Systems Engineering when the Schedule is Tight: Lessons from the Lunar Reconnaissance Orbiter

Systems Engineering Seminar at GSFC

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Abstract

- ***Systems Engineering when the Schedule is Tight: Lessons from the Lunar Reconnaissance Orbiter***
- Many projects are cost-constrained or driven by the performance necessary to meet a particular objective. The development of the Lunar Reconnaissance Orbiter (LRO), on the other hand, was dominated by the desire to launch this 7-payload spacecraft within 2-1/2 years of confirmation. Originally conceived as one of many small, annual robotic missions to explore the moon in advance of the next human campaign, LRO became the only NASA mission to the moon for the next few years. The team had to balance the strong push to meet a 2008 launch against the need to ensure that this first mission for Exploration succeeded. In the end, the reputation of Goddard Space Flight Center, the Explorations Systems Mission Directorate, and ultimately NASA hangs in part on LRO's fate. This presentation will provide an overview of the mission and explore some of the challenges the systems engineering team faced in the 4 years from concept to thermal vacuum test.

Topics

- Lunar Facts
- LRO Objectives
- Programmatic Environment
- Challenges and Approaches
- System Overview
- Observations and Lessons Learned

How far away is the moon?

9.1 um IR image from Mars Odyssey on April 19, 2001

Scale distance and size

- Earth = 12 inches in diameter
- Moon = 3-1/4 inches in diameter
- Moon distance = 30 feet
- Sun diameter = 108 feet
- Sun distance = 2-1/4 **miles**
- Pluto distance = 88 miles from sun

Moon Facts

- Diameter: 3476 km (27% of earth)
- Land area: 38 x 10^6 sq km (25% of earth)
  - More than North America and Europe combined
  - A little less than Asia
- Distance from earth: ~30 earth diameters
  - Minimum: 356,375 km
  - Maximum: 406,720 km

US Lunar Robotic and Apollo Missions

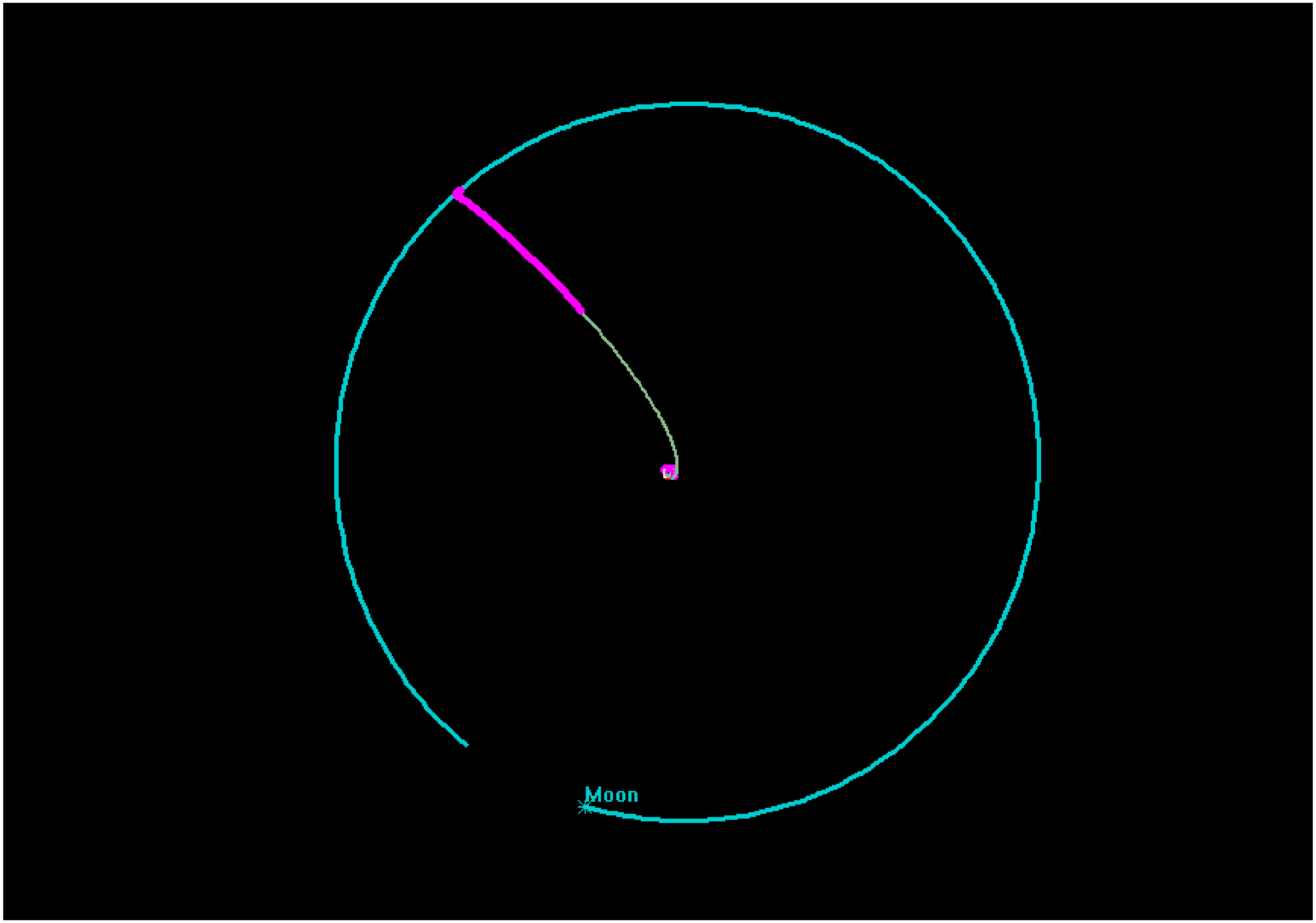
Mission	Launch Date	Type
Ranger 3	01/62	Hard Lander (missed the moon)
Ranger 4	04/62	Hard Lander (hit farside)
Ranger 5	10/62	Hard Lander (missed the moon)
Ranger 6	01/64	Hard Lander (TV failed)
Ranger 7	07/64	Hard Lander
Ranger 8	02/65	Hard Lander
Ranger 9	03/65	Hard Lander
Surveyor 1	05/66	Soft Lander
Lunar Orbiter 1	08/66	Orbiter
Surveyor 2	09/66	Lander (crashed)
Lunar Orbiter 2	11/66	Orbiter
Lunar Orbiter 3	02/67	Orbiter
Surveyor 3	04/67	Soft Lander
Lunar Orbiter 4	05/67	Orbiter
Surveyor 4	07/67	Lander (crashed)
Explorer 35	07/67	Orbiter
Lunar Orbiter 5	08/67	Orbiter
Surveyor 5	09/67	Soft Lander
Surveyor 6	11/67	Soft Lander
Surveyor 7	01/68	Soft Lander
Apollo 8	12/68	Orbiter (1st Human to orbit the moon)
Apollo 10	05/69	Orbiter Test LM in lunar orbit
Apollo 11	07/69	Mare Tranquillitatis (1st manned lunar landing)
Apollo 12	11/69	Oceanus Procellarum (near Surveyor 3 spacecraft)
Apollo 13	04/70	Flyby (aborted mission after onboard explosion)
Apollo 14	01/71	Fra Mauro (1st highland mission)
Apollo 15	07/71	Hadley-Apennines (1st use of rover, extended LM)
Apollo 16	04/72	Descartes (Lunar highlands)
Apollo 17	12/72	Taurus-Littrow (Last Apollo landing, 1st geologist lunar astronaut)
Explorer 49	06/73	Lunar Orbit radio-astronomy explorer (RAE-B)
Clementine	01/94	Orbiter (BiStatic radar indications of polar water)
Lunar Prospector	01/98	Orbiter (Neutron Spectrscopy indications of polar “water’)

Earth Rise, December 1968

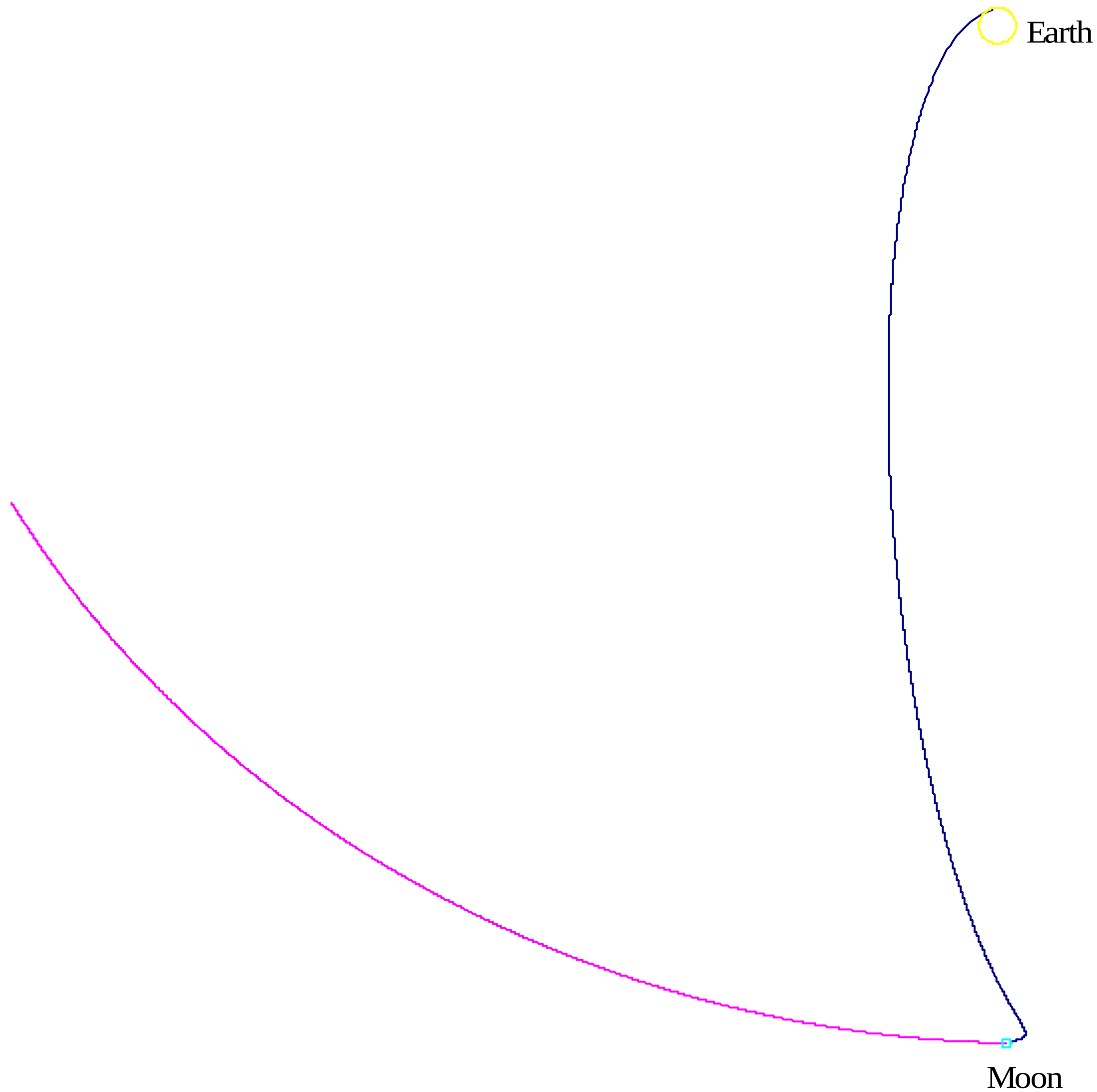
“Picture of the Century”

Copernicus from Lunar Orbiter 2, November 24, 1966, 45 km altitude

5 Days to the Moon

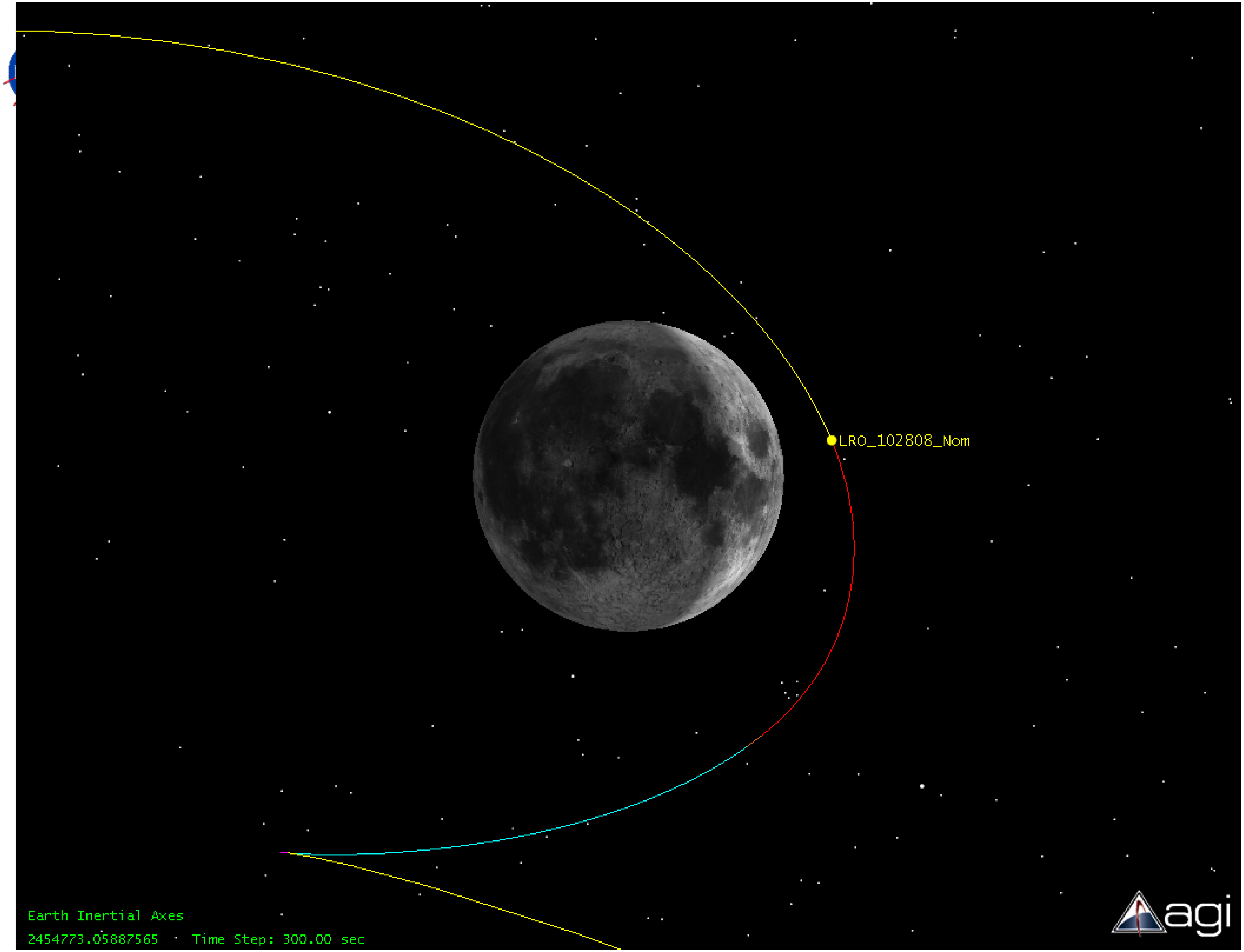


LRO Trans-Lunar Trajectory (N Pole)



Trip to the Moon

- Depart at 24,000 mph
  - Total kinetic energy = ½ * 2000 kg * $(10,800 \text{ m/s})^2$ = 1.2×10^{11} J
  - Total potential energy = 2000 kg * 9.8 m/s2 * 286,000 m = 5.6×10^9 J
  - Total energy = 1.2×10^{11} J = 32,500 kW-hr
  - Averaged over 19 minutes of burn = 100 MW
  - Enough energy to run 27 houses for a month!
- Arrive near the moon at 300 mph—slower than an airplane!


