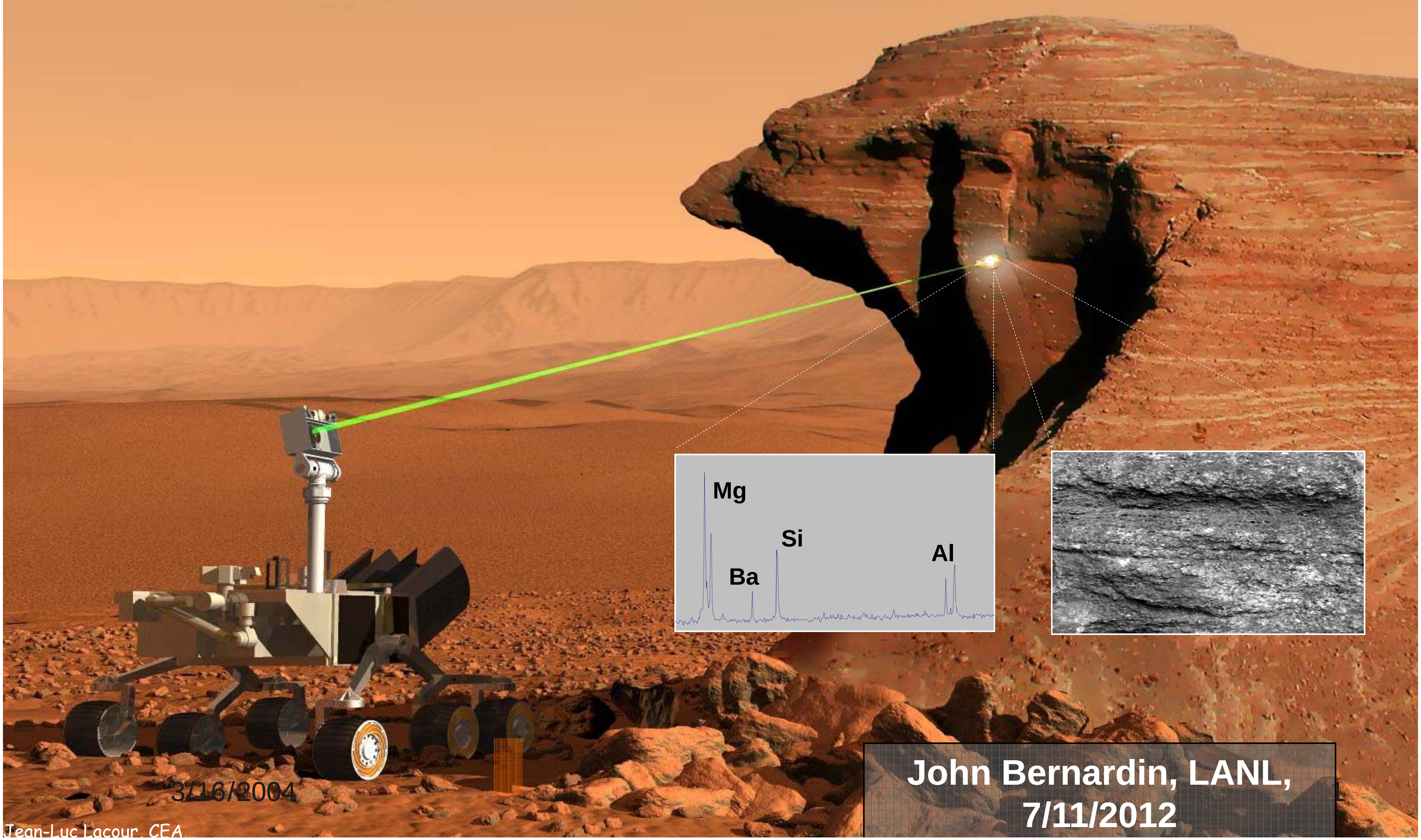
Mechanical & System Engineering Challenges Associated with the Development of the ChemCam Instrument for the NASA Mars Science Laboratory



John Bernardin, LANL,
7/11/2012

Presentation Outline

- The MSL Mission and Curiosity, the MSL Rover
- The ChemCam Instrument
- System Engineering ChemCam
- Mechanical Engineering ChemCam
- Launch and the Future Mission

NASA/JPL/Cornell

The MSL Mission and Curiosity

NASA/JPL/Cornell

The MSL Mission Science Goals

- Assess the biological potential of the site by investigating any organic and inorganic compounds and the processes that might preserve them
- Characterize geology and geochemistry, including chemical, mineralogical, and isotopic composition, and geological processes
- Investigating the role of water, atmospheric evolution, and modern weather/climate
- Characterize the spectrum of surface radiation

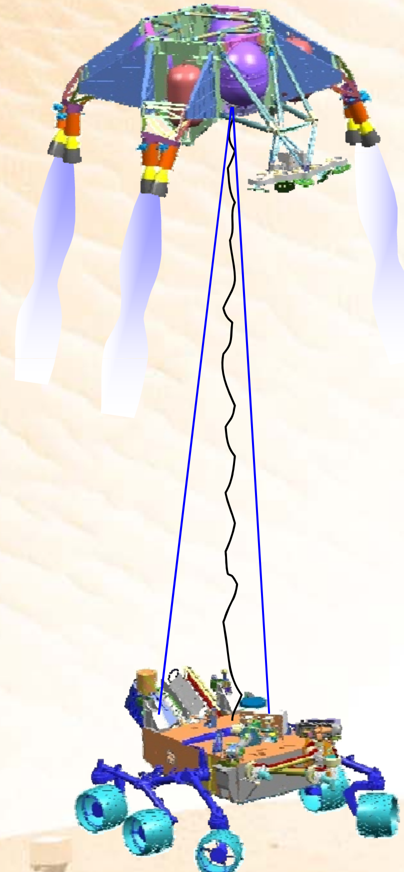
Mission Overview

CRUISE/APPROACH

- 8½-month cruise
- Arrives August 6, 2012

ENTRY, DESCENT, LANDING

- Guided entry and powered "sky crane" descent
- 20 × 25-km landing ellipse
- Designed to access landing sites ±30° latitude, < 0 km
- 900-kg (1 ton) rover



