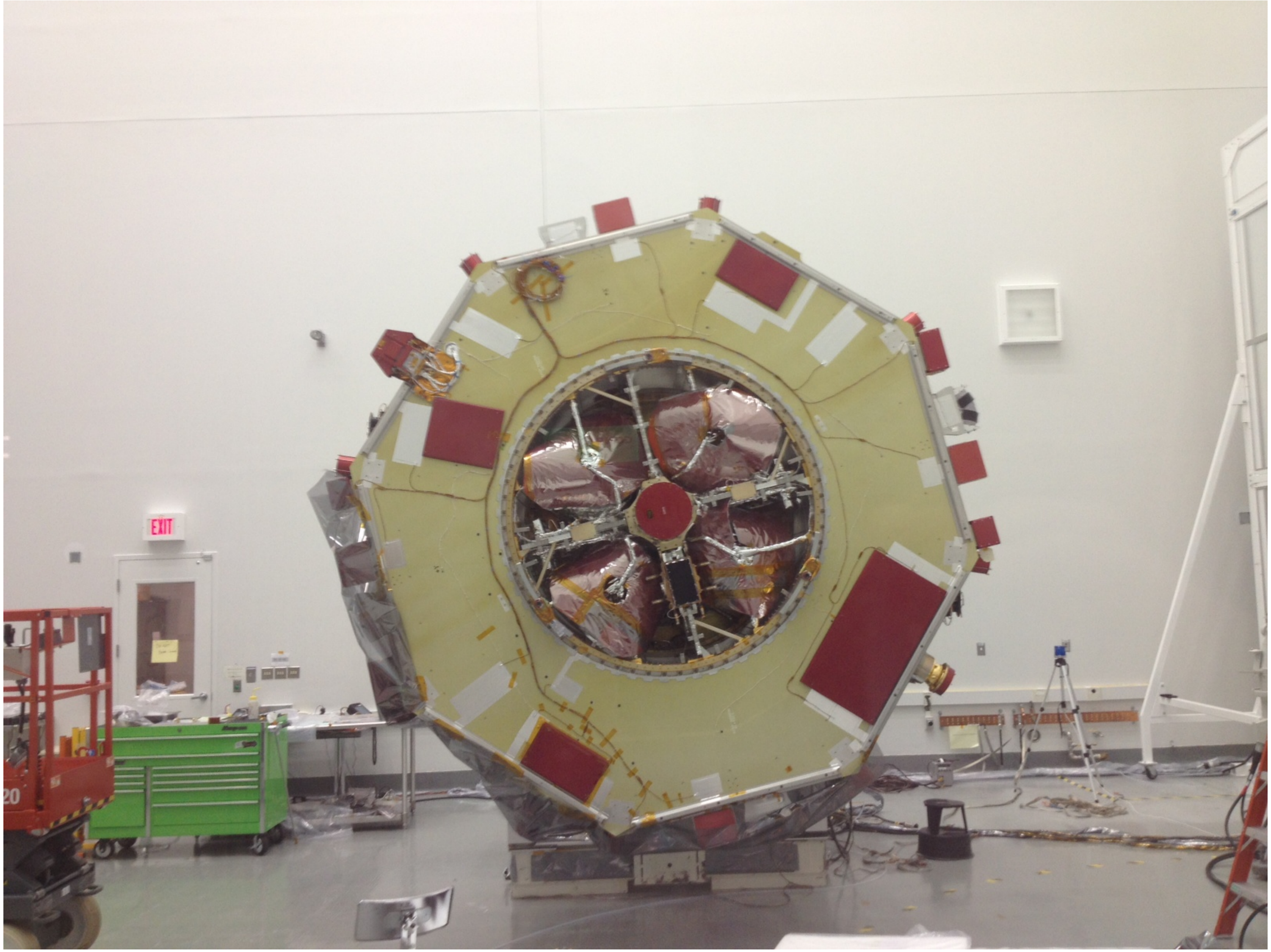
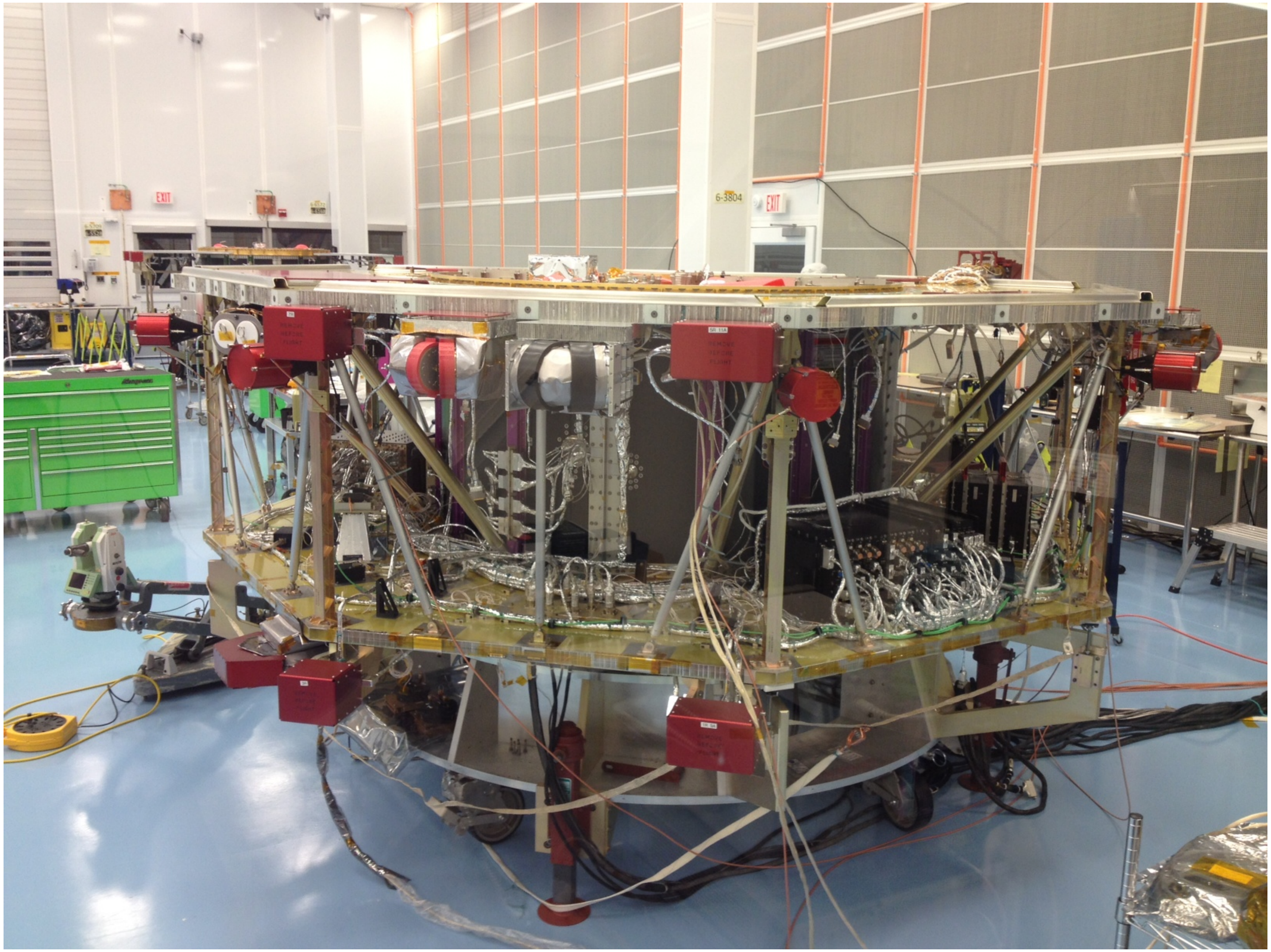