LRO_102808_Nom
Earth Inertial Axes
2454773.05887565 Time Step: 300.00 sec
agi

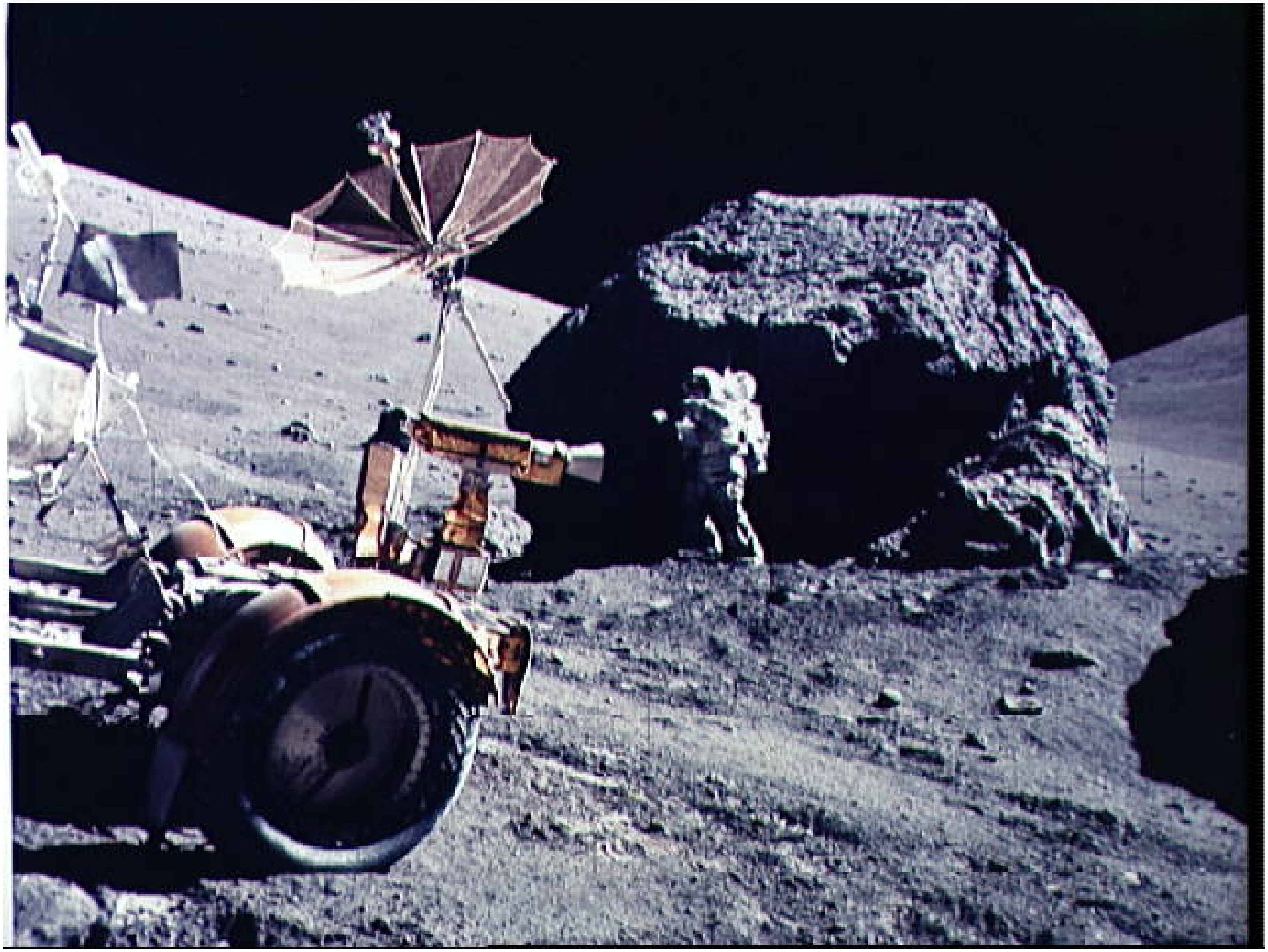
LRO Beginning

- January 2004, the President announced the "Vision for Space Exploration", sending a "series of robotic missions" to the moon "beginning no later than 2008".
- Announcement of Opportunity for LRO instruments released in June 2004; target launch October 2008.
- **Six** instruments selected in December 2004.
  - Selected instruments had strong relationship to recently-flown instruments
- Funding started in early 2005.
- Technology demonstration payload added in April 2005:
  - Mini-RF development significantly behind other instruments
  - Data rate and power consumption are significant

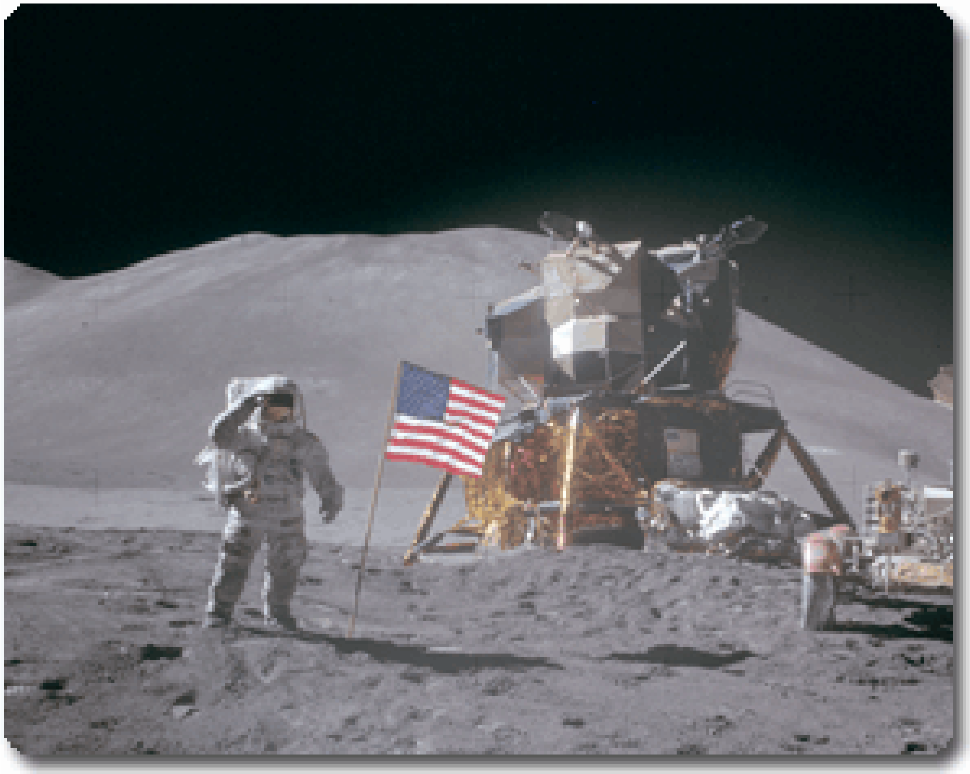
LRO Objectives, Polar Focus

- Characterize landing sites
  - High-resolution mapping
  - Surface characterization (slope, roughness)
- Identify resources
  - Water
  - Minerals
  - Sunlight
- Characterize radiation environment
  - Energy deposited in tissue-equivalent plastic
  - Neutron albedo

Lunar Rover, Schmidt, Big Boulder



Dangers of Poor Reconnaissance

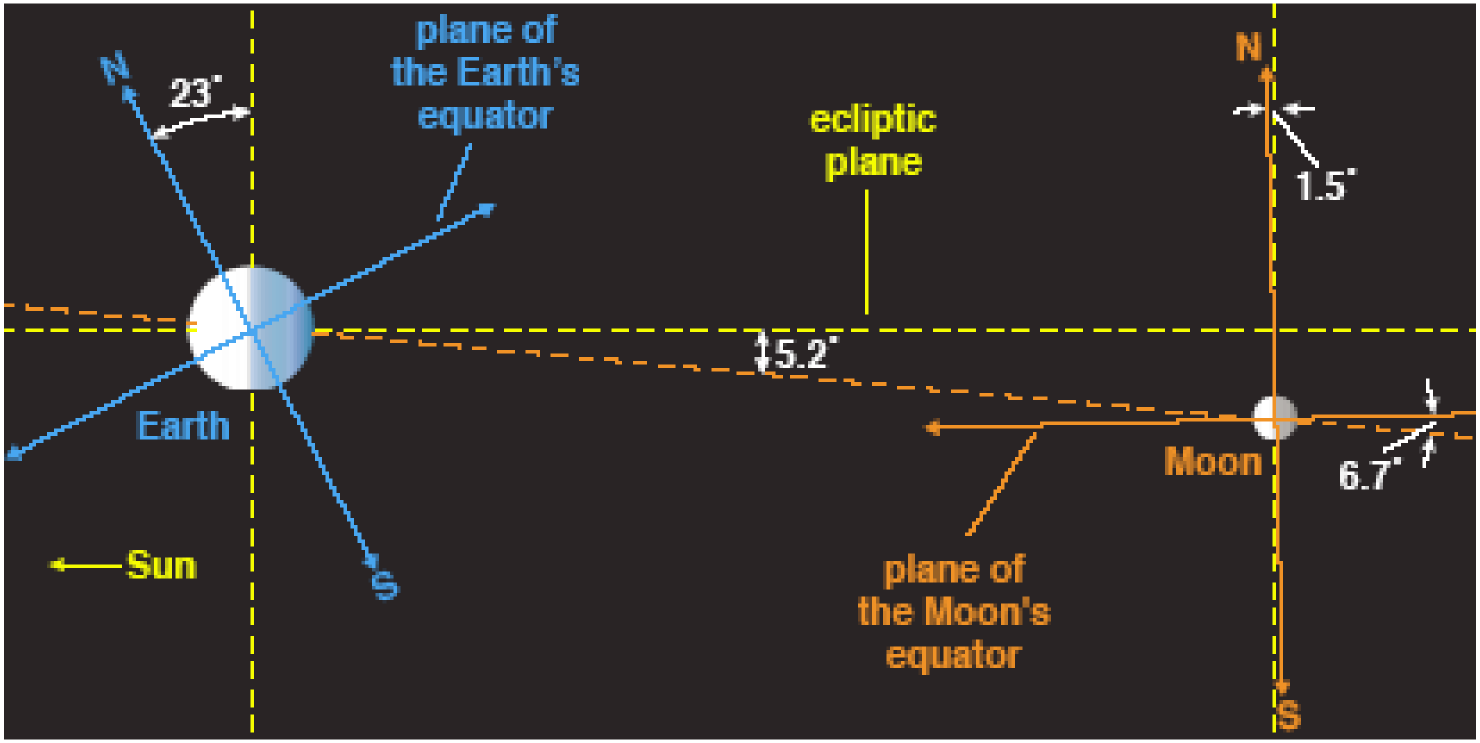


"The Apollo 15 Lunar Module accidentally set down on the rim of a crater such that its engine bell was damaged, and with one of the legs in the crater, at a tilt of 10°, just 5° below the maximum acceptable angle [Baker, 1982; Harland 1999]. Hazards from craters of this size are best detected with meter scale topography and high incidence angel (80°) images - both provided with the LROC NAC."

(LROC web site: http://lroc.sese.asu.edu/objectives.html)

Why the Poles and Where?

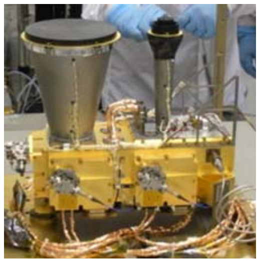
- Cold traps exist near the lunar poles (Watson et al., 1961)
  – Low obliquity of Moon affords permanent shadow in depressions at high latitude.
  – Temperatures are low enough to retain volatiles for t > τ_{Moon}.



LRO Instruments and Investigations

LOLA: Lunar Orbiter Laser Altimeter

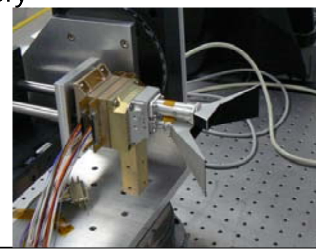
- Topography
- Slopes
- Roughness



Full Orbit
Autonomous

LROC/WAC: Wide-Angle Camera

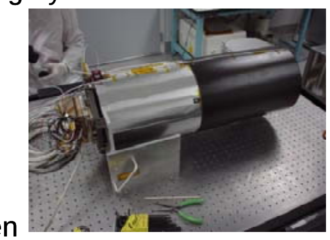
- Global Imagery
- Lighting
- Resources



Day Side
Autonomous

LROC/NACs: Narrow-Angle Cameras

- Targeted Imagery
- Hazards
- Topography



Day Side
Timeline Driven

LR: Laser Ranging

- Topography
- Gravity

GSFC LOS
Autonomous

DLRE: Diviner Lunar Radiometer Exp.

- Temperature
- Lighting
- Hazards
- Resources

Full Orbit
Autonomous

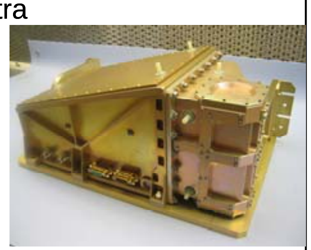
Mini-RF: Synthetic Aperture Radar

- Tech Demonstration
- Resources
- Topography

Polar Regions
Timeline Driven

CRaTER: Cosmic Ray Telescope…

- Radiation Spectra
- Tissue Effects



Full Orbit
Autonomous

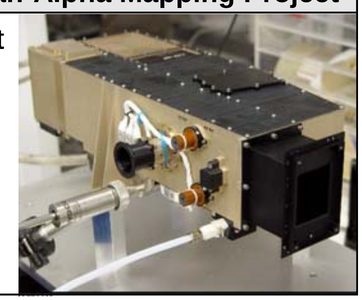
LEND: Lunar Explr. Neutron Detector

- Neutron Albedo
- Hydrogen Maps

Full Orbit
Autonomous

LAMP: Lyman-Alpha Mapping Project

- Water-Frost
- PSR Maps



Night Side
Autonomous

LRO Design Constraints (per AO)

- Polar, 50 km circular orbit
  - Harsh thermal environment (-140 to +140 deg C surface temperatures)
  - High-resolution imagery
  - All sun angles
- Delta II launch vehicle (now Atlas V)
  - Spinning upper stage
  - Tight mass constraint
- 14-month mission
- Class “C” reliability (largely single-string) with grade “B” parts and strong test program
- 2008 launch

Programmatic Environment

- Robotic Lunar Exploration Program (RLEP) office originally at GSFC under Science Mission Directorate
  - LRO the first of a series of small, annual missions assigned to GSFC in May 2004
  - LRO philosophy was "design to cost"
- RLEP moved under Exploration Systems Mission Directorate in May 2005
  - LRO Philosophy became "design to requirements": little desire by HQ to descope requirements; strong desire to fly Mini-RF
- RLEP moved to Ames Research Center in November 2005
  - Second mission began to slip past 2009
- **LRO asked to re-focus on cost as confirmation review approached**
- RLEP renamed Lunar Precursor Robotic Program (LPRP) and moved to Marshall Space Flight Center in May 2006
- Due to Exploration budget concerns, RLEP program office closed in early 2007, LRO reported directly to HQ
- RLEP re-opened by FY2008 appropriations

Milestones

- AO June 2004
- Funding start in January 2005
- System Requirement Review in August 2005
- Launch vehicle changed to EELV in November 2005
- Preliminary Design Review in February 2006
- Confirmation Review in May 2006
- Critical Design Review in November 2006
- Start of spacecraft integration in January 2008
- Pre-Environmental Review in June 2008
- Thermal Vacuum start in October 2008

Schedule

- We had a Level 1 requirement to launch in 2008
- HQ continued to emphasize this requirement
  - Exploration Systems Mission Directorate's (ESMD) credibility with Congress and OMB was tied to getting this first mission done on time
  - HQ offered extra funding after CDR in order to hold schedule
    - Some money was applied in key areas
    - Overall effect reduced cost by saving schedule: one component can hold up the entire development
- Independent Review Team expressed concern with LRO's schedule at each review
- LRO engineers frequently expressed concern with schedule
- LRO established a budget at confirmation which did not overly constrain the mission
- Project management and systems team needed to balance schedule against technical risk

LRO Fortune Cookie

People forget how fast you did a job –
but they remember how well you did it.