LAUNCH

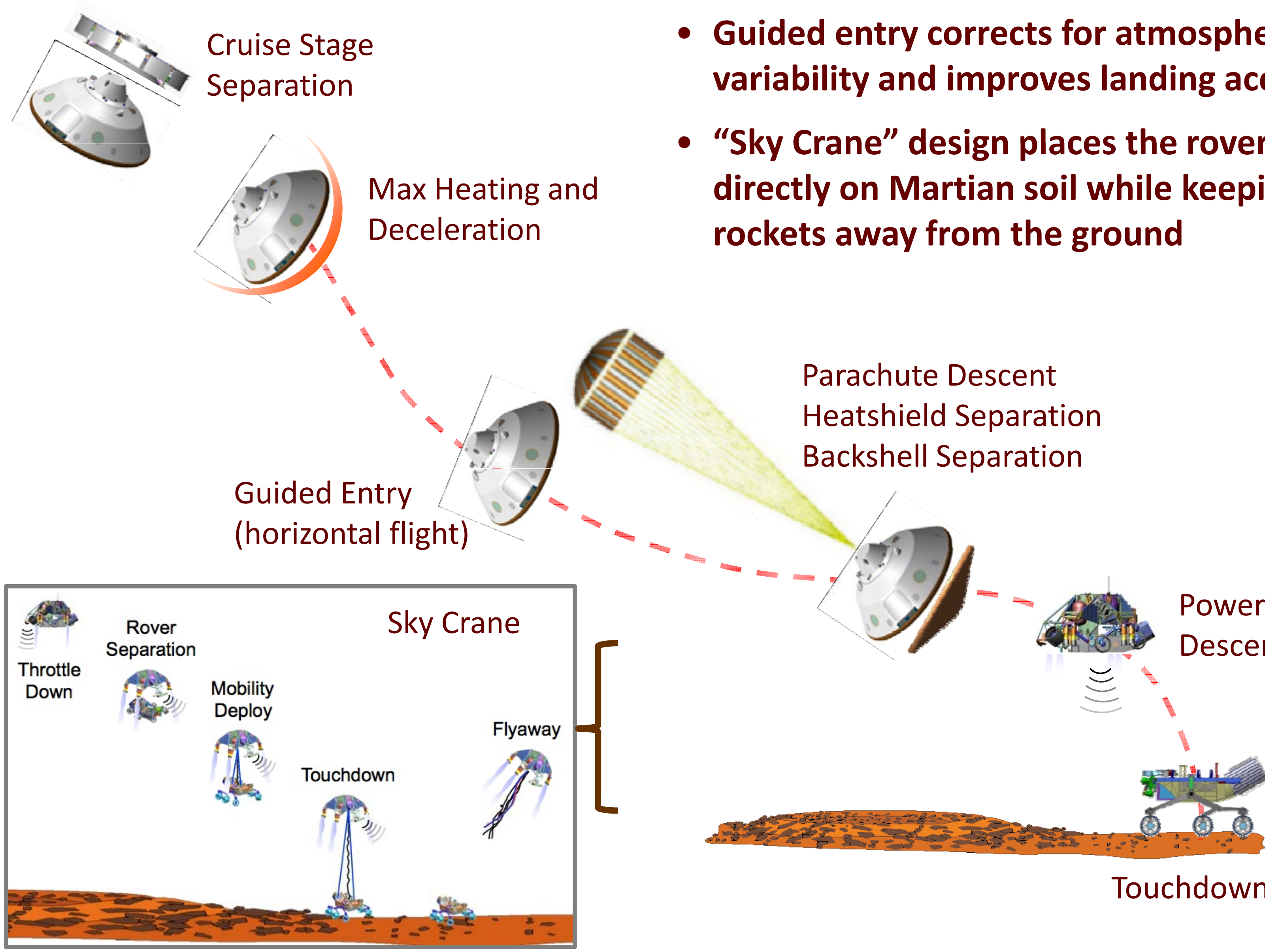
- Launched on Nov. 26, 2011
- Atlas V (541)

SURFACE MISSION

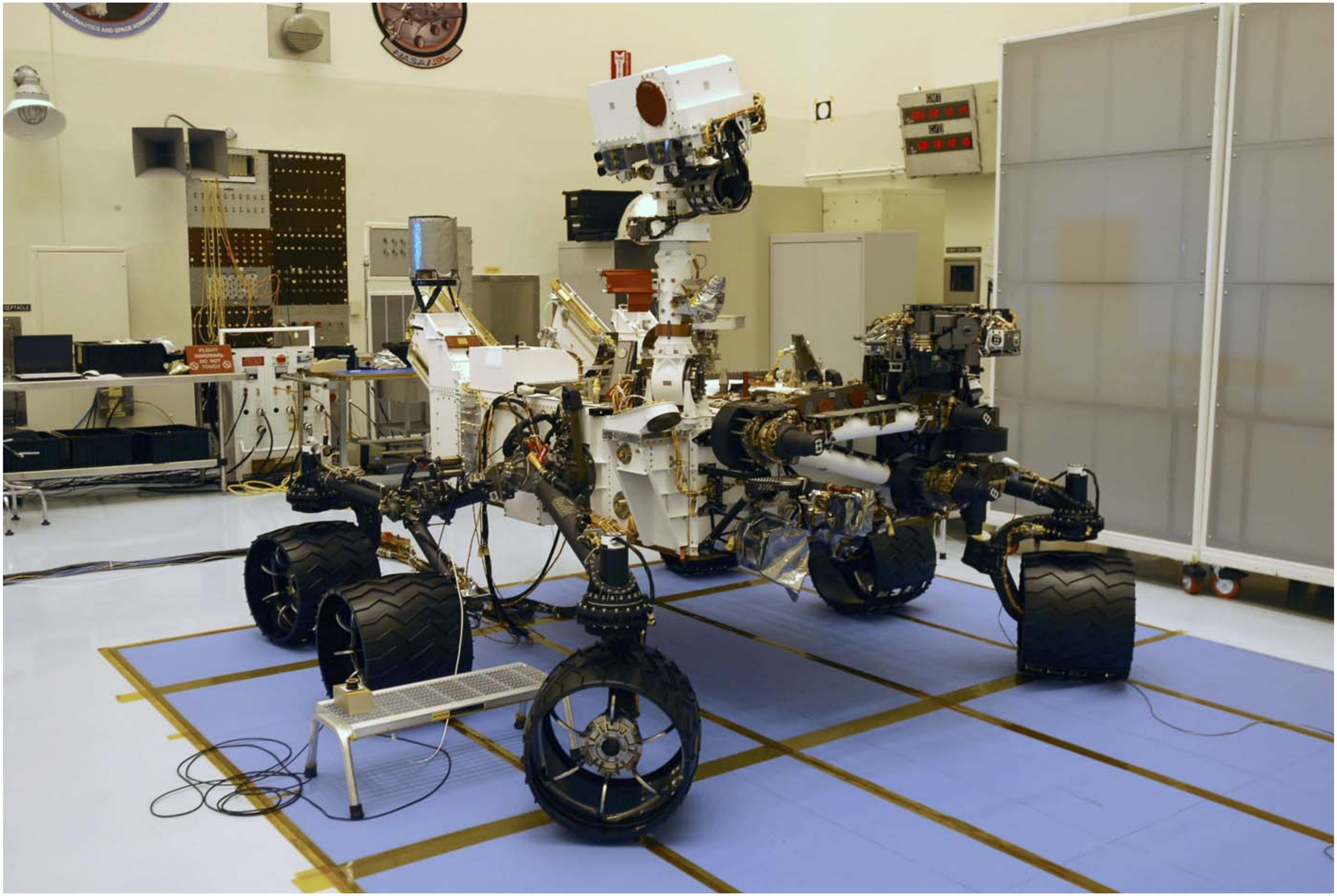
- Prime mission is one Mars year
- Latitude-independent and long-lived power source
- Ability to drive out of landing ellipse
- 75 kg (165 lbs.) of science payload
- Direct (uplink) and relayed (downlink) communication
- Fast CPU and large data storage