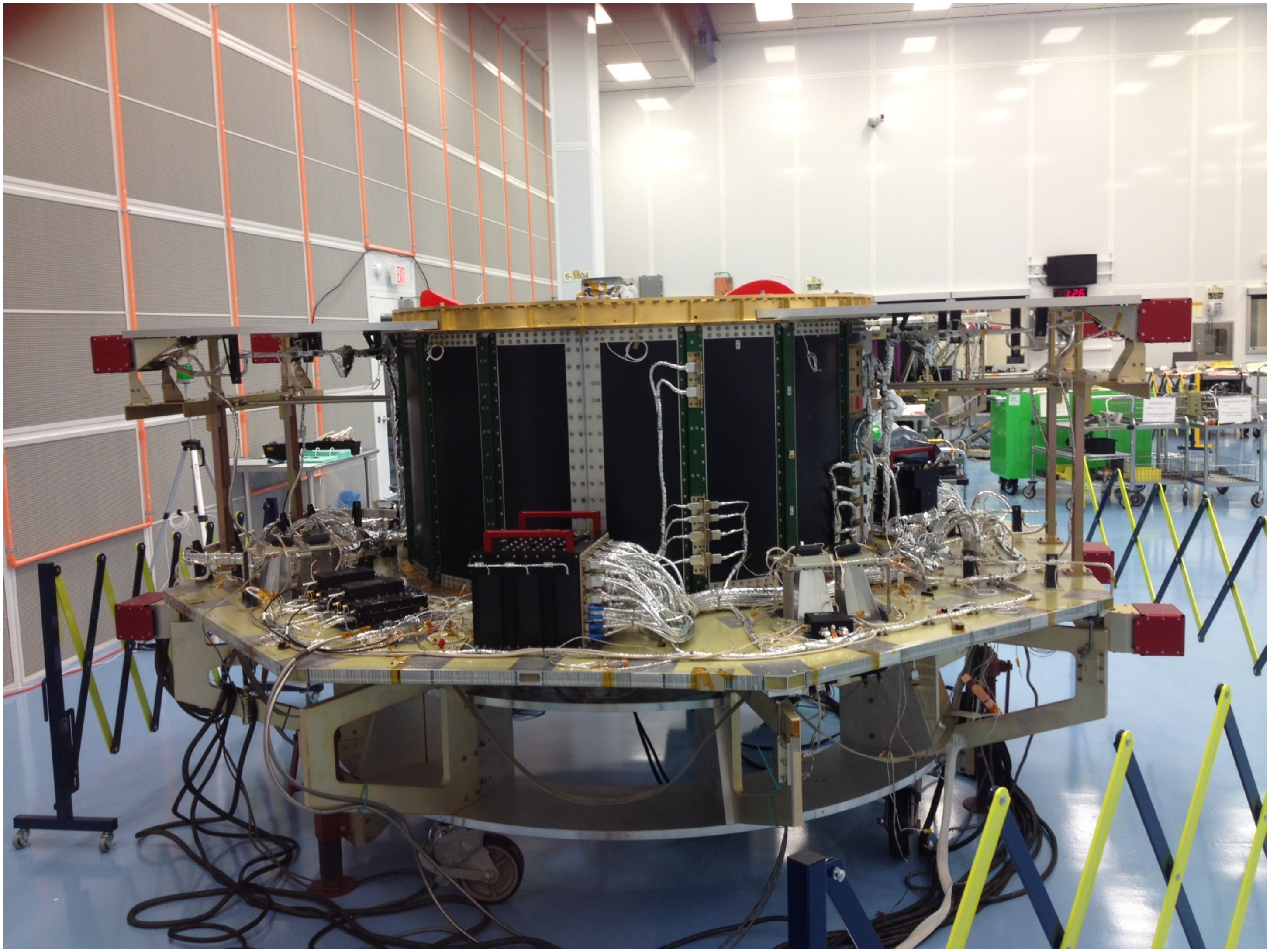