Lucky Numbers 40, 27, 33, 5, 14, 9

The Constant Challenge

- Find ways to get things done faster without compromising the technical integrity
  - Work harder (we all did this—good team spirit)
  - Add more people (mechanical team)
  - Design for parallel development
  - Test early
  - Manage risk
  - Challenge the standard way of doing business
  - Focus on the people
  - Make decisions and move on
- All of the above were necessary!

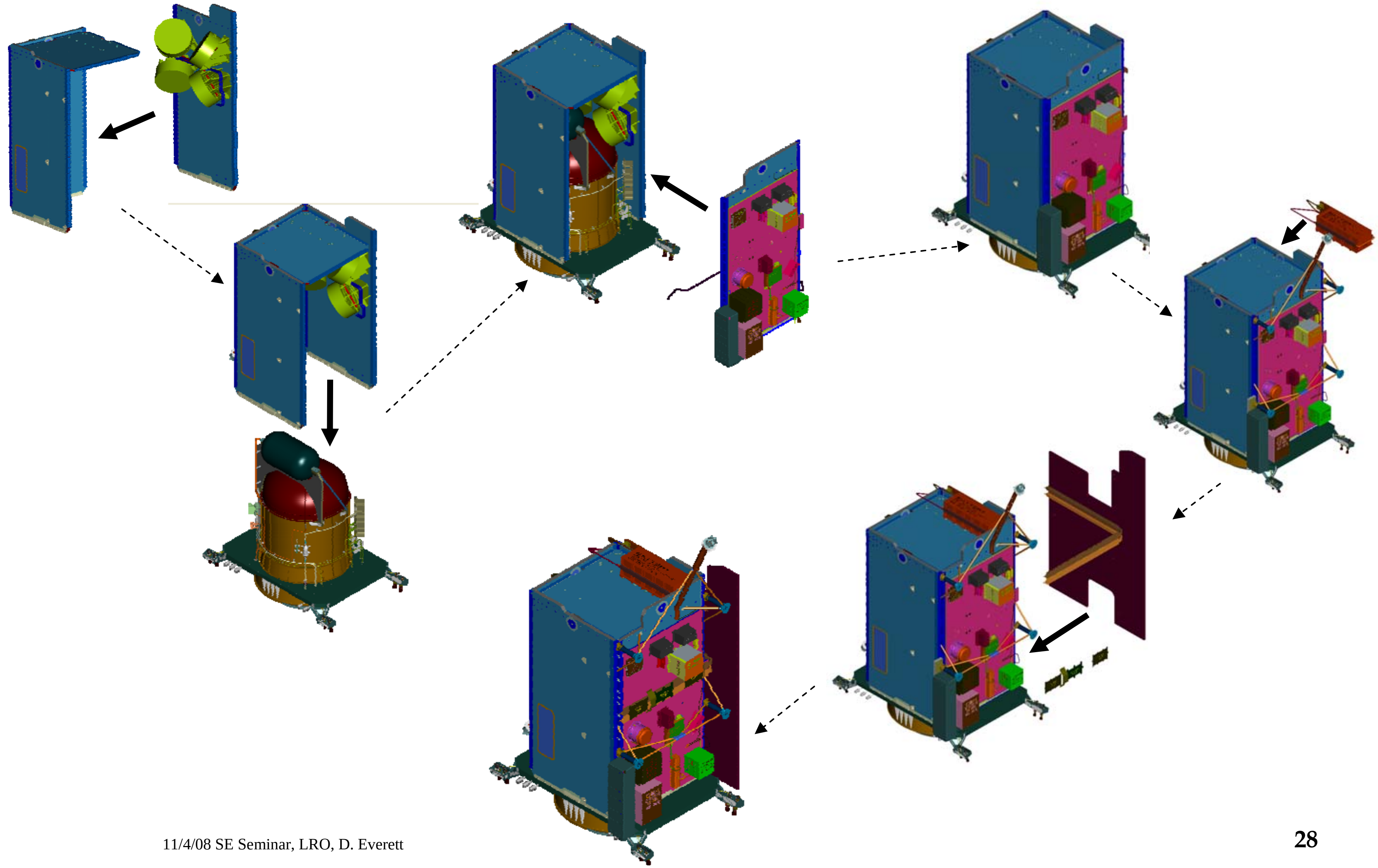
Launch Vehicle Change

- In September 2005, the propulsion team identified a risk associated with the nutation time constant of LRO’s propellant tank.
  - Almost half of the Orbiter’s mass is liquid fuel
  - Delta II upper stage is spin stabilized
  - We would not know until spring of 2006 (after drop-tower testing) whether LRO could meet launch vehicle requirement for NTC
- Conducted trade of options:
  - Accept risk and proceed with current design: too risky to schedule
  - Redesign with bi-propellant: too much schedule impact
  - Redesign for Evolved Expendable Launch Vehicle: beyond project’s scope to make this decision
  - Redesign with solid rocket motor: impact on mechanical and thermal
- Briefed HQ in November 2005

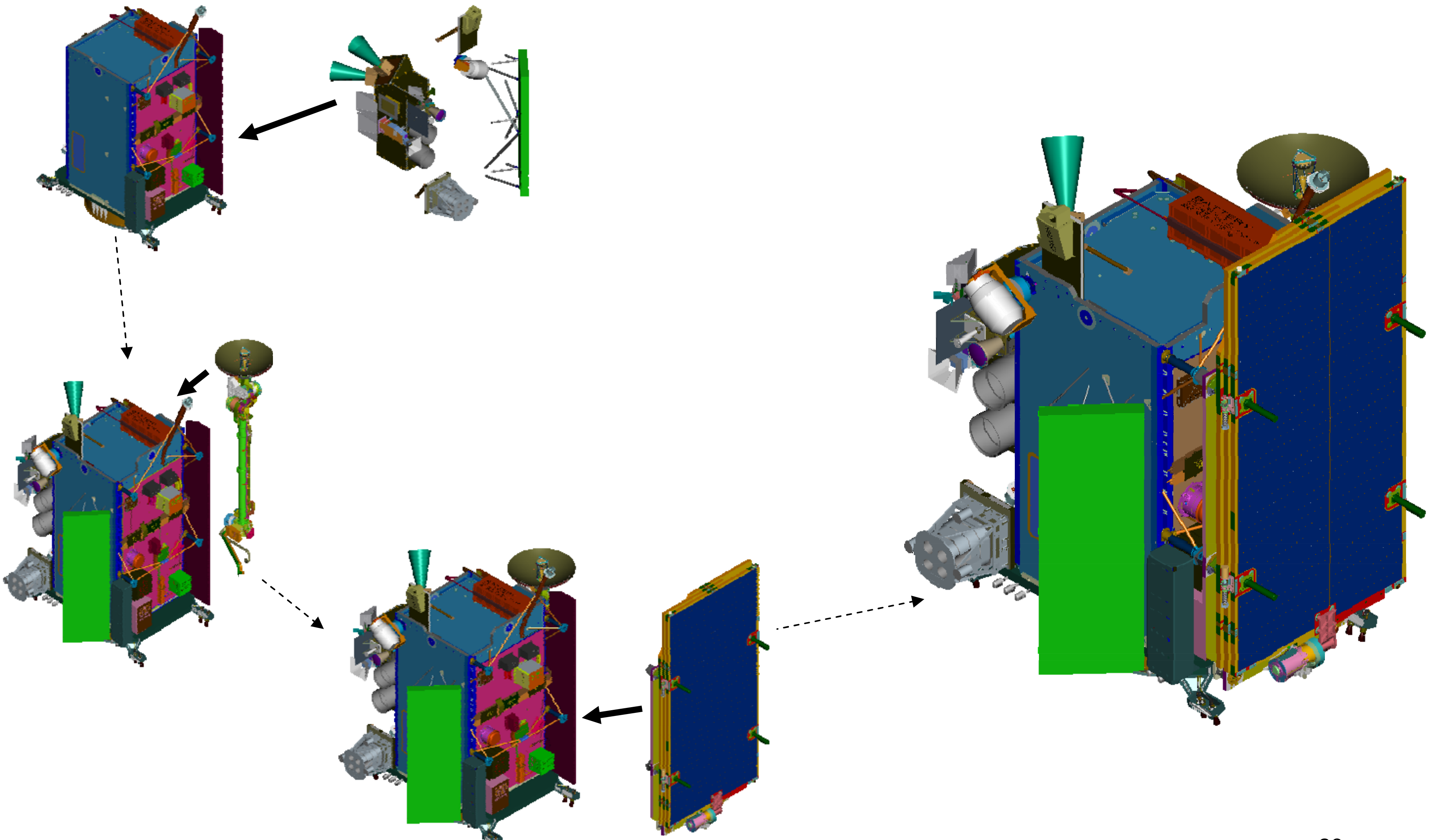
Launch Vehicle Change (cont.)

- Associate Administrator decided during the briefing to move LRO from Delta II to EELV
  - Solved NTC problem
  - Allowed use of surplus propulsion components from X-38
  - Provided additional launch capability for secondary payload
- LRO Mechanical team re-started system design with the following guiding principles:
  - Set mass limit with capability of two fuel tanks from X-38
  - Create modular design for parallel assembly
  - Couple significant mass to minimize thermal transients
- Mechanical and thermal teams were significantly behind at mission PDR in February 2006
- PDR-level peer reviews for mechanical and thermal in May 2006

Orbiter Modular Integration (1)



Orbiter Modular Integration (2)



Test Early: Interface Tests

- We conducted interface tests with each instrument and with most other components as soon as breadboards were available
- We discovered problems at nearly every interface test: reversed polarity signals, timing issues, etc.
- All problems were easy to correct, since the tests were early
- We only experienced one interface problem during Orbiter-level integration (1553 transformer reversed)
- Time saved with interface testing easily exceeded time spent on the tests
- Example: transponder
  - Added scope to contract to implement interface test in July 2007
  - Detector lock and rcvr clock signals swapped, soft reset not implemented, spacecraft software error caused repeated strobing of hardware reset, telemetry database updated, GSE aux command changed to a square wave
  - Integration of flight unit in February 2008 found no issues

Risk Management

- Monthly meetings with each of the subsystem leads provided input to our risk management process
  - One-on-one atmosphere was good for identifying potential issues at the system level
  - Kept the subsystem leads thinking about risk
  - Kept the database up-to-date
- Monthly risk management board meetings provided:
  - Insight to project management
  - Forum for project-level decisions about risks
- The LRO team did not wait for monthly meetings to address critical risks
- Example: propulsion tank NTC issue
- Example: hard drive radiation test failure
- Example: C&DH power converter delayed delivery
  - Built flight spare card with slightly lower quality part
  - Started investigating risk associated with flying this part
  - Bought time while we worked with the vendor to get flight part delivered

Improved Process: Procurements

- The LRO team executed a number of procurements, including:
  - Inertial Measurement Unit
  - Star Trackers
  - Coarse Sun Sensors
  - Transponder
  - Modulator
  - Traveling-Wave Tube Amplifier
  - Solar Array
  - Battery
- We had significant **systems support** for each of these:
  - Ensuring the proper environmental requirements
  - Ensuring good interfaces
- Our **manufacturing engineer** worked with each vendor after selection:
  - Tailor SOW and specifications to use vendor processes as much as possible without sacrificing quality
  - Check preliminary parts list for issues
  - Ensure proper testing was part of the vendor's plans
- Example: Few problems with procured components at time of delivery
- Example: transponder parts issue avoided

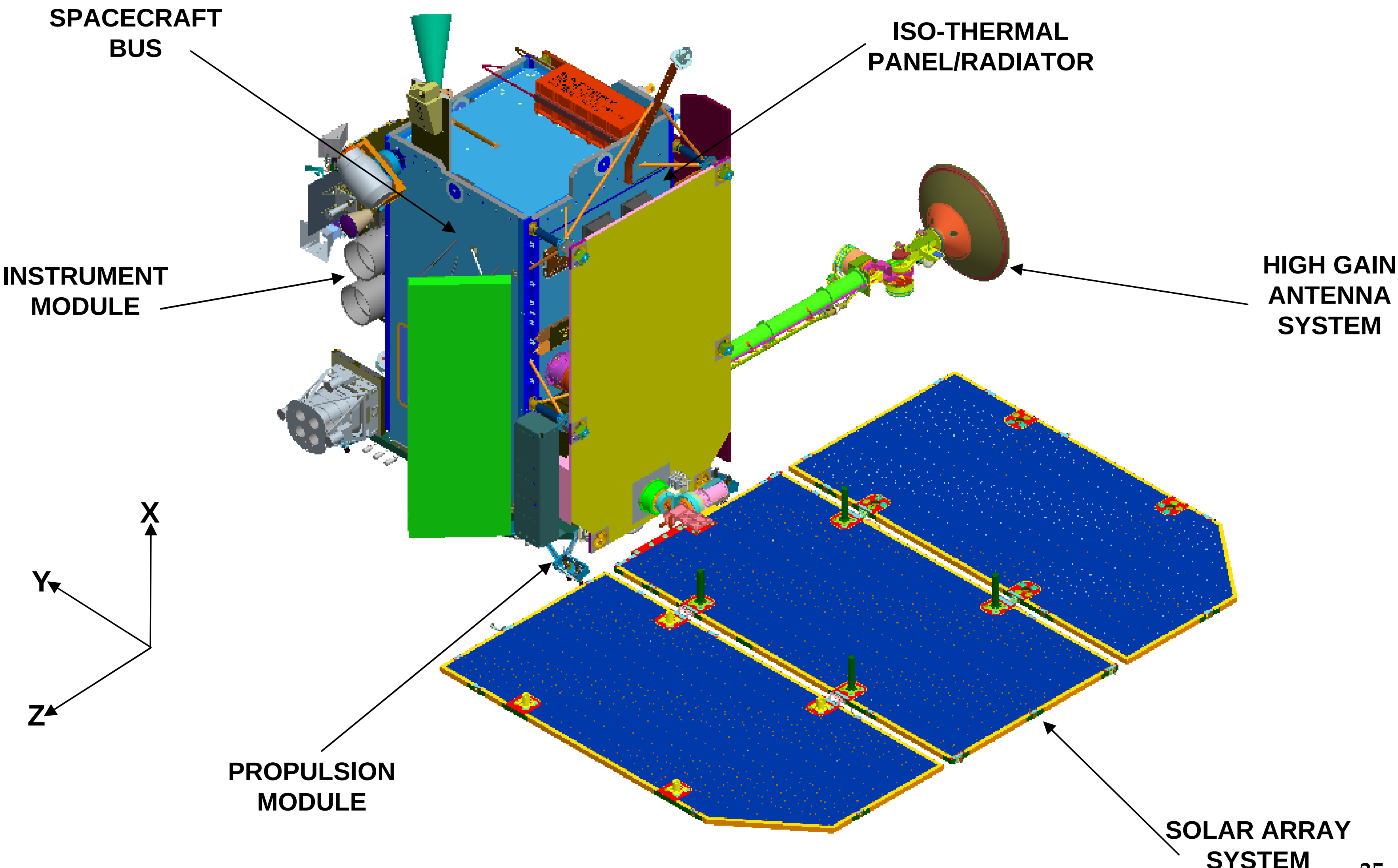
Focus on the People

- We solved problems quickly by bringing our full talent to bear
  - Diverse perspectives
  - Minority opinions
- Constant effort to get people to voice their concerns
  - Some people don't want to be a bother
  - Some people don't realize the full impact of their concern
  - Some people don't think their voice will make a difference
- Some people require more effort
  - Maybe their style doesn't match your style
  - Perhaps they have less experience
  - Perhaps they worry too much
  - Or maybe they just think differently
- Example: propulsion trade to solve NTC problem
- Example: coarse sun sensor circuit design issue
  - Small discrepancy bothered engineers performing test
  - Pursued source (with systems support) until flaw was discovered