MSL Entry, Descent, and Landing

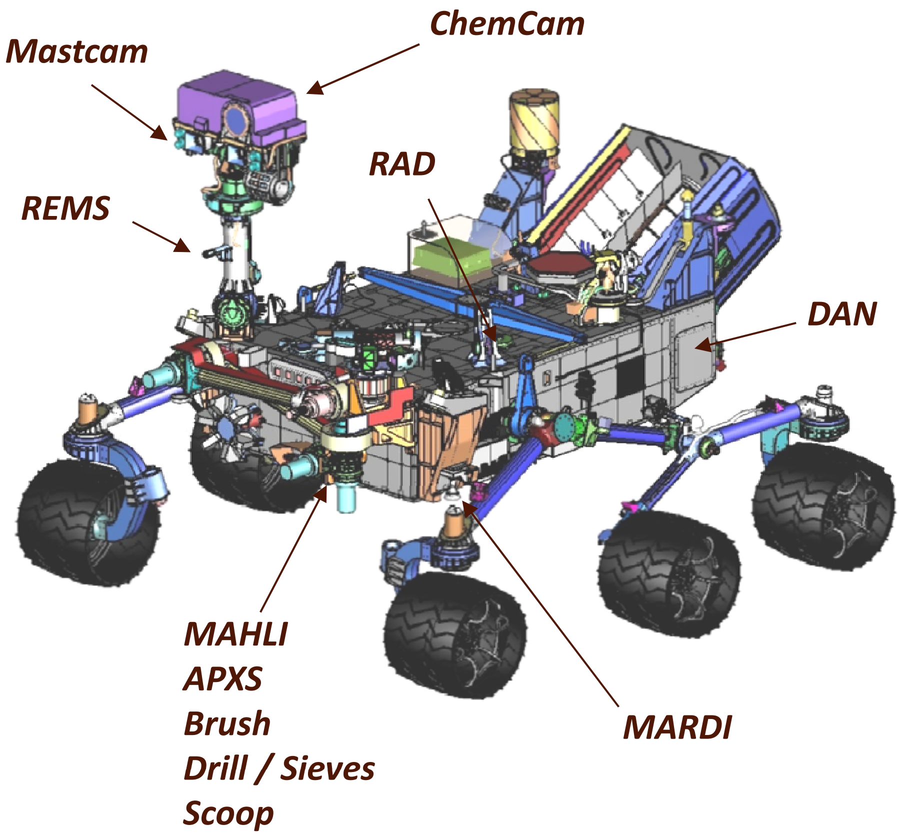
- **Guided entry corrects for atmospheric variability and improves landing accuracy**
- **"Sky Crane" design places the rover directly on Martian soil while keeping the rockets away from the ground**



Curiosity – the MSL Rover



MSL Science Payload



Wheel Base:	**2.8 m**
Height of Deck:	**1.1 m**
Ground Clearance:	**0.66 m**
Height of Mast:	**2.2 m**

REMOTE SENSING

Mastcam (M. Malin, MSSS) - Color and telephoto imaging, video, atmospheric opacity

ChemCam (R. Wiens, LANL/CNES) – Chemical composition; remote micro-imaging

CONTACT INSTRUMENTS (ARM)

MAHLI (K. Edgett, MSSS) – Hand-lens color imaging

APXS (R. Gellert, U. Guelph, Canada) - Chemical composition

ANALYTICAL LABORATORY (ROVER BODY)

SAM (P. Mahaffy, GSFC/CNES) - Chemical and isotopic composition, including organics

CheMin (D. Blake, ARC) - Mineralogy

ENVIRONMENTAL CHARACTERIZATION

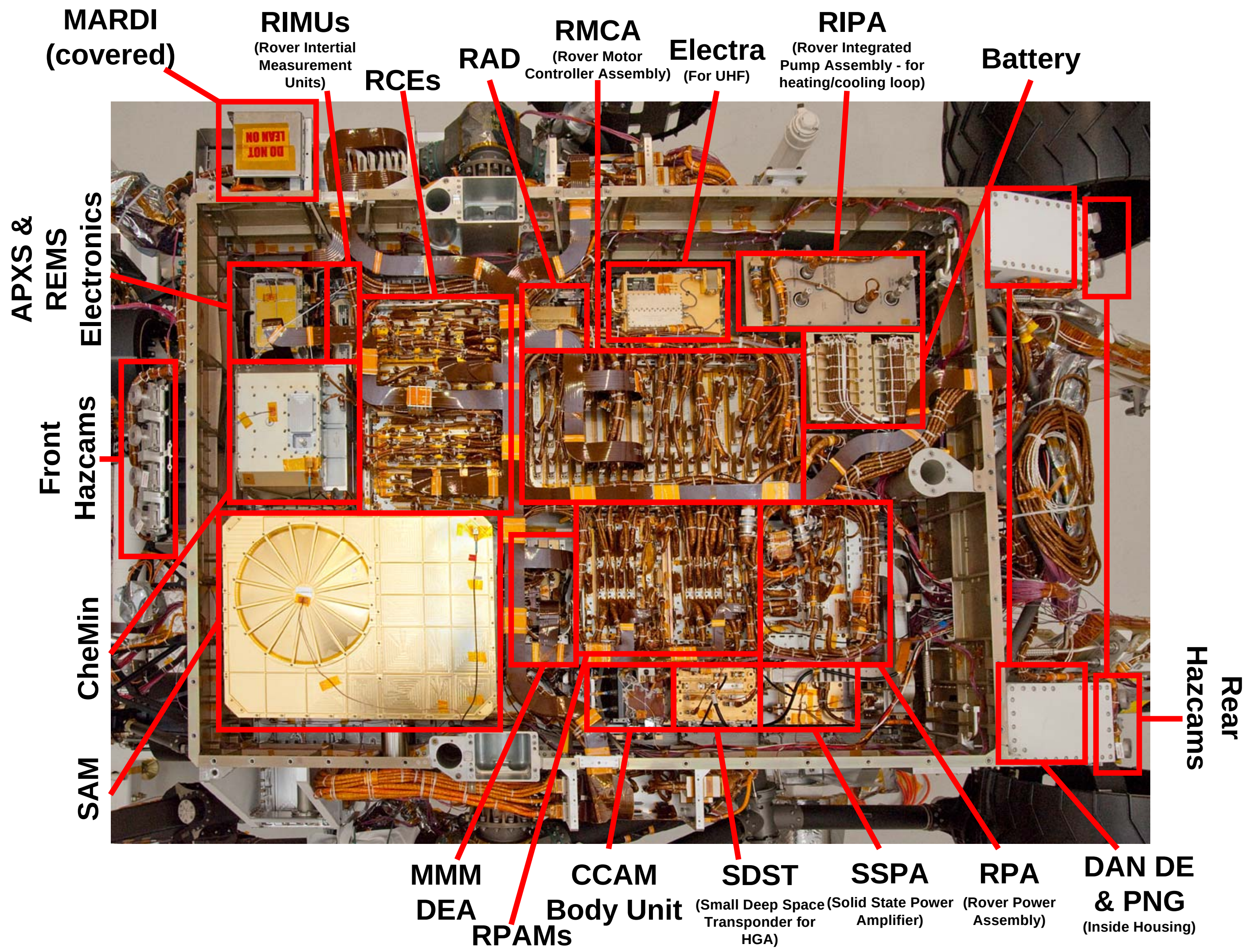
MARDI (M. Malin, MSSS) - Descent imaging