Observatory 4 (3th bird)



Observatory 3
(4rd bird)



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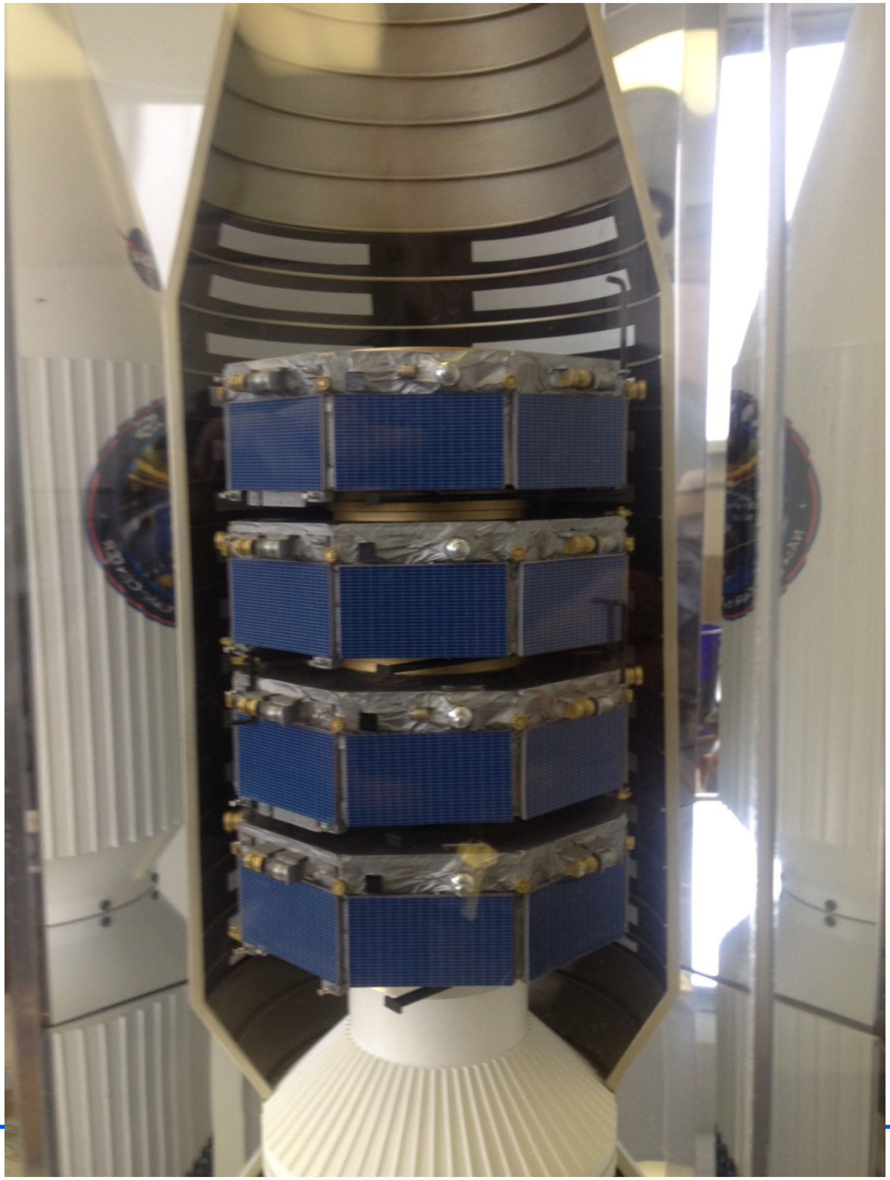
Stack Config
No model, only a photo, its pouring.