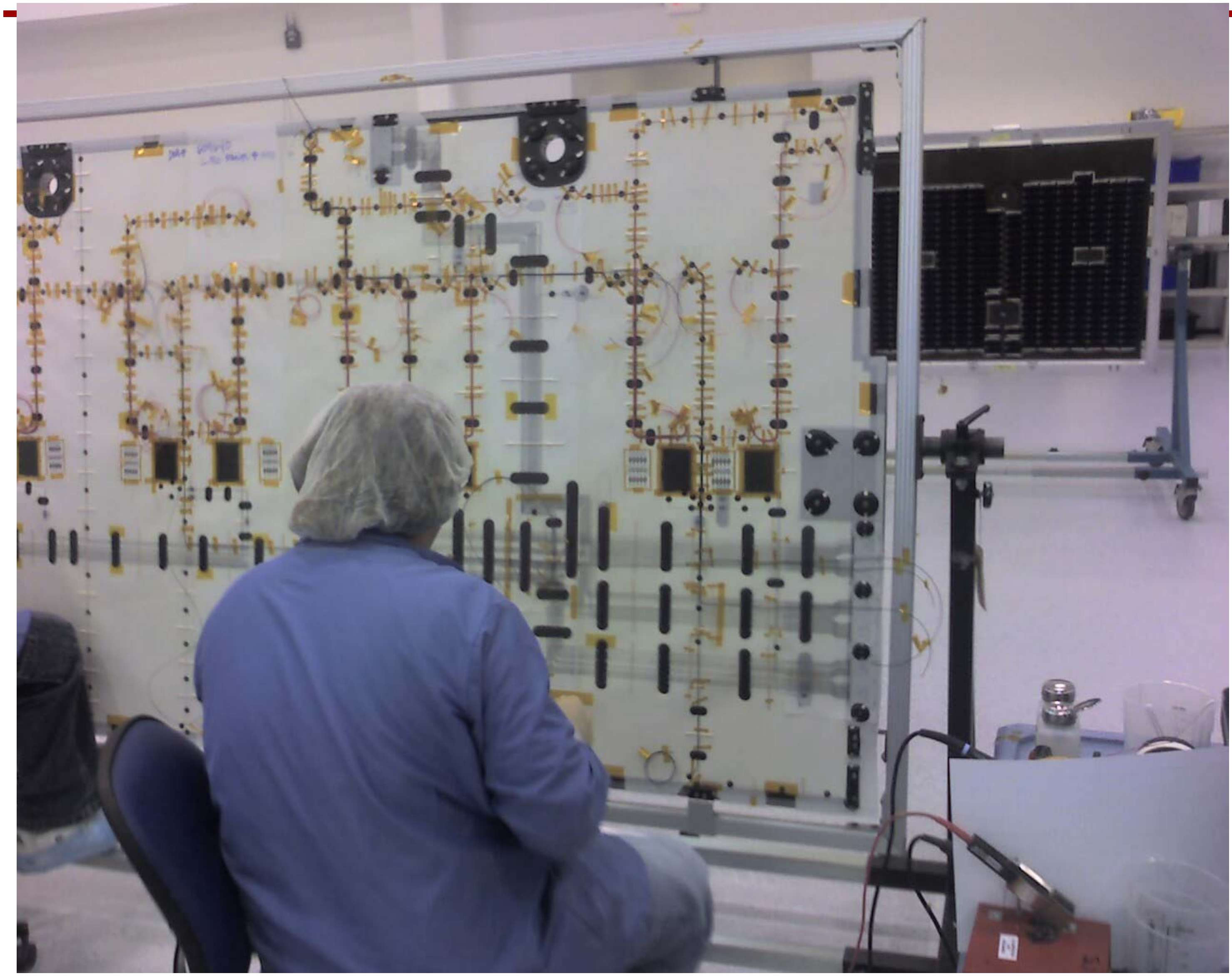
Decision Making

- There is no fool-proof method to make multi-parameter decisions with high-stakes risks
- LRO's formula:
  - Take input from multiple people (diverse perspectives)
  - Analyze what can be analyzed
  - Pick a path using **engineering judgement**
  - Follow the chosen path unless you hit an obstacle
- We did not spend a lot of time looking for other options if we found one that met schedule, cost, and performance requirements
- Challenges with this approach:
  - Viable solution is not always the "optimal" solution
  - Review teams like to see evidence of careful, exhaustive trade studies, with clear, analytic rationale
- Example: comm system redundancy
- Example: direct orbit insertion
- Examples: reaction wheel board layout issue, Diviner actuator damage
  - Band-aid fix to save schedule or significant delay to implement "clean" fix

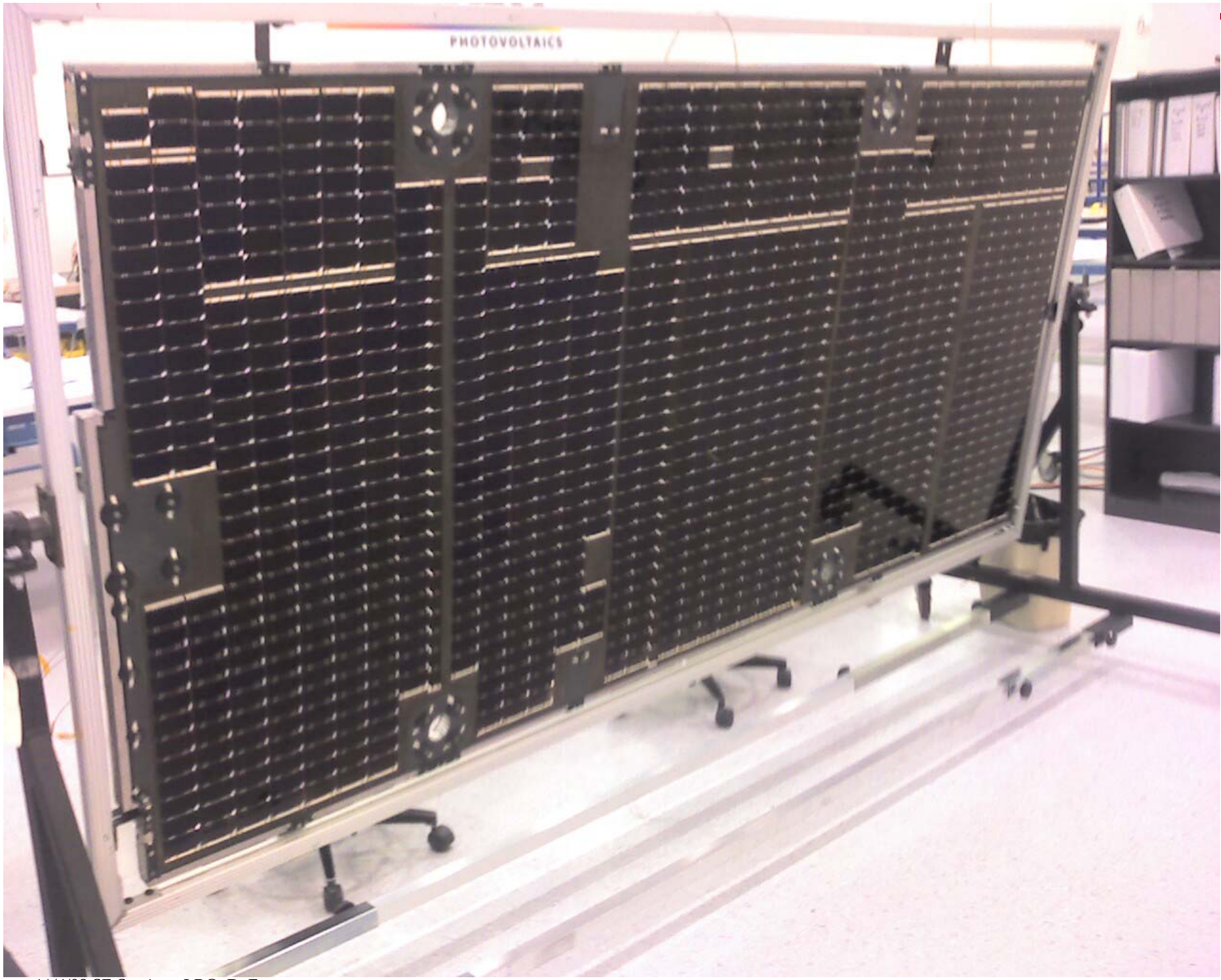
LRO Spacecraft



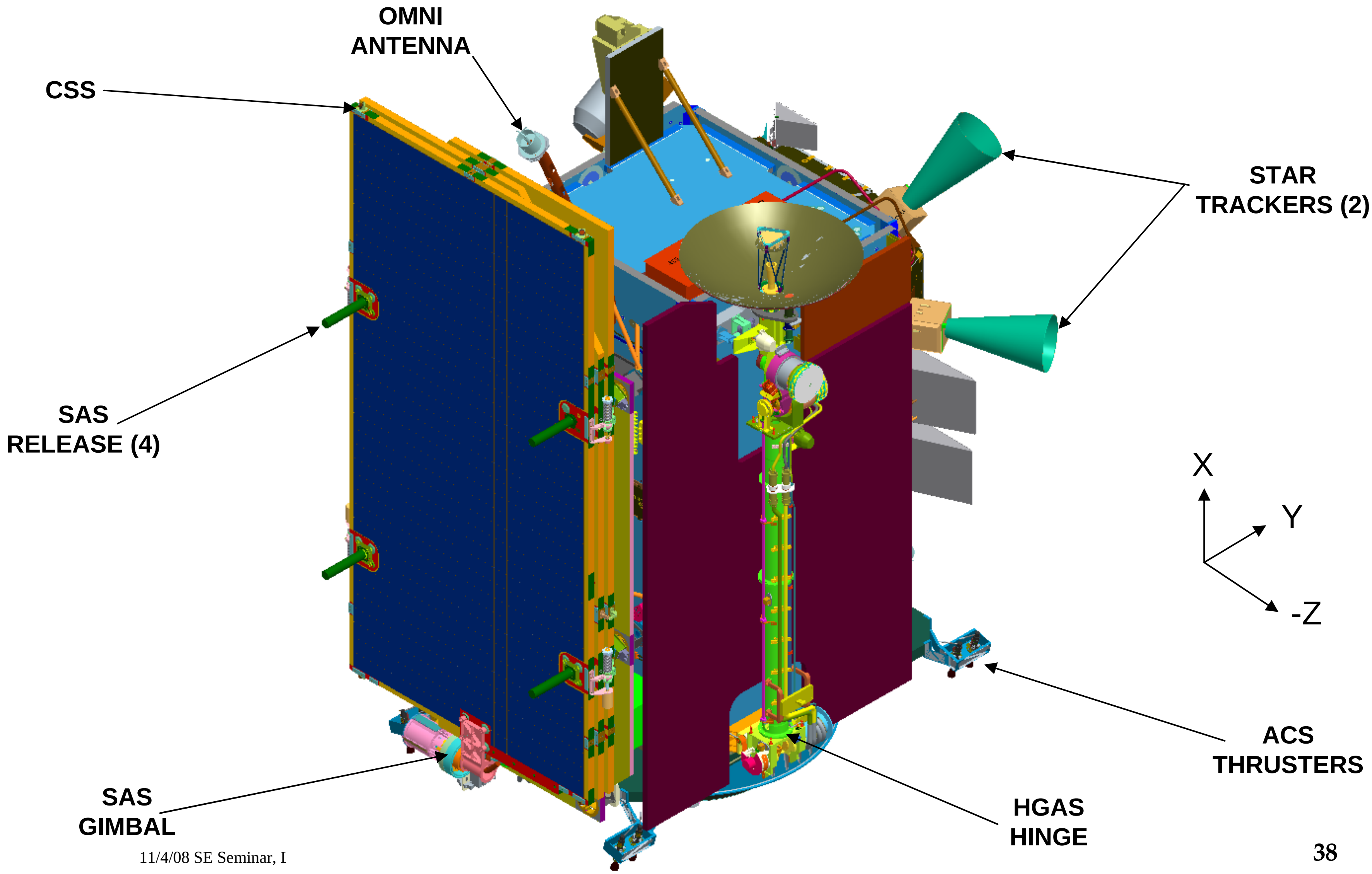
Back of Solar Panel #2 (July 2007)



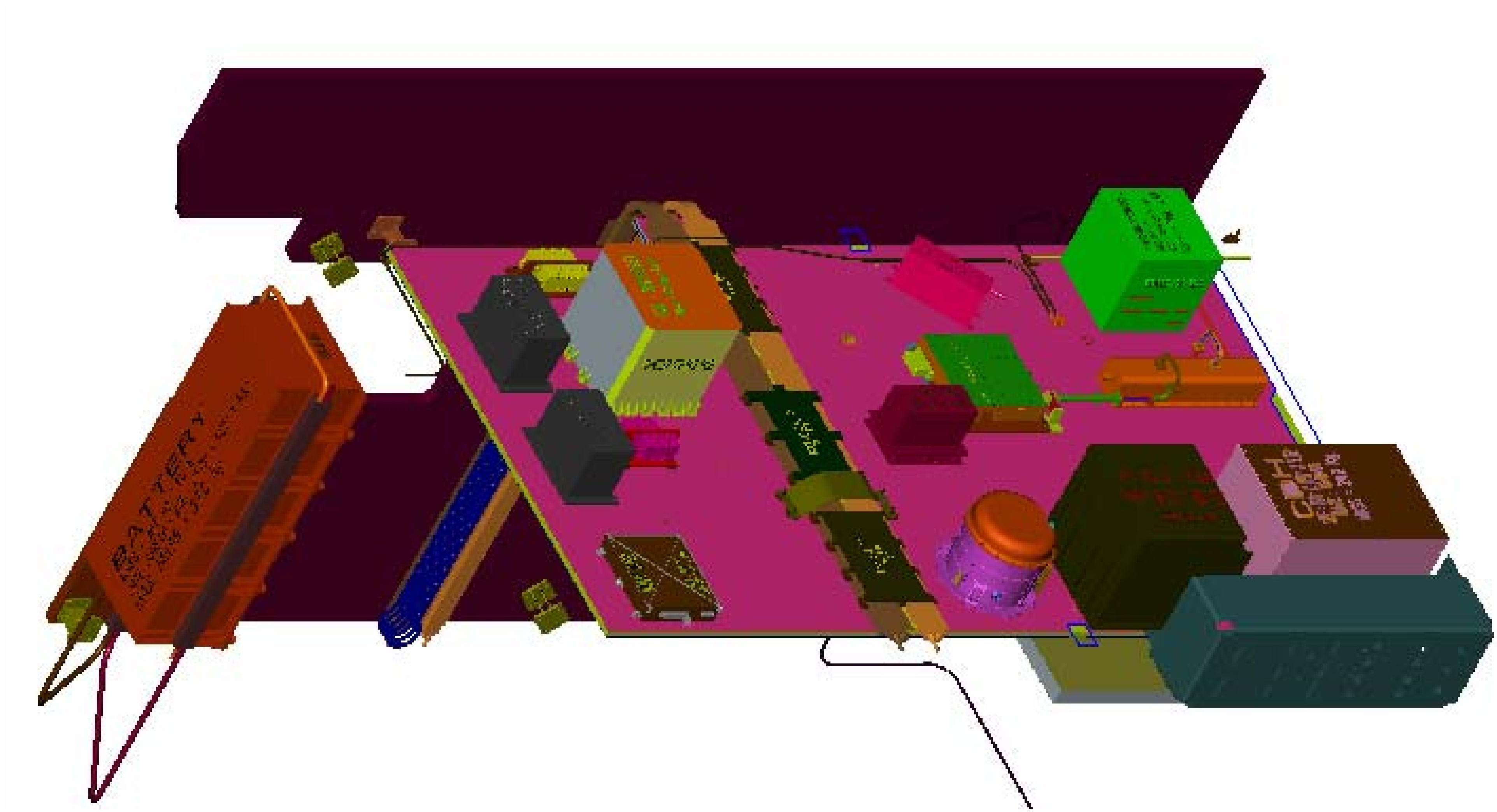
Front of Solar Panel #2 (July 2007)