REMS (J. Gómez-Elvira, CAB, Spain) - Meteorology / UV

RAD (D. Hassler, SwRI) - High-energy radiation

DAN (I. Mitrofanov, IKI, Russia) - Subsurface hydrogen

What's Inside



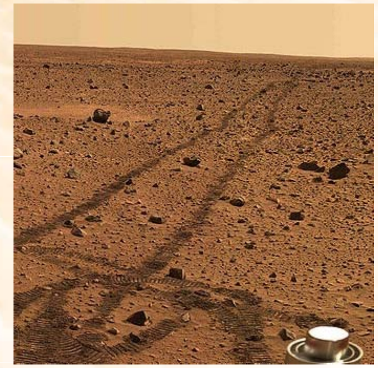
Science Strategy

1. REMOTE SENSING

- Landscape imaging
- Sampling of rock and soil chemistry

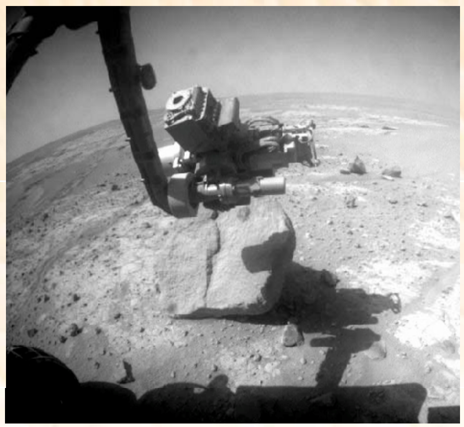
2. TRAVERSE/APPROACH

- Driving ~100 m per sol
- Imaging and profiling chemistry along the drive
- Locating sampling targets



3. CONTACT SCIENCE

- Removal of surface dust
- Chemical and hand-lens observations of a specific target

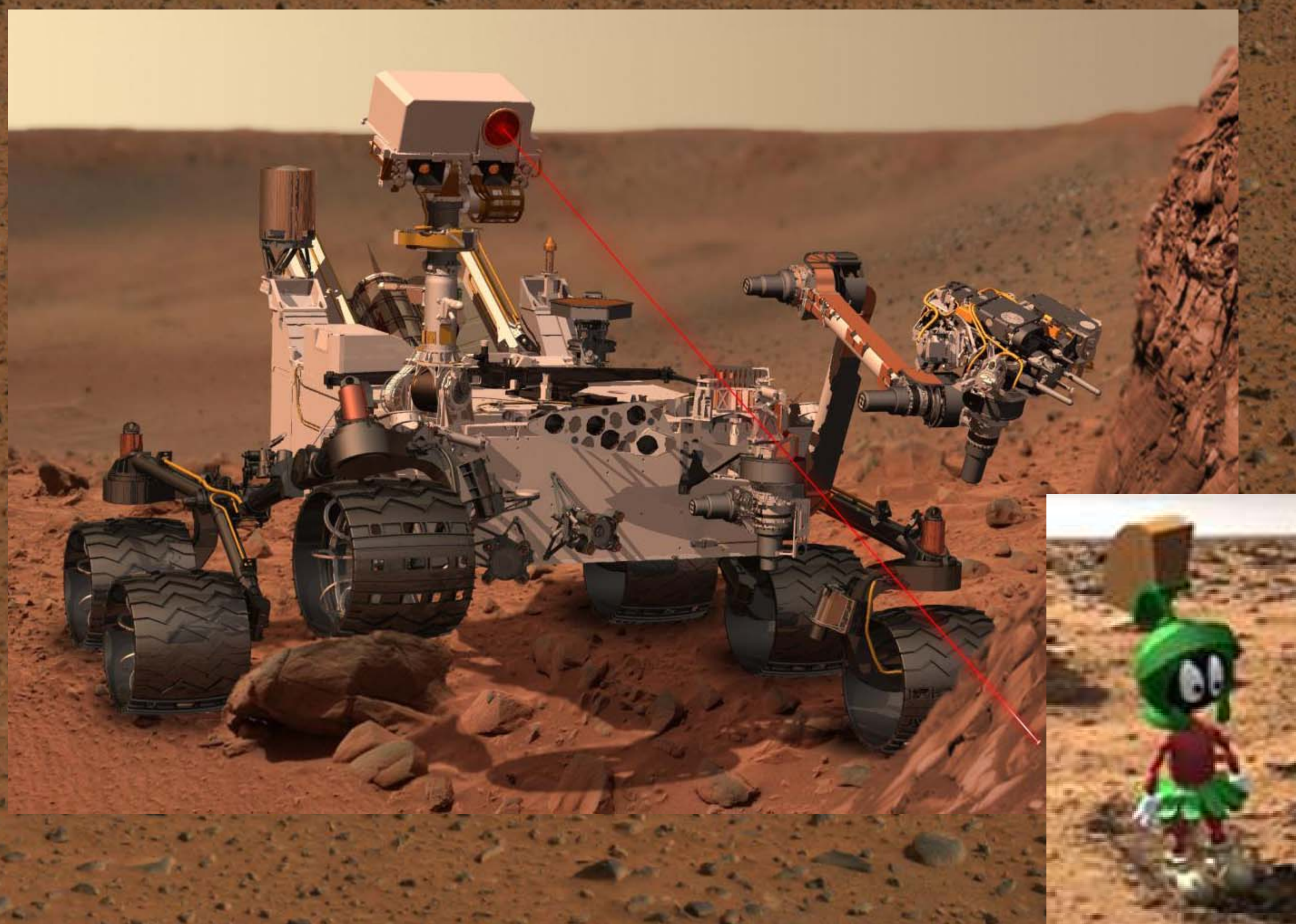


4. SAMPLE ACQUISITION/ANALYSIS

- Drilling, processing, and delivering sample material to the rover's lab instruments
- Analyzing for mineralogy, organics, elemental and isotopic chemistry

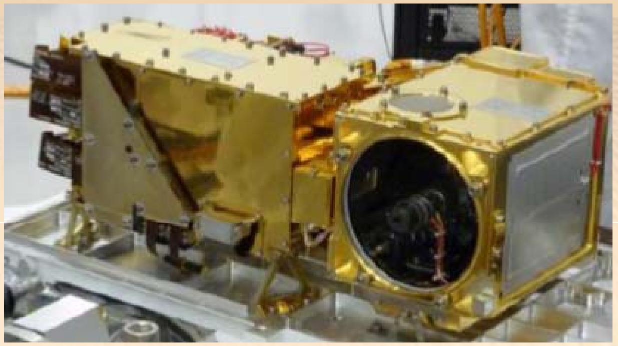
Each class of activity may require multiple sols. Results from each class are reviewed on Earth before moving on to the next. Weather and radiation monitoring occur on all sols.