Design Challenges
Precision Flying

- **Precision flying – 10 km tetrahedron formation with an average of 14 days between maneuvers**
  - Low Signal Strength GPS – New Development
    - GPS contact till at least 15 Re
    - Did I mention we're spinning!
  - Attitude Control
    - Star Sensor
      - Angular position and rate
    - Accelerometer – New Development
      - "Measure" the delta V, not just the number of thruster pulses...
      - Sensitive enough to detect an earthquake in Central America
    - Control algorithms that don't use an IMU, but do use an accelerometer – New Development
    - Oh, we're spinning as we fire!
      - Think about that for a moment. How can you get a precise burn while you're spinning? Answer: lots of hard work and really good people.
      - We've also go 60m wire booms we can wrap around the bird.
  - Propulsion and Engine Valve Driver
    - Manly 1 and 4 pound thrusters
      - Limited by the bending strength of the 12m axial boom. We really don't want them to collapse.
      - Pulse width modulated thrusters (8Hz) – New Development
        - Puts the thrust centroid where we want it, the center of mass.
  - Mathematicians, I mean, Flight Dynamics Team – Entirely New Developments
    - Reference orbit software
    - Formation maintenance techniques and analysis tools
    - Apogee Raise technique "The Snake"

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Design Challenges: Flight Dynamics

These guys had a harder problem, but they’re about it.

Movie and Popcorn (and chance to hit the exits)

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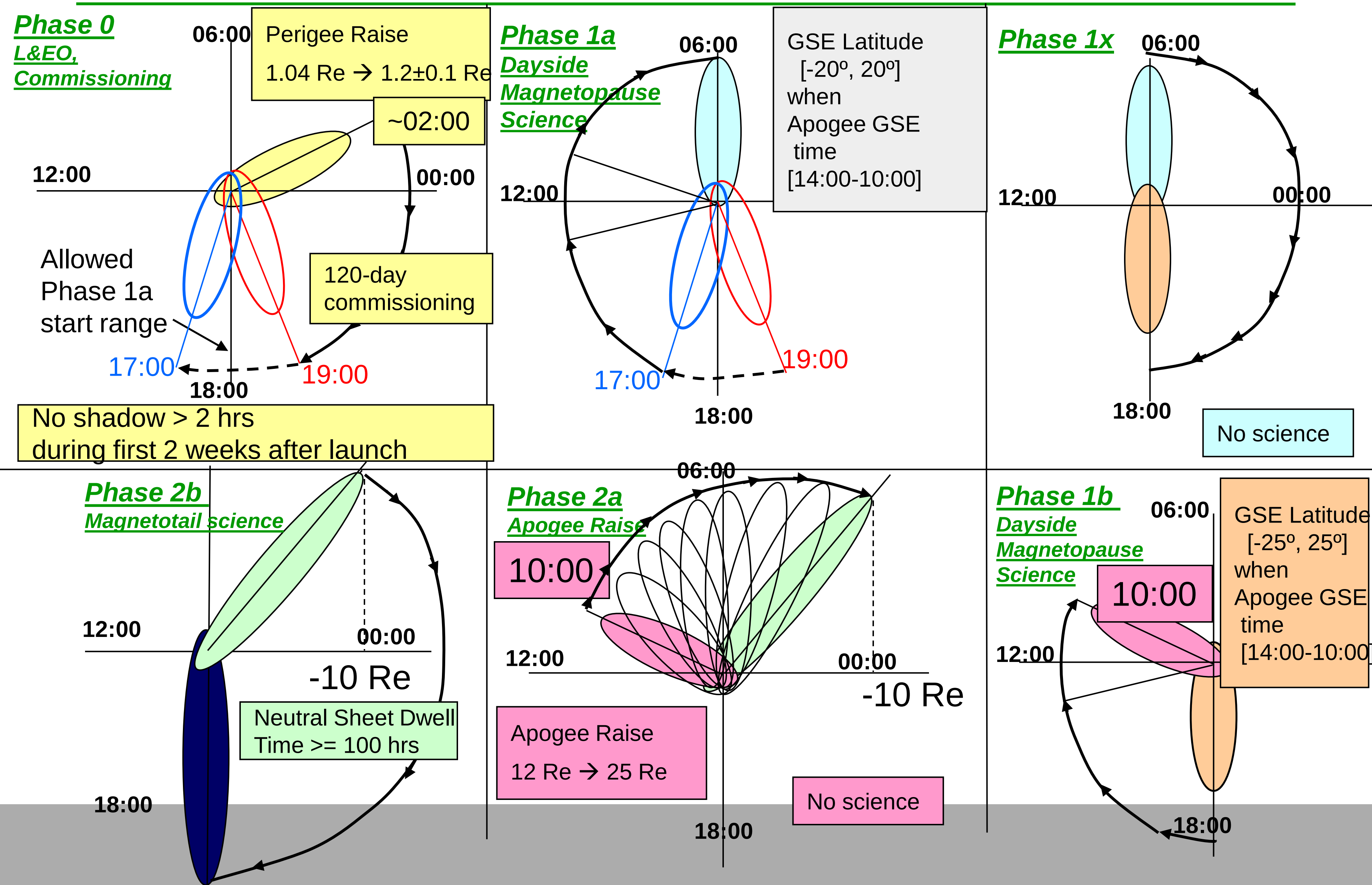
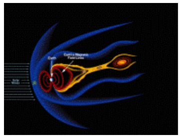
Mission Phases