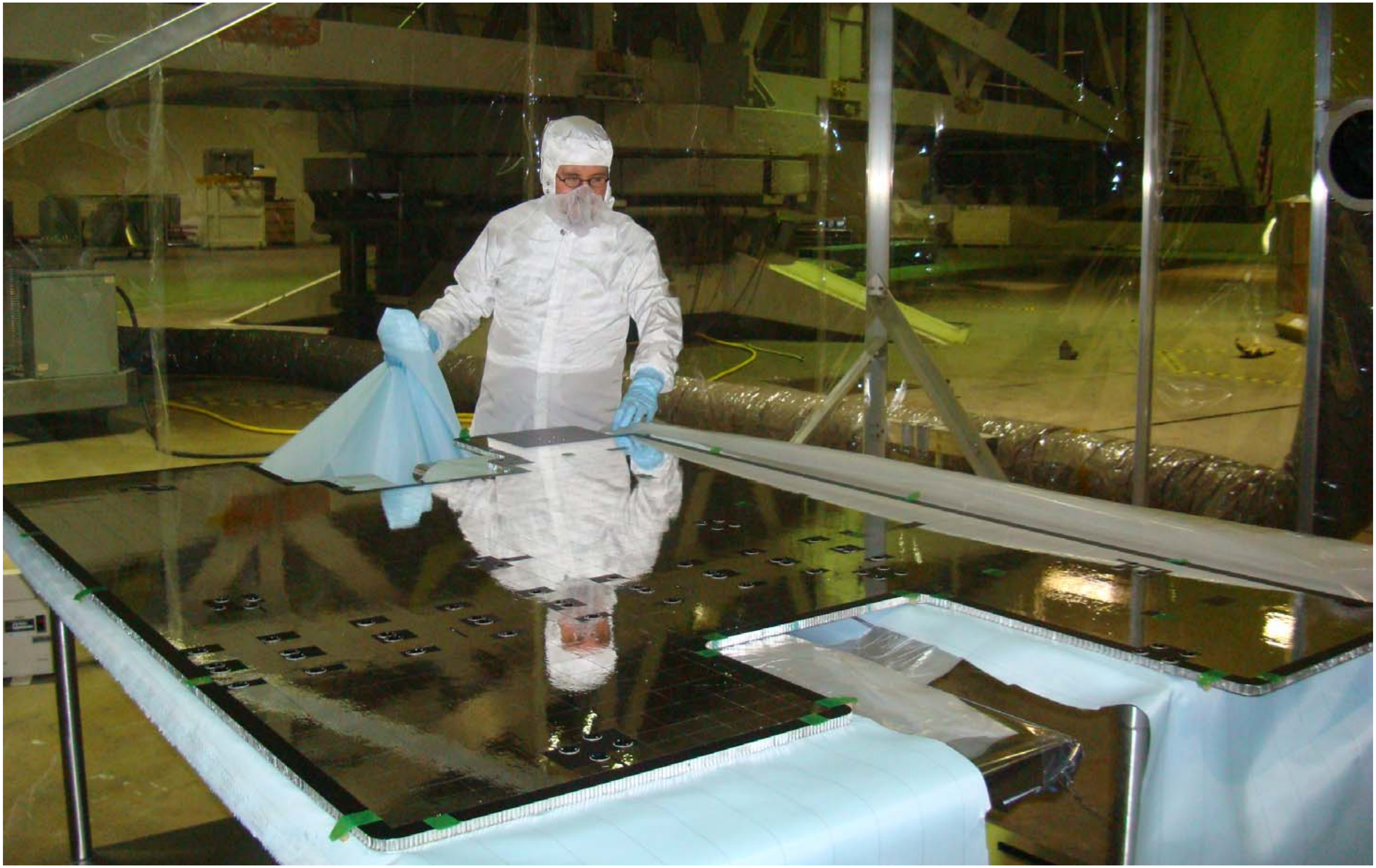
LRO Spacecraft (Launch Config)



Avionics Deck



Thermal Engr Inspects Radiator

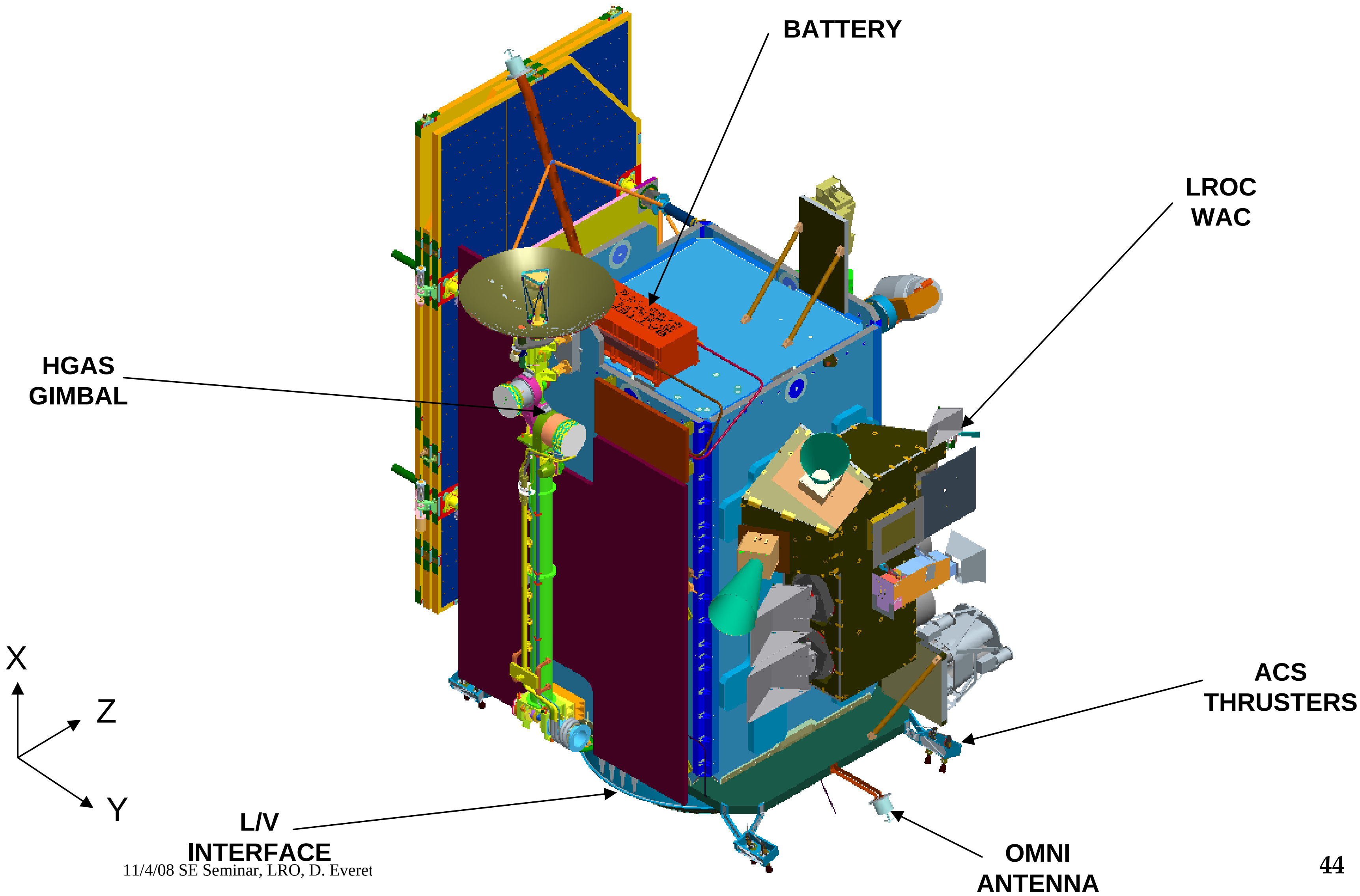


Flight Integration Begins, Jan 2008

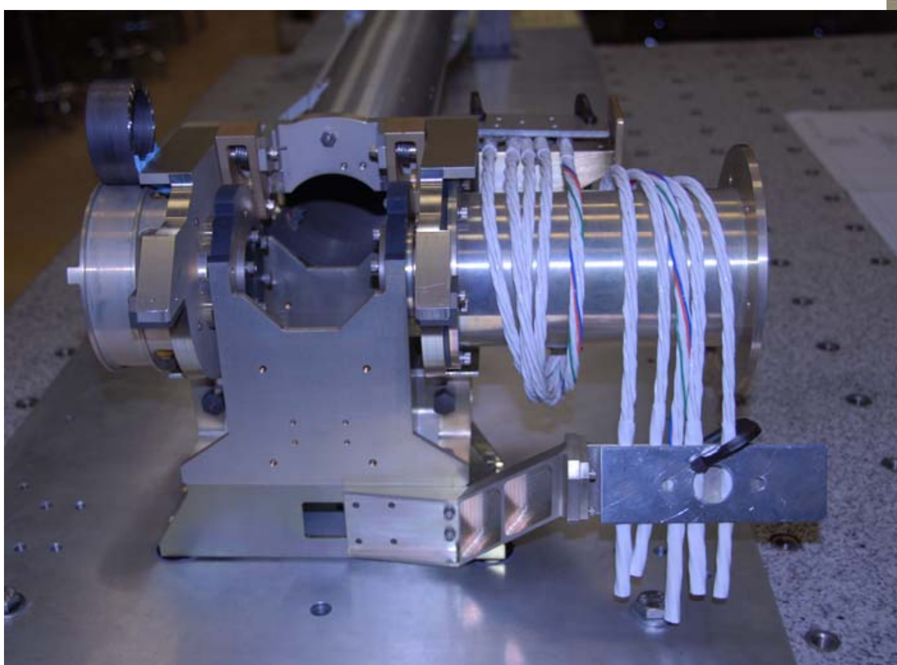
PDE Safe-to-Mate, January 2008

Instrument Module going to Bakeout

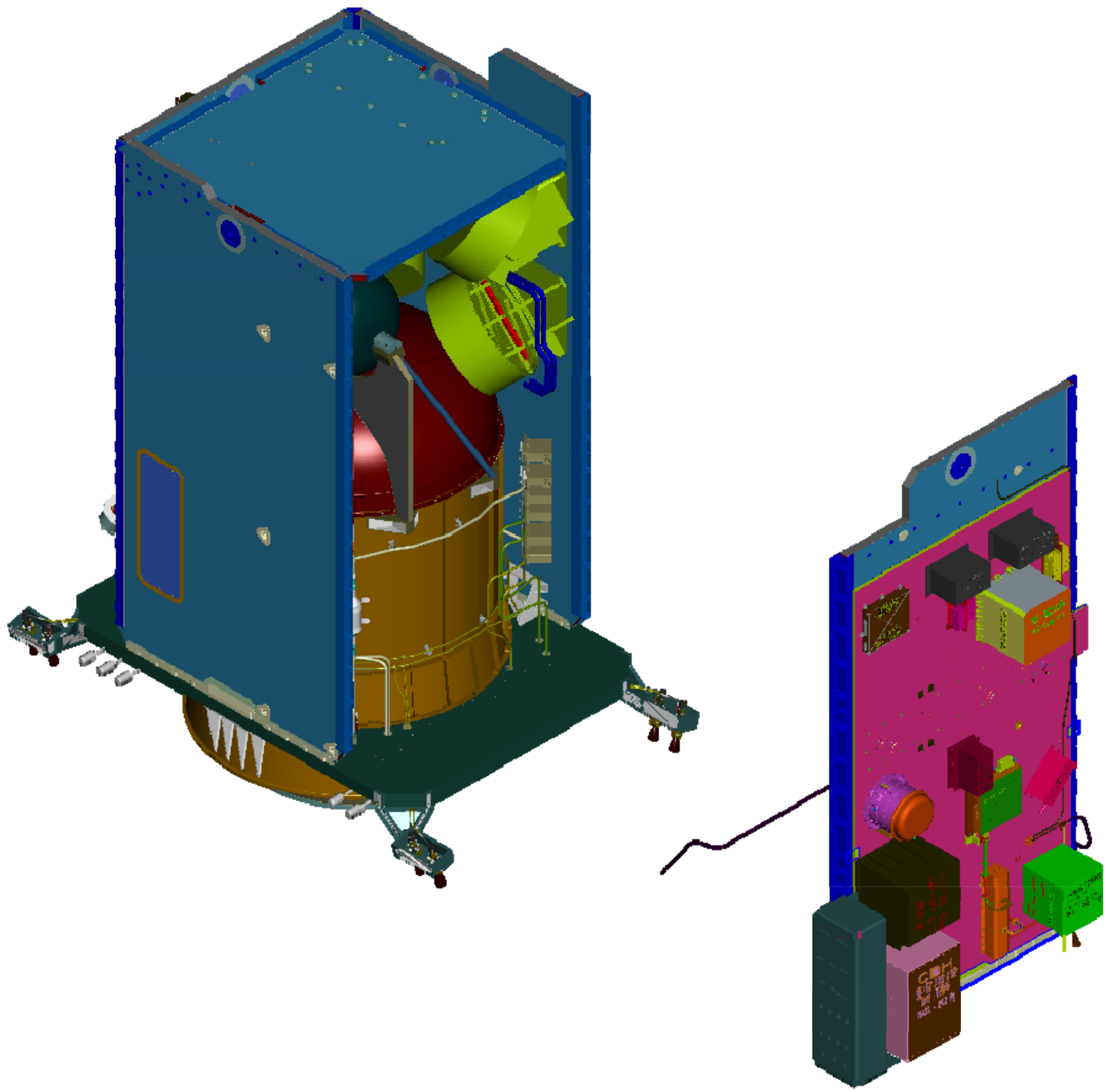
LRO Spacecraft (Launch Config)