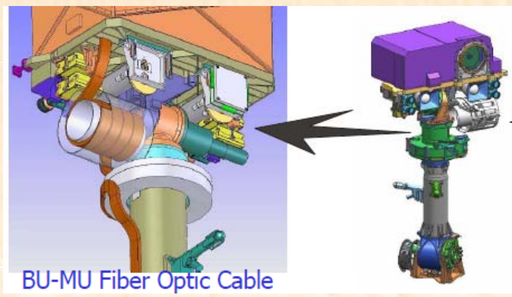
The ChemCam Instrument

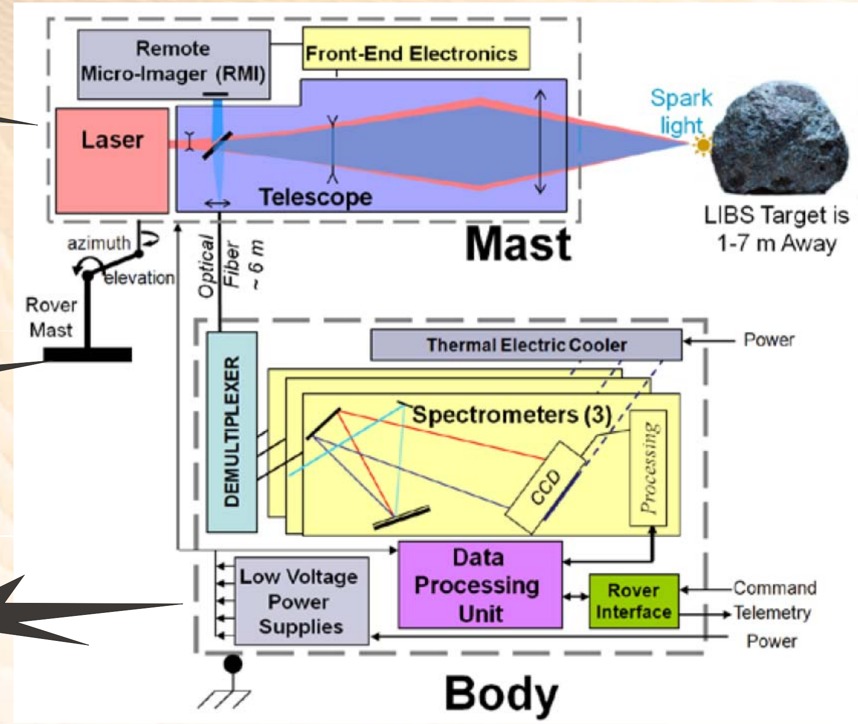


NASA/JPL/Cornell

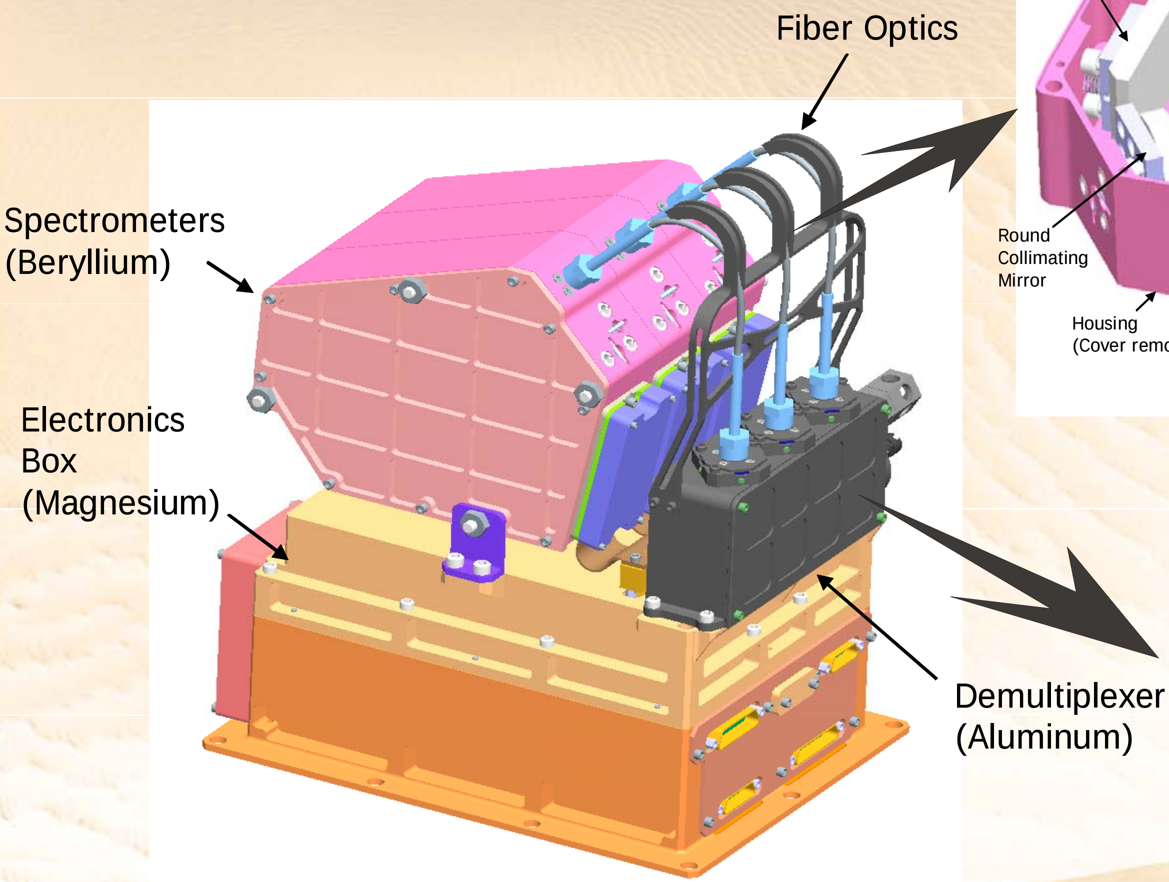
ChemCam

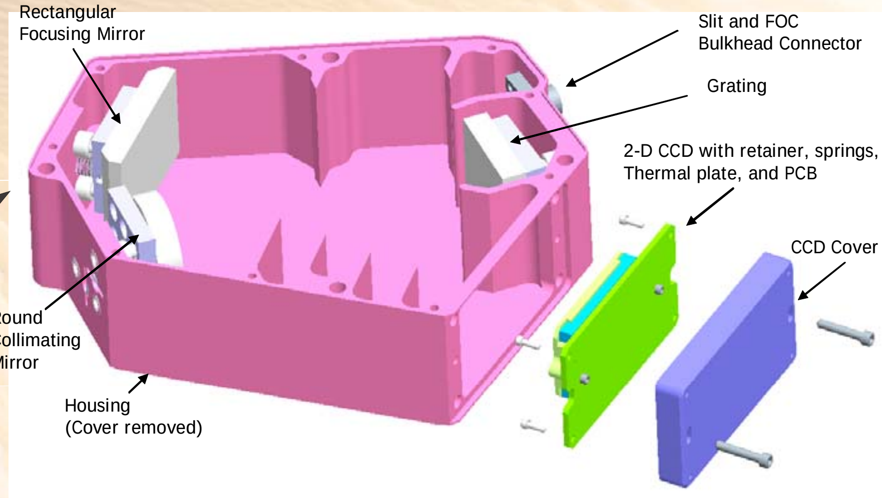


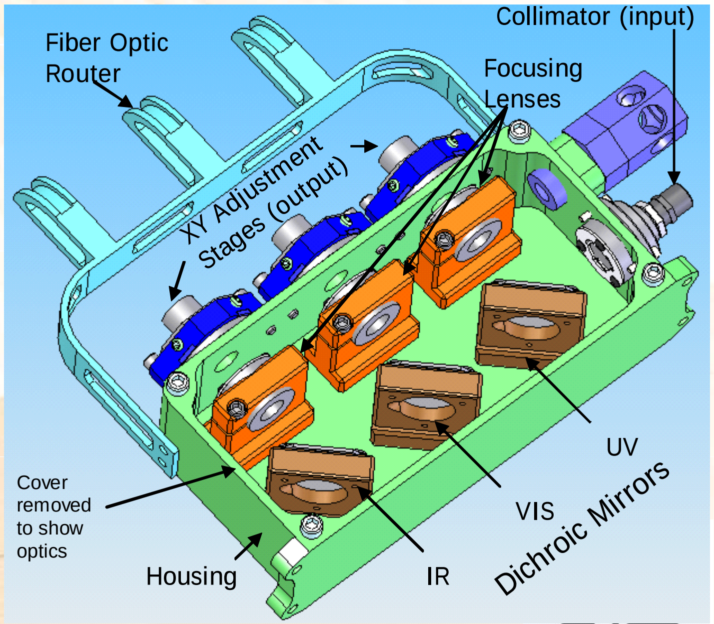

BU-MU Fiber Optic Cable


Remote
Micro-Imager (RMI)
Front-End Electronics
Laser
Telescope
Spark
light
LIBS Target is
1-7 m Away
Mast
azimuth
elevation
Rover
Mast
Optical
Fiber
~ 6 m
Thermal Electric Cooler
Power
DEMULTIPLEXER
Spectrometers (3)
CCD
Processing
Low Voltage
Power
Supplies
Data
Processing
Unit
Rover
Interface
Command
Telemetry
Power
Body