Design Challenges
Magnetics and Electrostatics

- **Magnetic Signature (B-field)**
  - 0.1 nT magnetics requirements – toughest magnetics problem Goddard has faced
    - 5 m mag booms
    - 10 mA chassis current (MAX!)
    - Near universal avoidance of all magnetic materials
    - Allocations, measurements, and demaging of all boxes, fasteners, etc
    - Magnetic cancellation of the Solar Arrays and Battery currents
    - Full observatory level testing
- **Electrostatics (E-Field and Low Energy Electron Science)**
  - All exterior surfaces are grounded, with small exceptions
    - Germanium Black Kapton blankets, all grounded
    - Optical Solar Reflectors (radiators) with a conductive coating, all grounded
    - 1000’s of elements of the axial booms, all grounded with tiny ground wires
    - Separation system, that is usually left with the upper stage, modified to ground all surfaces, including moving ones.
    - Solar array coated with a conductive coating and interconnects
      - So very, very expensive
    - …

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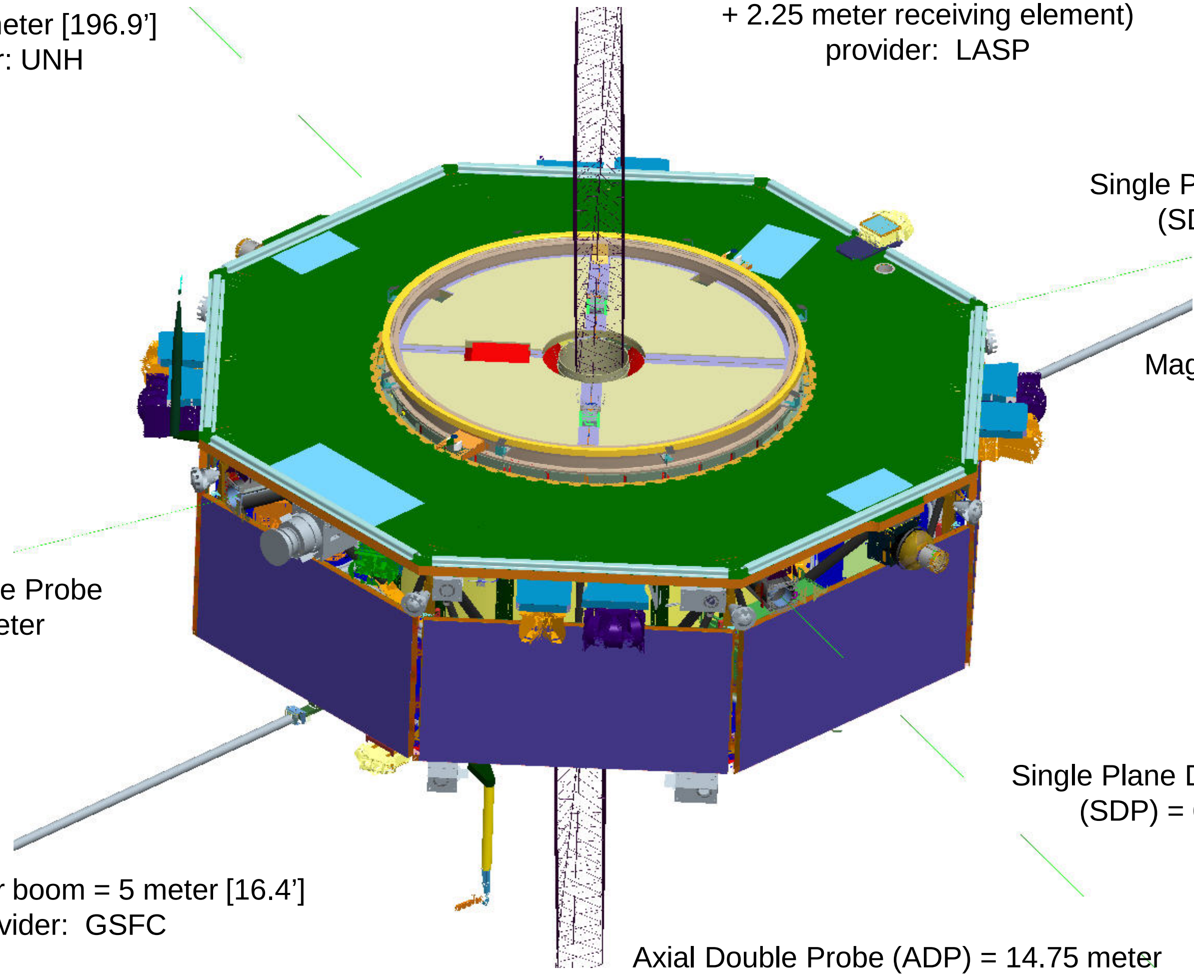
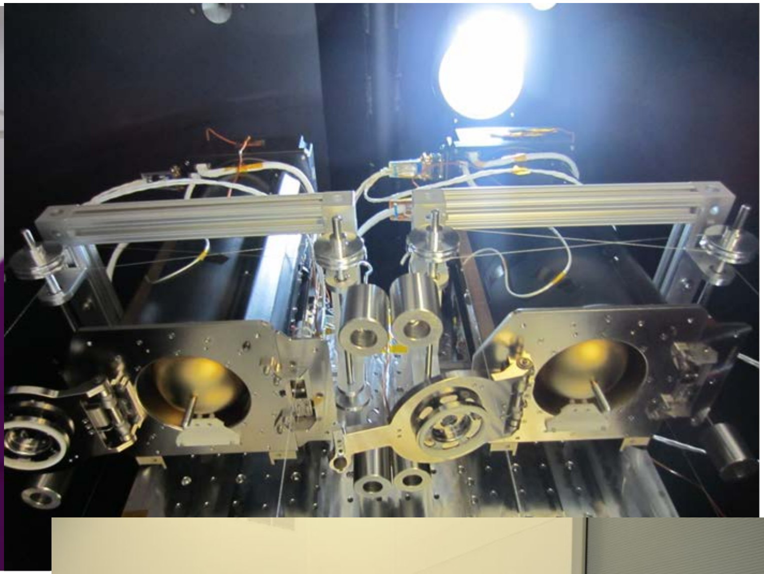
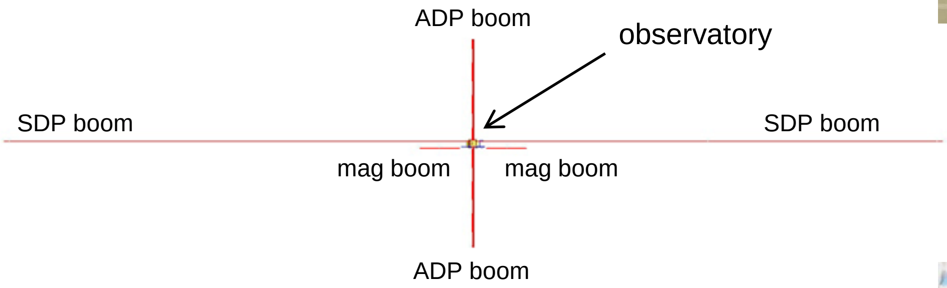
Design Challenges
8 Booms



8 of these guys per bird





Operations Challenges
4 month Commissioning?!