HGAS Boom

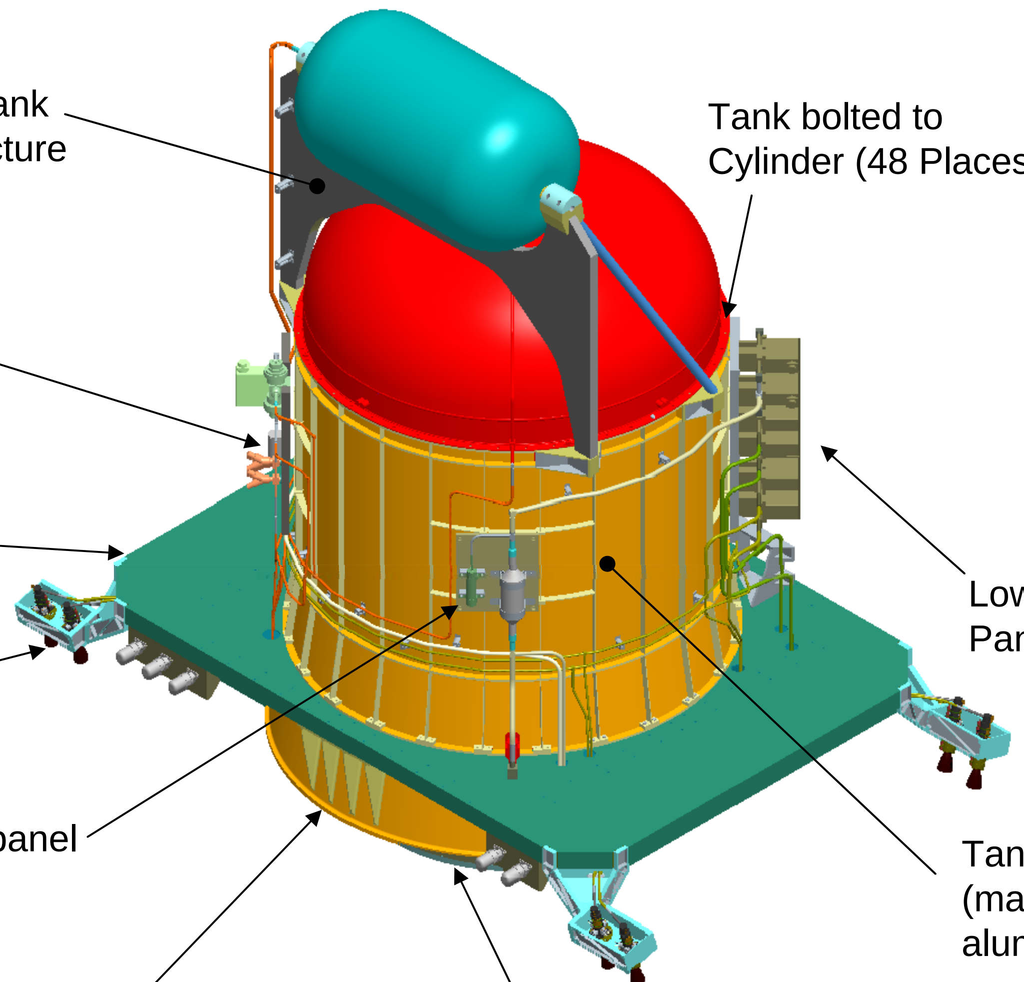


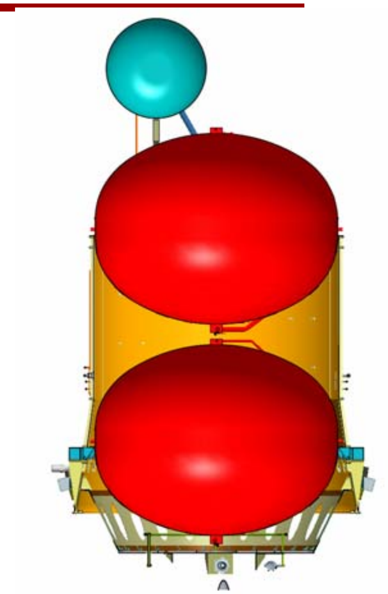
Propulsion Tank and Wheel Locations



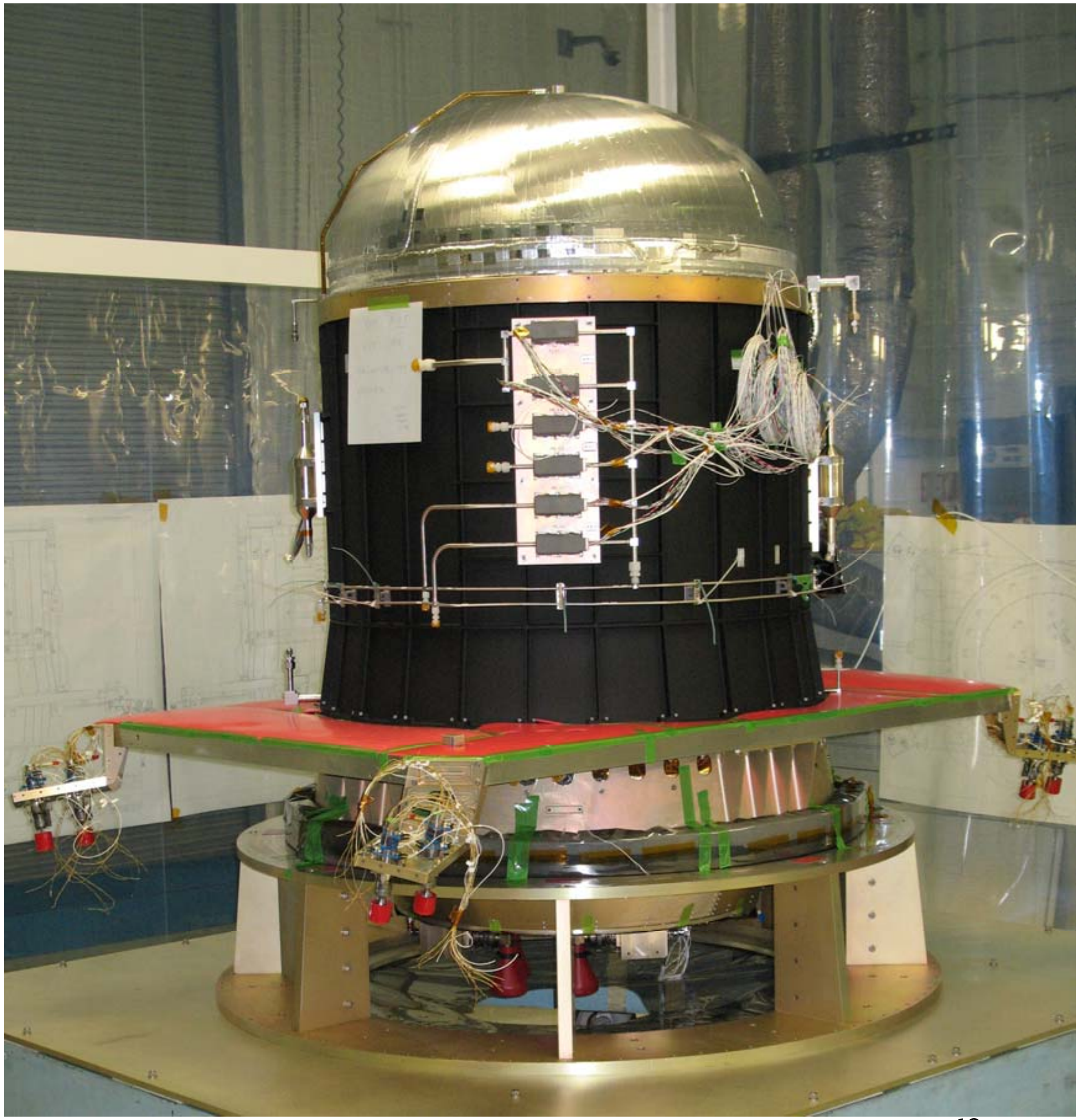
Reaction Wheels, January 2008

LRO Propulsion Module



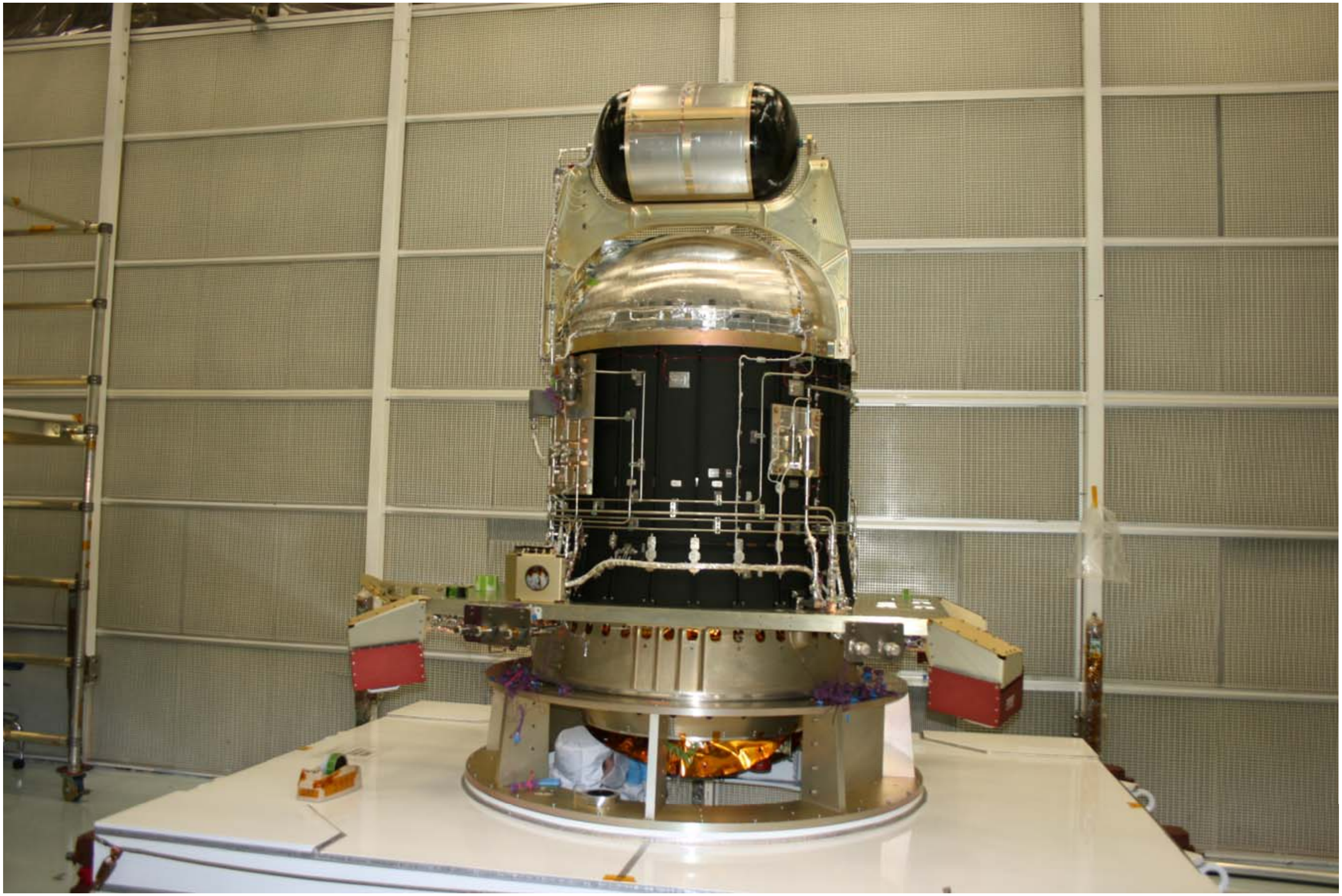


Propulsion Module



Assembly Team

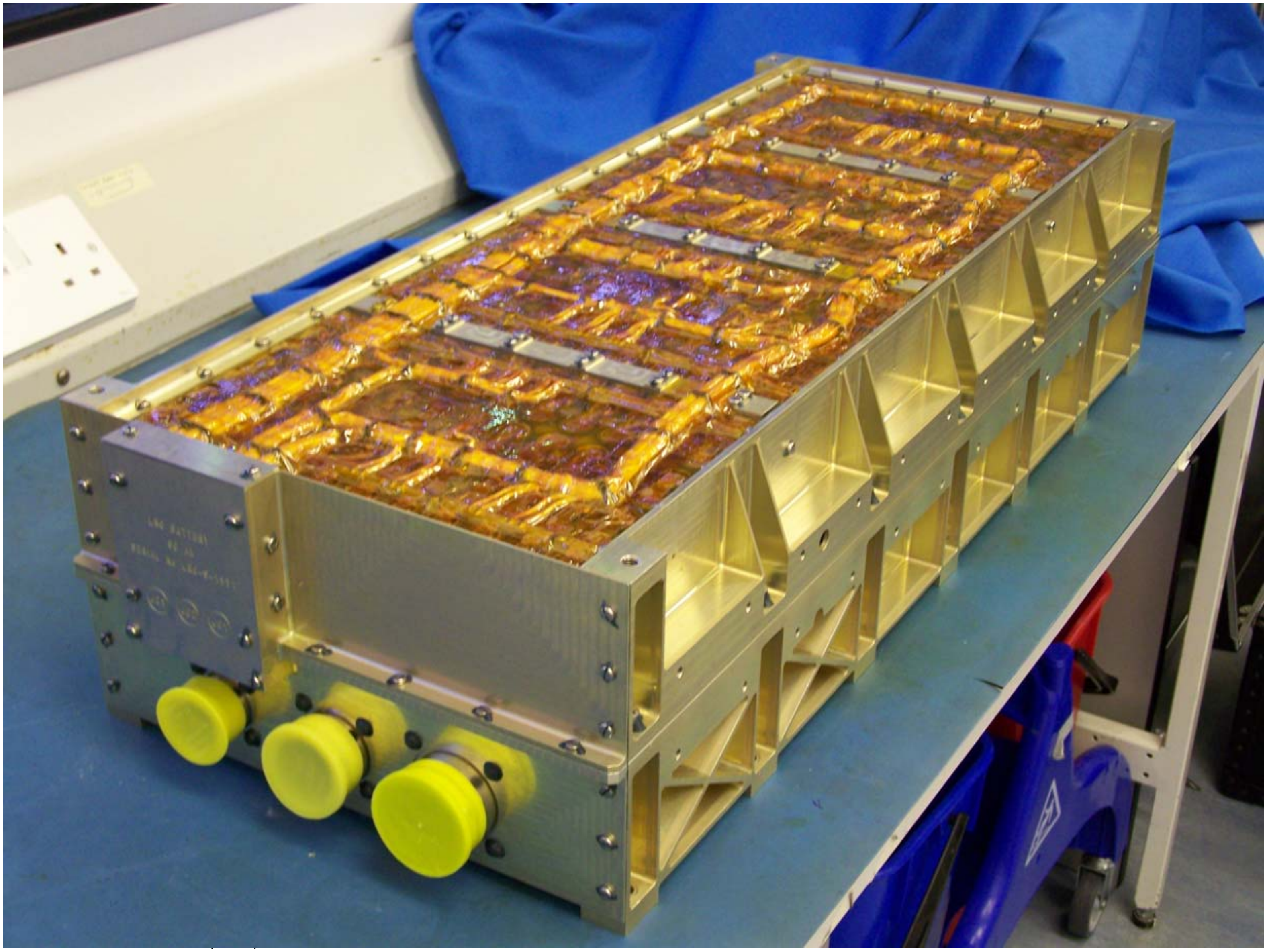
Propulsion Module, January 2008



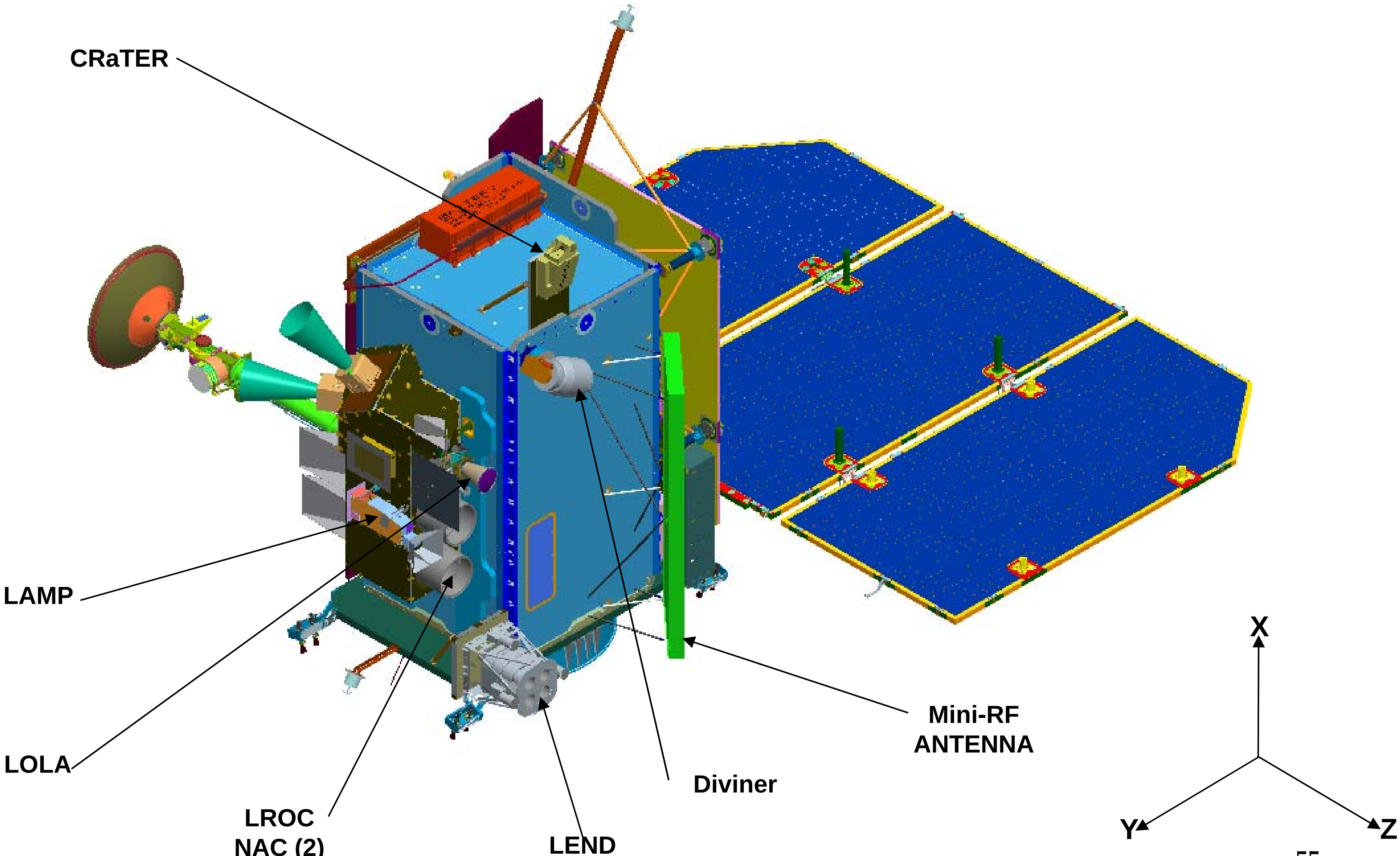
+Y Panel Integration, 3/13/08

Star Tracker

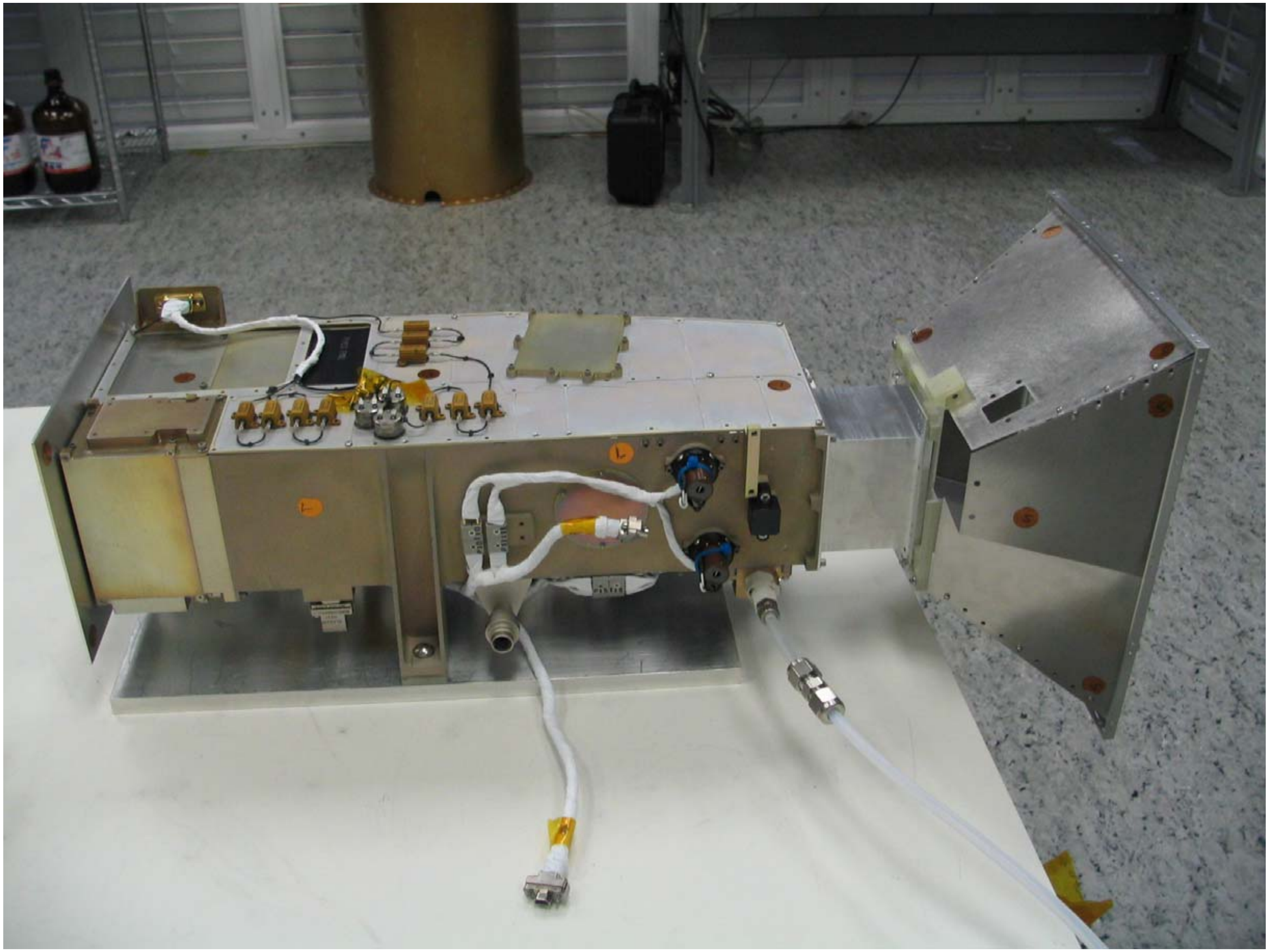
Qual Battery



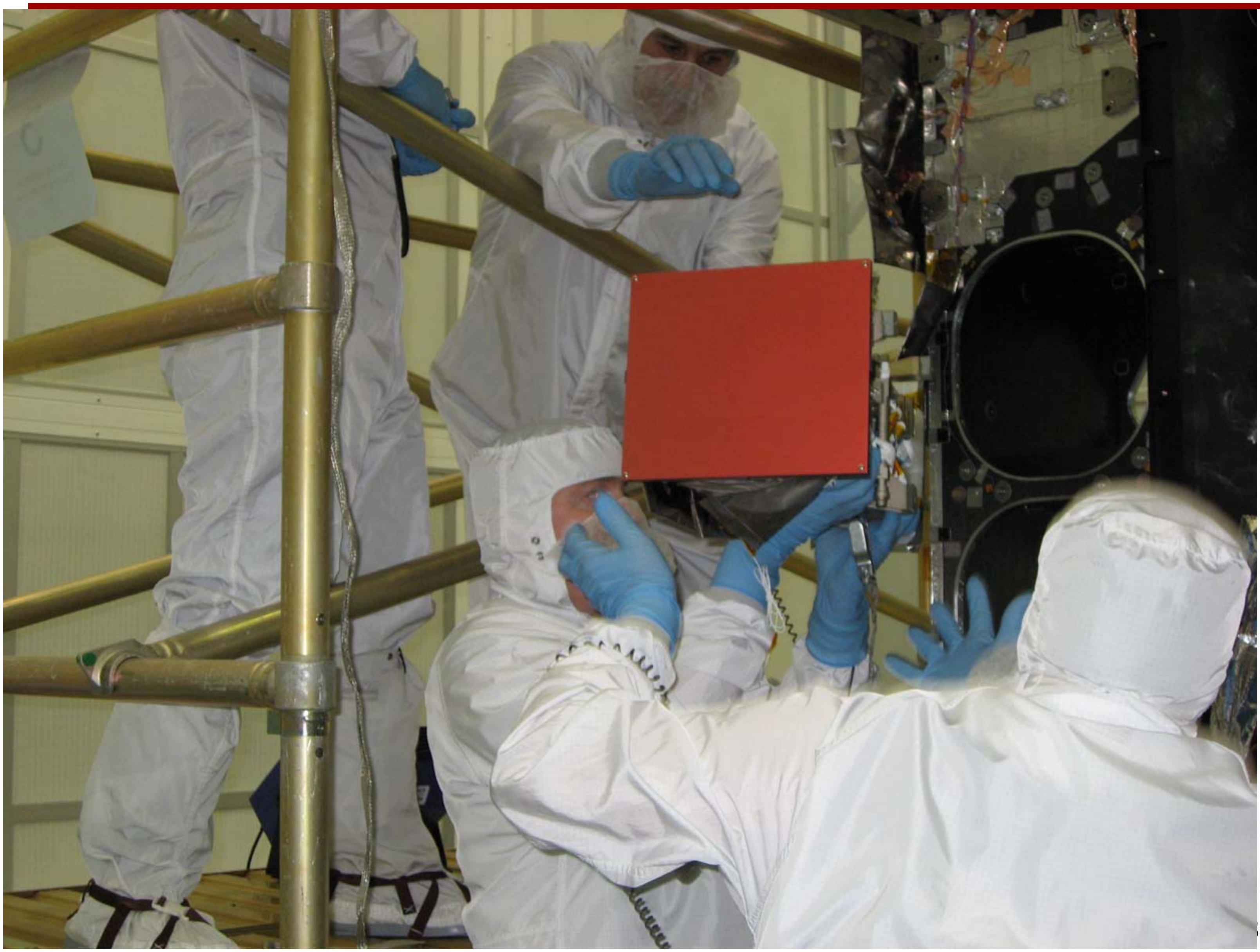
LRO Spacecraft



Flight LAMP without LTS or blankets



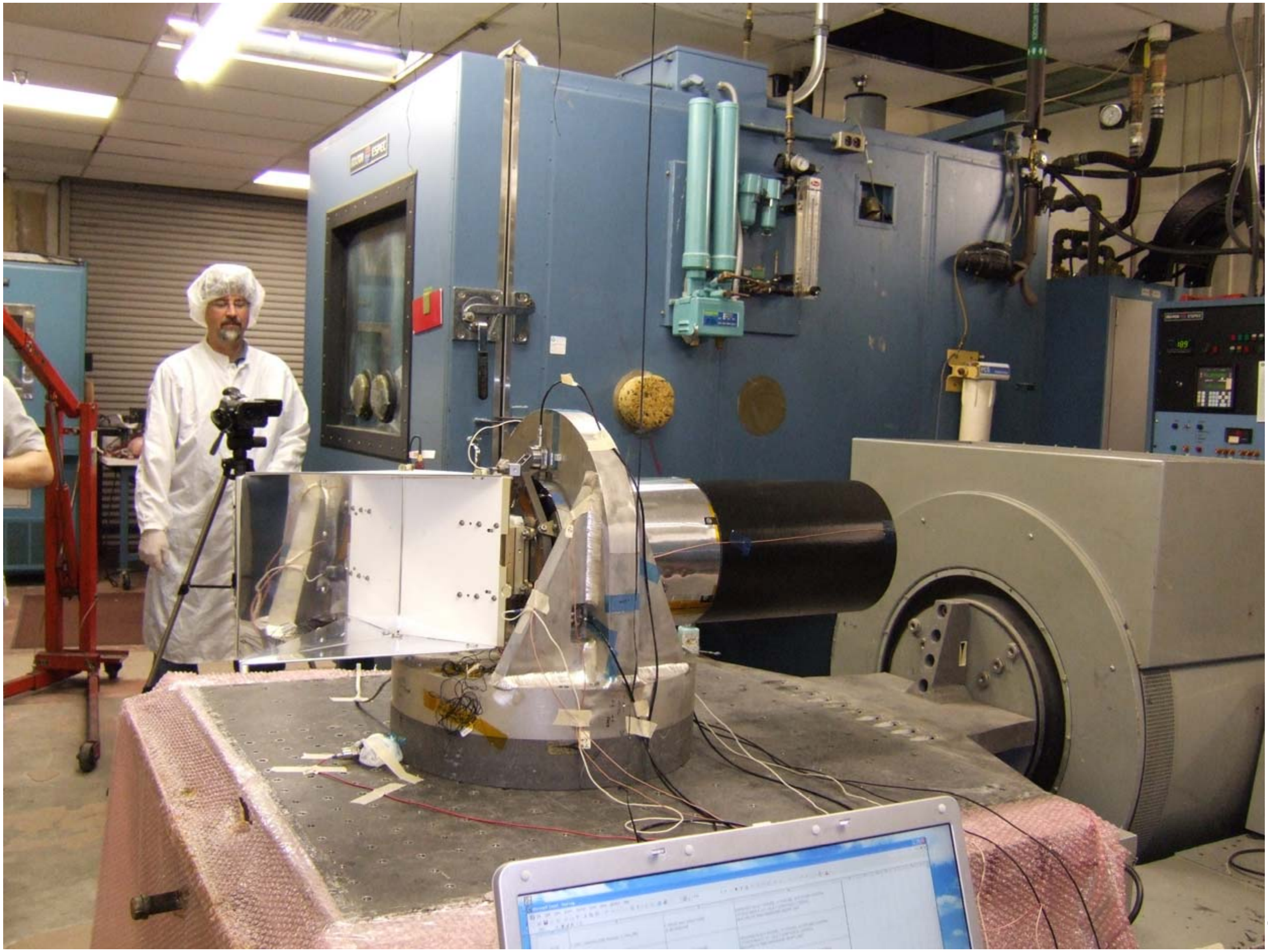
LAMP Integration, 3/20/08



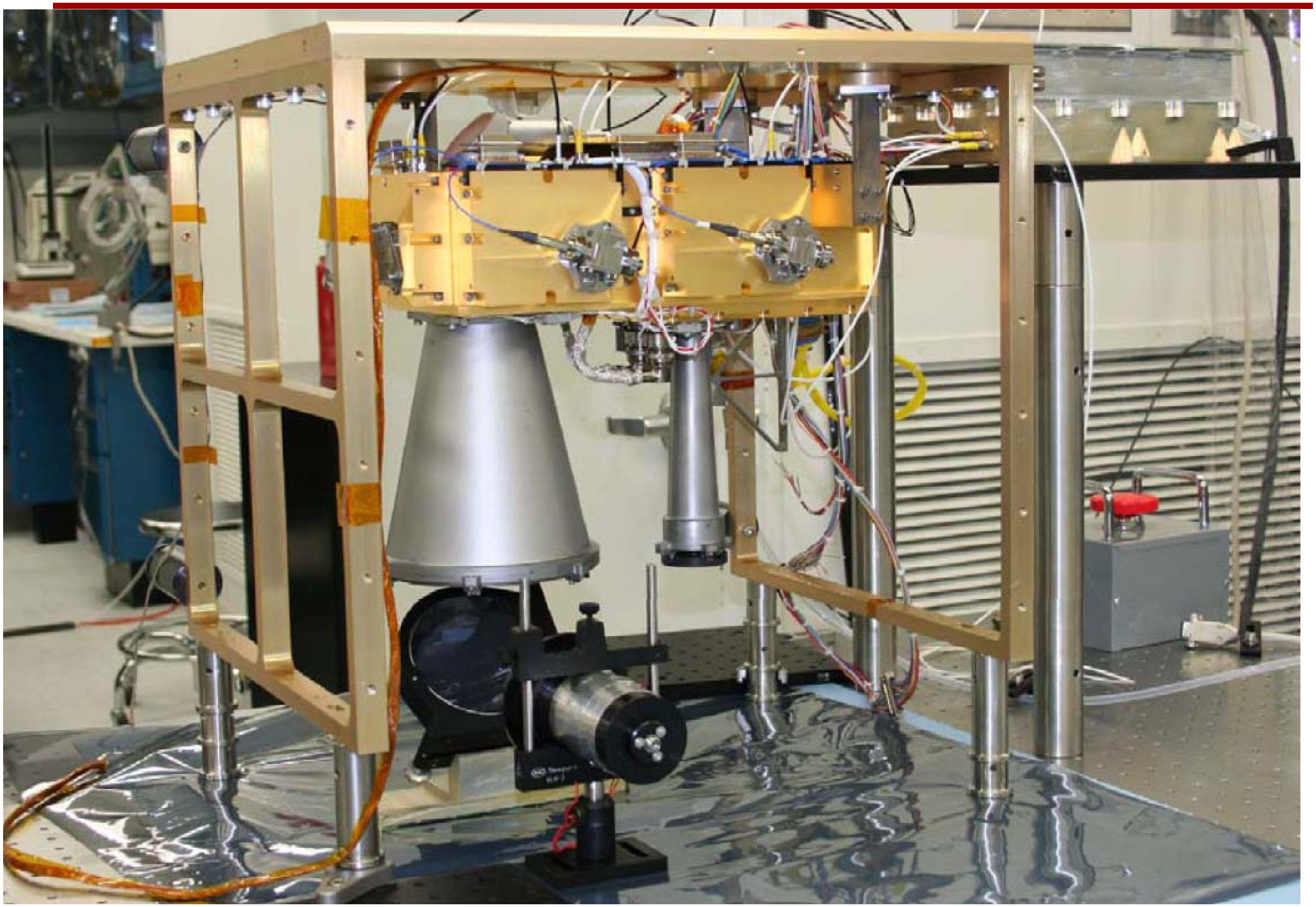
Diviner and Crater on LRO, 4/3/08

LEND Engineering Unit at Flatsat

LROC NAC During Vibe

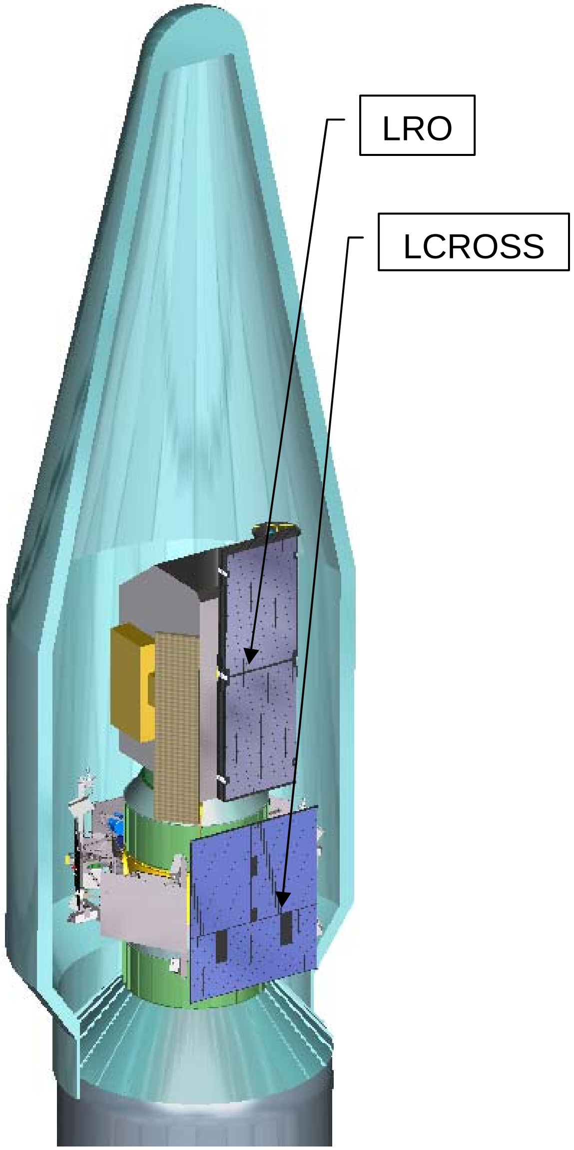


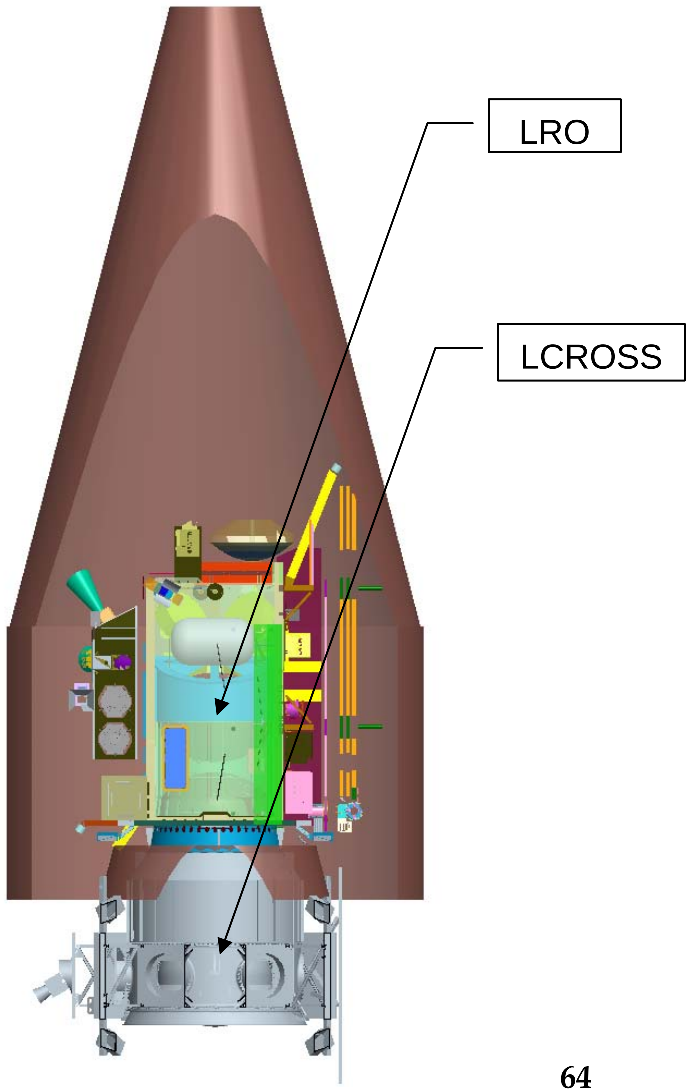
LOLA Receiver Telescope Test




READING

LRO in Launch Vehicle

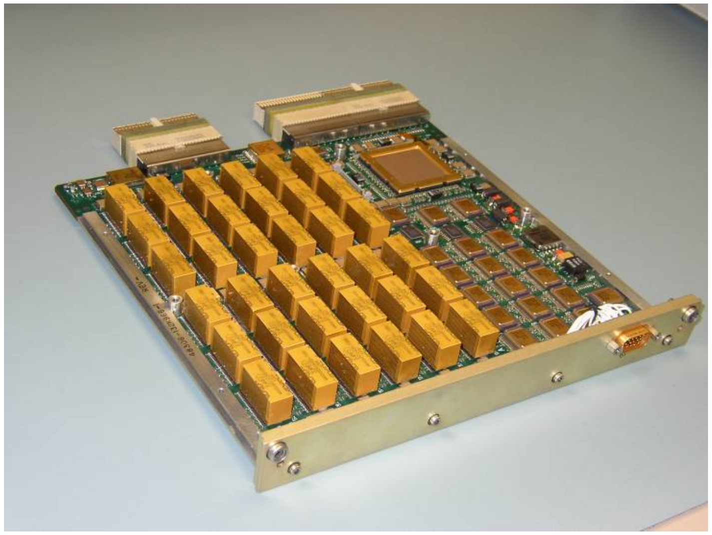


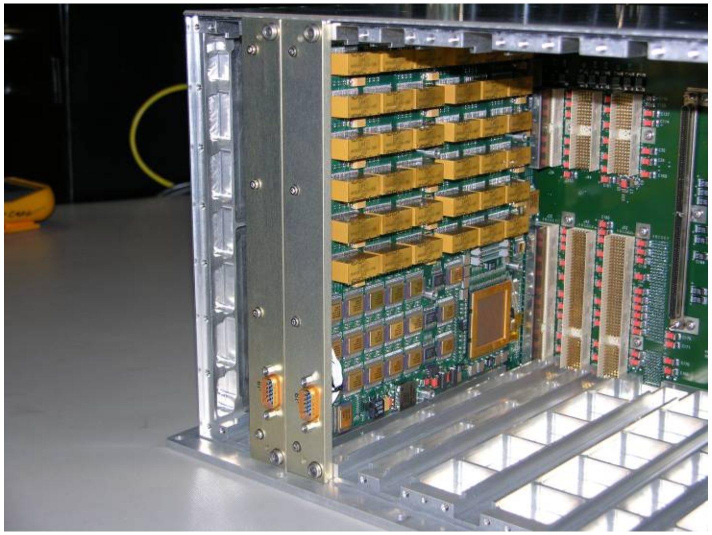


LRO Data Generation

LRO Data Volume Budget				
Type	**Data per Orbit (Mbits)**	**Data per Day (Gbits)**	**Files per Orbit**	**File per Day**
CRaTER	610.24	7.78	77	972
Diviner	180.52	2.30	23	288
LAMP	168.22	2.14	2	26
LEND	20.52	0.26	2	26
LOLA	187.47	2.39	24	299
LROC	34,763.26	443.00	28	351
Spacecraft	86.04	1.10	11	138
Total (Gbits):	36.02	458.97	167	2,100

Data Storage Board Photos





WS1 Antenna Assembly at White Sands

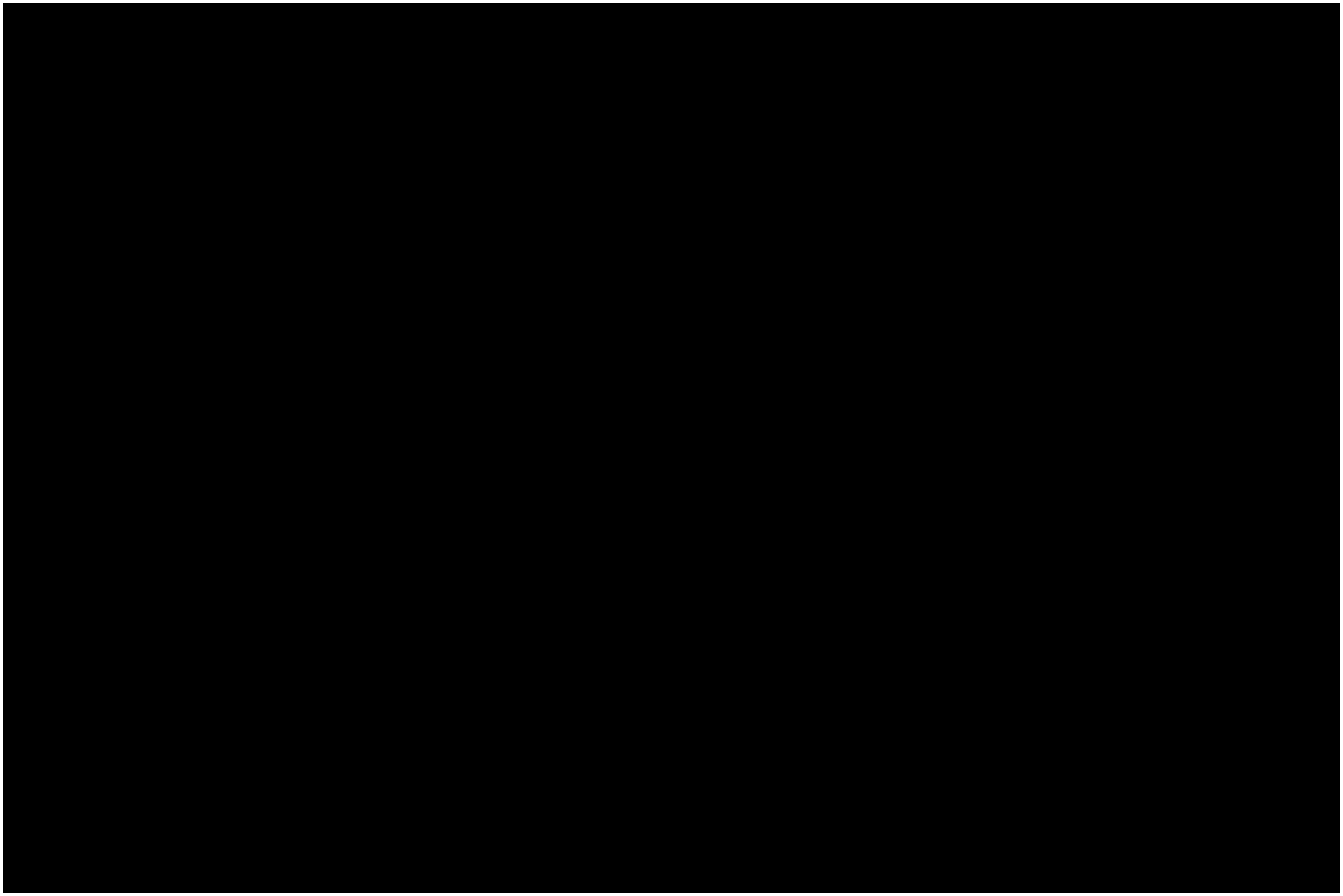
Over 50 Issues Last Year!

- Nearly every component had some sort of problem during the build phase:
  - C&DH:
    - Assembly issues—rework