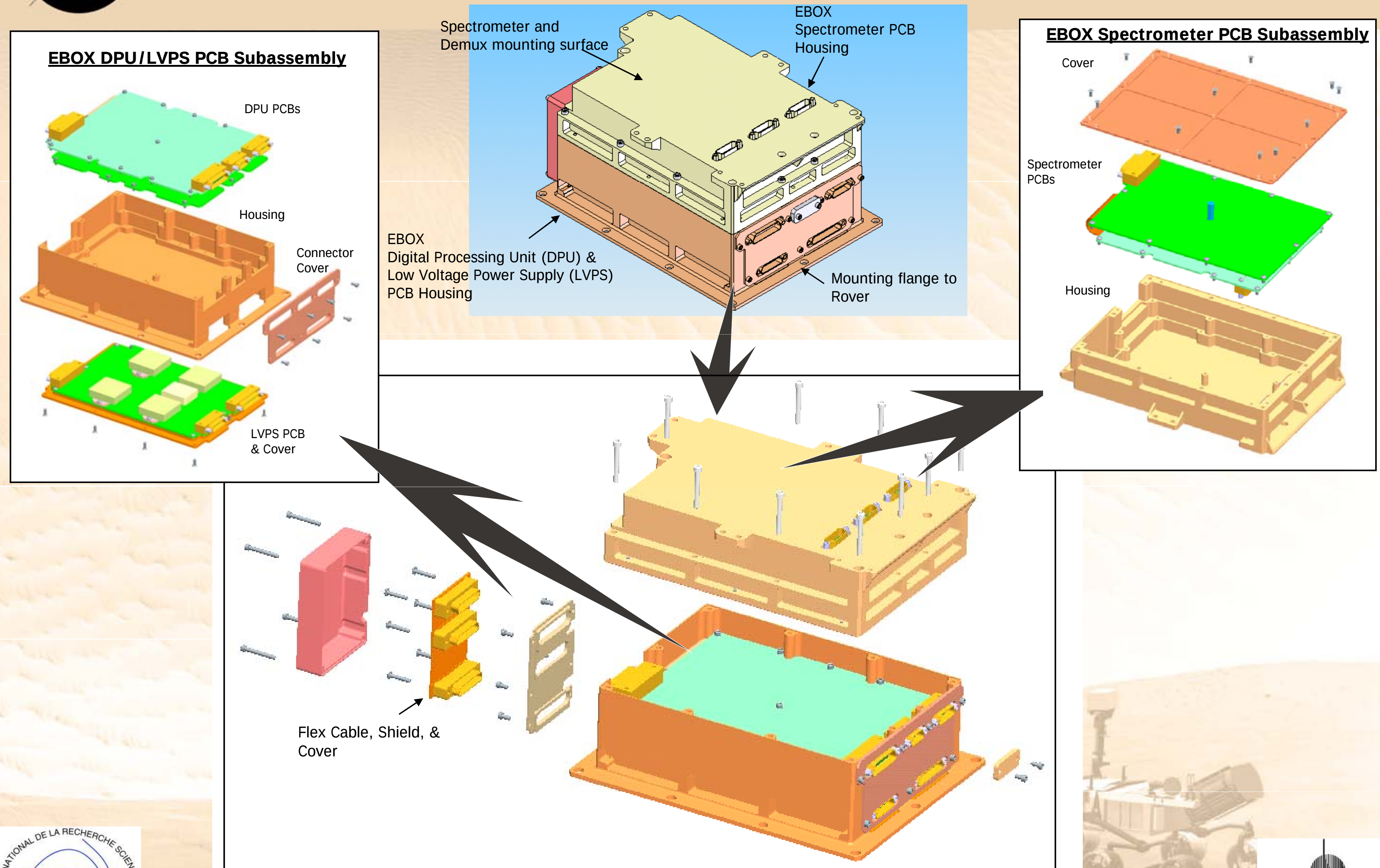
Body Unit Description







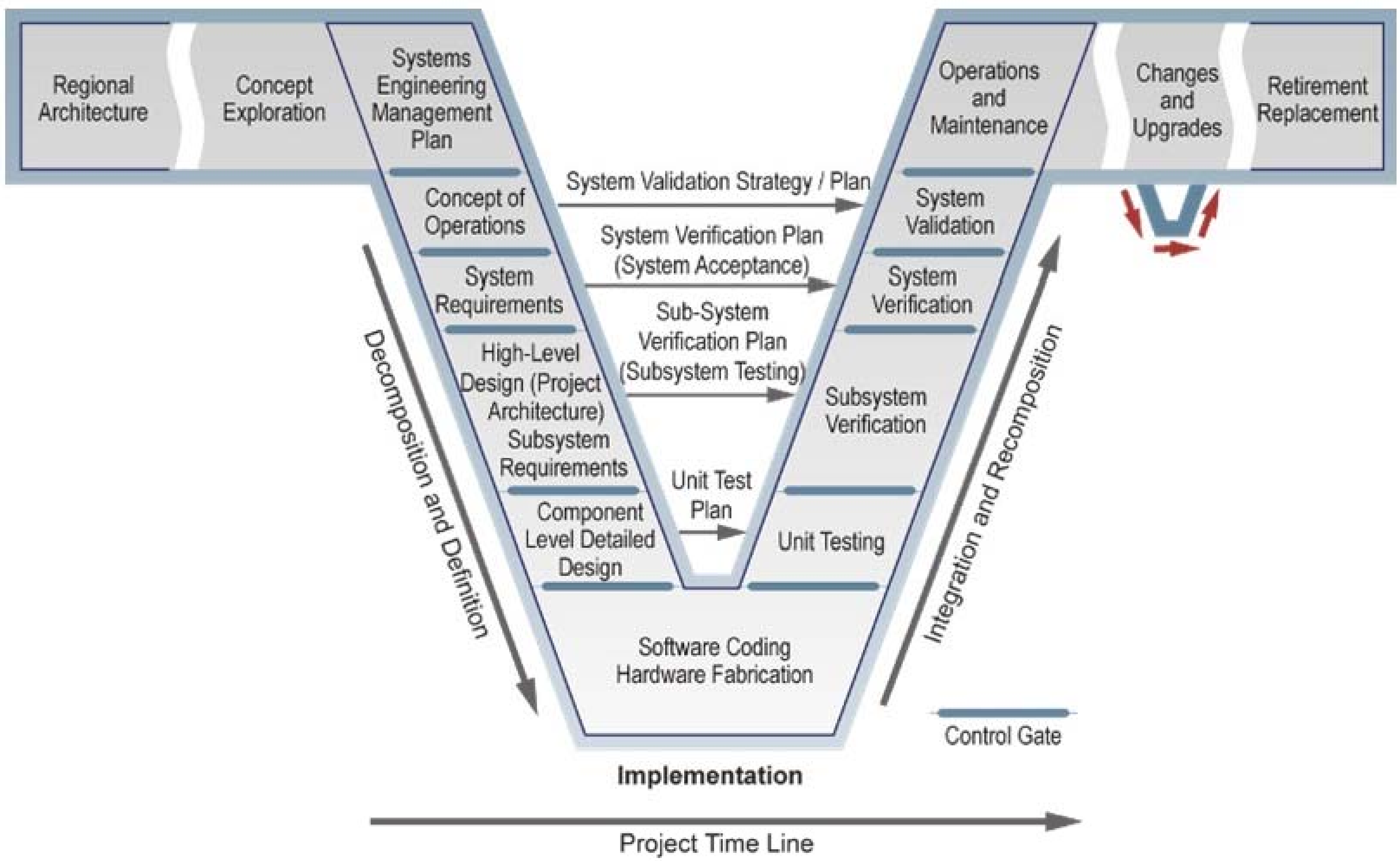
Body Unit Description



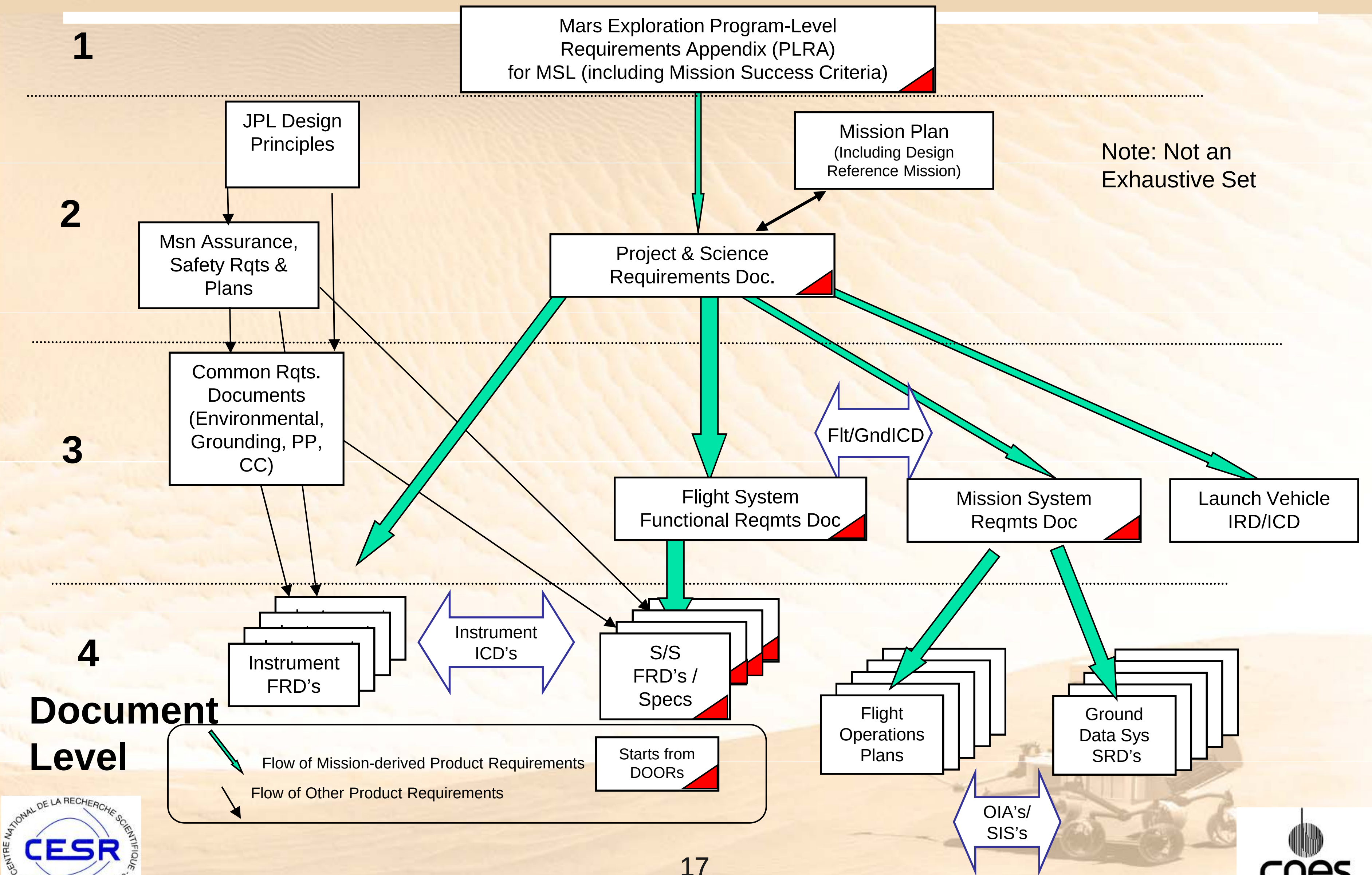
System Engineering ChemCam

NASA/JPL/Cornell

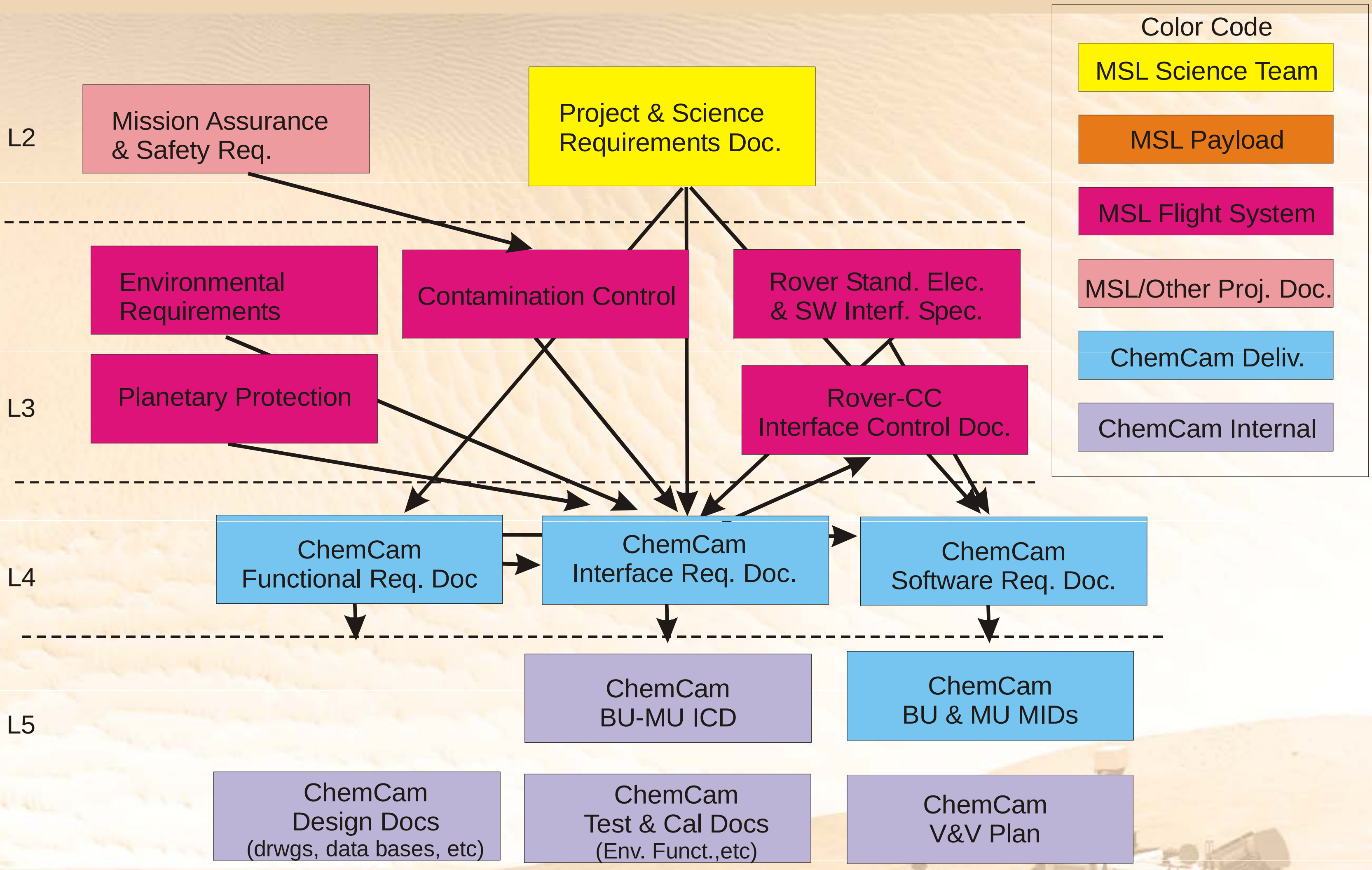
The Classic System "V" Approach



MSL Requirements Flow Down



ChemCam Requirements Flow Down



200+ requirements needing formal verification!

System Functional/Performance Model

			Observed from 5.4m Standoff Distance				
Element/Oxide	Wavelength (nm)	Spectrometer	Concentration (Mole wt%)	Accuracy	Precision	S/N Observed	Required S/N
SiO_2	288.2	UV	44.64	2.10%	0.77%	568.0	81.3
Al_2O_3	308.2	UV	13.50	8.16%	5.97%	28.5	28.5
	309.3	UV	13.50	3.57%	1.81%	52.0	<10.0
Fe_2O_{3tot}	404.5	VIS	6.21	7.49%	5.49%	14.4	<10.0
CaO	714.8	IR	7.12	4.80%	1.46%	27.3	<10.0
MgO	285.21	UV	8.46	11.33%	6.43%	357.0	357.0
TiO_2	**453**	**VIS**	**0.70**	**1.57%**	**10.42%**	**28.1**	**28.1**
Na_2O	589.6	IR	2.22	7.82%	10.21%	78.7	78.7
K_2O	**766.5**	**IR**	**0.20**	**9.01%**	**1.49%**	**64.1**	**64.1**
	769.9	IR	0.20	4.26%	1.32%	42.6	13.0
Minor Elements							
C	247.8	UV	0.525%	TBD	20.1%	23.9	23.9
Sr	407.7	VIS	252 ppm	9.26%	21.42%	12.1	12.1