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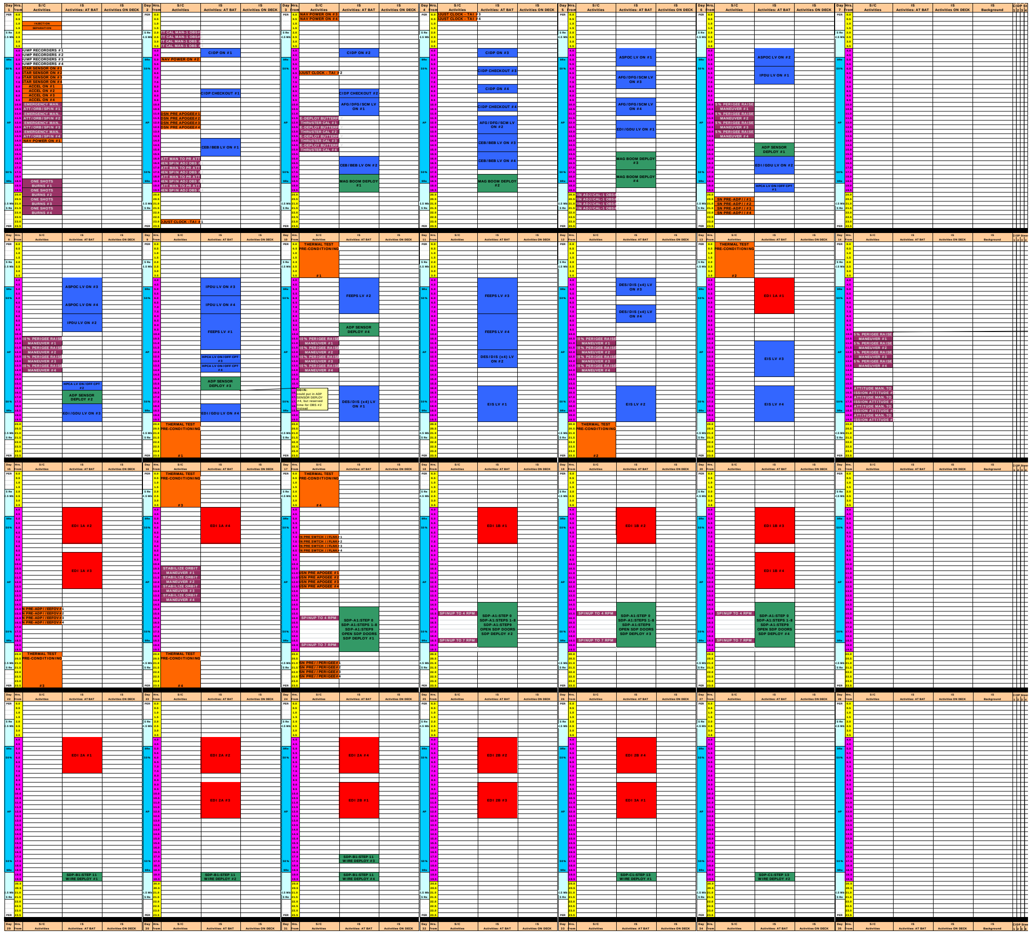
- **100 instruments**
  - 32 booms (plus 8 whip antennas)
  - 60 **high voltage instruments** to bring up slowly
  - Self compat testing
- **4 spacecraft to checkout**
  - Thrusters to calibrate
  - GPS to commission
- **Formations to form**
  - Perigee raises
  - string of pearls
  - then form the tetrahedron
- **Engineering, Ops, and Science teams to grind into paste**
  - Lessons learned from Cluster (ESA) mission: plan, plan and replan – they didn't, we are.



Why are we here again?

Obviously, so I can preach about SE responsibilities and decision making processes.

Classical view of PM vs SE responsibilities

	Project Management	Systems Engineering
Cost	X	
Schedule	X	
Technical	x	X

"Your job is to push for the best technical solution, not just meet requirements, and don't worry about the cost or schedule impacts."

Angry words directed at yours truly in the early mid-90's

The correct, well my, view of responsibilities

	Project Management	Systems Engineering
Cost	X	X
Schedule	X	X
Technical	X	X

"Recognizing that not all technical problems are equal, your job is to maximize the probability of mission success by using all resources at your disposal, including money and time."

Money wasted can't be spend on something useful; same with schedule.

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How are Decisions made? System Engineering Motivators

- **Why are decisions made? One man's view.**
  – Plain and Simple: fear of failure
    - Probability of Pete's *(one more expletive deleted)* in front of a mishap investigation board, PPAMIB > 1 – Psuccess.
    - Ultimately, failure of a mission is the responsibility of the MSE,
      – All major architectural decisions (hardware and ops) are his.
      – All designs and test plans are reviewed by him, or those he assigns.
      – Observatory tests, the final check of your systems, are his responsibility.
      – The level of responsibility is that much greater on in-house missions.
    - The engineering technical authority system makes it impossible for the MSE to say the responsibility lies anywhere else. "Well, I thought it was a bad idea, but my management…," won't cut it when you can appeal any bad call – it makes it your responsibility.
      – Regardless of the current administrator's recent e-mail to the contrary, failure still isn't an option.
  – Desire to maximize success – maximize science return
    - Minimum mission success criteria are for HQ to protect themselves from your mistakes.
    - Full mission success is the only goal systems engineers should consider – you will be blamed for the failures long before minimum success is reached.

Two sides of the same coin: Desire for success and fear of failure.

How are Decisions made? System Engineering Motivators

- **What decisions are worth making?**
  - Those that avoid failure, particularly those that have the highest probability of avoiding failure.
    - An extra day in Thermal Vac is worth more than installing brass washers on the mag boom before vibe testing, if those washers don't invalidate the vibe test (current example).
    - If it's in the way and it is worth less than something that will be short changed, get it out of the way – <u>Schedule responsibility of an MSE that leads to a better technical solution.</u>
  - Those that maximize science return, as long as they do not increase the probability of failure.
    - Adding hardware to improve spacecraft performance beyond that necessary to meet requirements takes away money from instruments, which are the real reason we fly. <u>Cost responsibility of an MSE that leads to better science return.</u>

Some Example Decision: So where's the IMU?