    - SBC noise problem—rearrange spacewire ports
    - Power supply parts delays—build extra unit
  - Comm
    - Transponder Software design flaw—change ground stations
    - Transponder Hardware design flaw—replace part, jumpers
    - Modulator assembly problems—bring in-house
    - Modulator performance at cold—modify circuit
    - TWTA design error in ground protection circuit—fly as-is
  - GN&C
    - Wheel board layout problem—redo
    - Star Tracker resets—change part
    - MIMU part failure—replace part

Over 50 Issues Last Year (cont.)!

- Nearly every component had some sort of problem during the build phase:
  - Software performance problems—update code
  - Power: PSE frequency shift during vibe—tighten and retest
  - Payloads
    - CRaTER ETU part failure—flight parts OK
    - Diviner actuator damaged during test by long screw—re-work
    - LAMP board damaged by long screw—replace board
    - LEND power surge during thermal vacuum—replace unit (flight spare)
    - LOLA housing corrosion—fly as is
    - LOLA overtest during sine burst—no damage
    - LOLA corona during thermal vacuum—no damage
    - LROC NAC vibration failure—redesign mount for secondary
    - Mini-RF strut failure during thermal vac—redesign strut

LRO Integration



Current Status

- Basic statistics
  - Mass: 1910 kg wet, 1015 kg dry, 50 kg dry margin
  - Power: 680 W, capability > 823 W
- Completed Thermal Balance
  - Gimbal cable wrap power dissipation issue
  - Remainder of the system performed well
- Thermal cycling started
- CPT in December
- Operations testing until ship in February
- Launch delayed to April 24 by manifest issues

Mistakes

- Expect mistakes!