	421.6	VIS	252 ppm	7.46%	19.90%	18.8	18.8
Li	670.8	IR	7.5 ppm	11.33%	1.06%	13.1	13.1

Green elements are at the accuracy requirement with the observed S/N

System Functional/Performance Model

Most Complicated System Engineering Task of ChemCam

S/N

Required S/N driven by mineral composition accuracy requirements

Signal

perfect alignment

Source (line strength)

1.Laser phot density

energy/pulse
coatings
MTF
distance

Material

concentration
transition

Atmos

pressure confinement
breakdown

Collection

dust

2.telescope

aperture
coatings
FO coupling

3.fiber

length
connectors

4.demux

coatings
alignment

5.spectrometer

Slit width
NA
coatings
grating

Environment

- Background
- Temperature
- Radiation Damage

Noise

thermally stable

Detector

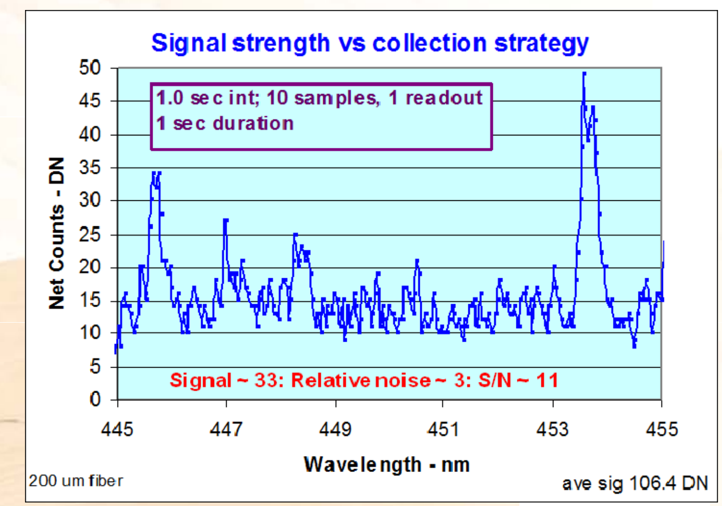
drk noise
read noise
cross talk
phot stats
relative cal error

Clutter

adjacency
offset

Ambient

imperfect subtraction



Photon Budget from S/N Model Drives Optical Design

					K - 769	K - 766
Source Line strength (photons/shot/mm^2/sr/line)					**2.12E+09**	**3.26E+09**
Target distance - mm					9000	9000
Telescope Semi-aperture - mm					55	55
	solid angle - sr				0.000117	0.000117
	trans to fiber interface				**0.4**	**0.25**