- **The ACS team asked for an IMU, which would have improved our delta-V execution performance and is typical for almost all Goddard missions.**
  - <u>A very good and very fair question.</u>
- **"Show me you can't meet requirements without one and we'll add it in."**
  - Also a good and fair question.
- **"We did the analysis and we can meet requirements without one, but it we could do better with one.**
- **MSE calculation**
  - Cost of flying without an IMU
    - 2 man-years of extra analysis = $0.5M
  - Cost of flying with an IMU
    - $8M for hardware
    - $1M for personnel to monitor
    - $12M for an extra about 2 months of integration and test (over the fleet)
  - Not required by the mission; ~$21M cost.
    - Descope of an instrument, maybe two, would have been required at that point in the project lifecycle.

Technical decision based on cost and schedule considerations.

Some Example Decision: Where's the X-band downlink?

- **All major missions have an X, Ka, or Ku band downlink for science data. Where's ours?**
- **MSE calculation**
  - Cost of flying without an science downlink
    - None
      - Wrong!!! Probably cost a couple/few million to manage the extra complexity of operations – very long DSN contacts (as much as 8 hours for the constellation). Didn't know this at the time.
  - Cost of flying with an IMU
    - $8M for transmitter
    - $2M for antennas
    - $2M for personnel to monitor
    - $18M for an extra about 3 months of integration and test (over the fleet)
  - Not required by the mission; Nearly infinite upside.
    - Cost impact (about $30M threatened project survival)
  - As a result, the X-band survived until just after lunch on the first day.

Another technical decision based on cost and schedule considerations.

Some Example Decision: Why Block Redundant?

- **The probability of full mission success for 4 single string spacecraft with 100 instruments, even with the ability to tolerate instrument failures, was diminishingly small – about 20%.**
  - Recall the responsibility comment a few pages earlier?
- **For a block redundant architecture the probability rose to about 70%.**
  - Still very low, but we have 4 birds and 100 instruments…
- **MSE calculation**
  - No one believes reliability calculations. They are only relative, not absolute, right? Yes, unless you can do a Bayesian update (fancy math that incorporates actual failure data) considering 100 flight years of Goddard on-orbit failure data.
    - Bayesian analysis made the analysis essentially unassailable, which was, well, essential to not get shot down.
  - About a $40M increase required – driven mostly by schedule impacts ($6-7M/mo during I&T) rather than hardware.
  - Increase in Ps to 70% from 20% for ~4% of the total cost?
    - HQ saw this as a good insurance policy against failure (and against needing to explain failure).

Technical decision based on not wasting 9 years of my career. Oh, and the taxpayer’s money.

Some Example Decision:
Coldfire Processor?
"Dude, you're killing me!"

- **Flight Software and C&DH wanted a Rad750, or like powerful computer, but:**
  - Powerful processors require … well, they require power
  - Power needs to be dumped via radiators
  - Radiators bleed heat, particularly in umbra, even if the CDH is off.
  - MMS must survive <u>4 hour</u> umbras!
    - The Thermites have done miracles, but there are limits.
    - The Electrical Power System can only stuff so much energy in the batteries.
  - Fairing size, Instrument view factors, and Inertial stability limited the size of the Observatory diameter and therefore the size of the Solar Arrays --- and therefore the energy in the battery.
  - Result: We got the processor we needed, maybe not the processor we wanted, and we got a bird that can survive a 4 hour umbra and fit in a 4m fairing.

The knee bone is connected to the shoulder blade; or FSW is limited by fairing size.

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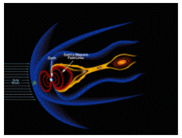
Maybe one more Example Decision:

4 Thermal Cycles at the Instrument Level? Heard of GEVS?

- **A waiver to the GEVS rule to cycle each box 8 times at the instrument level was requested and eventually granted.**
- **Why did we ask for it? Doesn't this increase your risks?**
- **Yes and no.**
  - Yes. At the instrument level the risk is higher.
  - No. At the overall Observatory level the risk is lower because the likelihood of not having all of the instruments present for Observatory level testing is reduced.
    - 4 cycles doesn't seem like much time, but when you have 16 units then it slows the whole process down immensely.
      - With 100 instruments, the Instrument Suite team is naturally racing to keep up.
    - MMS will have more TV cycles, per design, than any other Goddard mission. In a like manner, common workmanship issues will be (have been) found with so many cycles.
    - Because MMS can tolerate failures of instruments, we can tolerate them, even if we'll fight to avoid them. This is very much unlike other Goddard missions.

What's the right answer? Perfect instrument testing maximized Observatory level testing? A judgment call that fell in the favor of the Observatory level.



Simple Spinner?

- **Like I said, “Hardly.”**
  - The team has its hands around things now and the complexity of the mission no longer seems do daunting. MMS is a great training ground for the next generation of engineers; they’ll will be able to take on any other complex mission and make it fully successful too.
  - I have to wonder if “simple” is a term we should retire – there is no such thing in this business and there probably wasn’t in our father’s day.
- **Next Mission?**
  - Personally, I look forward to retiring in place on a nice, 3 axis-stabilized, nadir pointing, single telescope mission. Nahhhh!

One last example decision: Everything we're doing in I&T

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