  - We all make mistakes; the challenge is to avoid the fatal ones
  - Treat mistakes and failures as a normal part of the job—keep things out in the open, clean up, and move on
- Some of our bigger mistakes (so far):
  - Underestimated the system-level complexity of the High-Gain Antenna System and the Solar Array System
    - Interplay of RF and thermal
    - Actuator electronics implementation impacted thermal
    - Gimbal blankets
    - Resistive losses in solar array cables
  - Failed to anticipate the impact of the change in the center's engineering services contract
    - Major contract change right in the middle of the build phase
    - Created uncertainty, impacted workforce

Observations and Lessons Learned

- Don't be afraid to point out to stakeholders decisions that can be made to relieve your problems (launch vehicle example)
- Programmatic constraints affect the development:
  - Tight schedules force decisions
  - Tight budget approaching confirmation forces optimization
  - Extra money after CDR can save schedule and probably save money in the long run
- Even if the schedule is tight, make sound technical choices (remember the fortune cookie)

Observations and Lessons (cont.)

- Interface tests save money in the long run—test early and often
- Plan early for parallel development and assembly
- Decouple delivery events so that integration can move forward even if one item is late
- Systems engineering is all about the team
  - Success depends on the performance of the entire team
  - Some people on the team will require more effort, but the extra effort is required to get different perspectives
  - Be flexible and optimistic