	NA match to fiber				0.12	0.12
	fiber core - mm				0.3	0.3
Fiber image area at plasma - mm^2					27.25654	27.25654
Plasma diameter (top hat) - mm					5	5
	(image must<=plasma diam or limit to 5 mm				19.63495	19.63495
					19.63495	19.63495
Det int time - sec					**3.333333**	**3.333333**
Laser rep rate - Hz					15	15
Shots per read					50	50
Photons delivered to tel fiber - phot/read/line					9.77E+07	9.39E+07
Demux trans					**0.58**	**0.58**
Fresnel		0.963		2	**0.927369**	**0.927369**
Fiber joints		0.966	NO.	0	**1**	**1**
fiber length - m		0.995	meter	5	**0.975249**	**0.975249**
Gain at fiber (demux output interface)						
	DN/phot				**7.94E-06**	**8.21E-06**
	gain improvements					
		cyl lens			1.8	1.8
		NA match	0.12	0.22	1	1
		slit size	14.3	14.3	1	1
	projected gain				**1.43E-05**	**1.48E-05**
Digital counts output - DNs/read					**406.8**	**404.3**
	with improvements				**732.2**	**727.7**
Read noise - RMS DN					3	3
NEP at gain FO - photons					**3.78E+05**	**3.65E+05**
					2.10E+05	**2.03E+05**
Loss due to dust/scattering			0.1		**0.9**	**0.9**
Loss due to alignment			0.288		**0.712**	**0.712**
~S/N					**86.9**	**86.4**
					156.4	**155.4**
Required S/N (LIBS LAB)					**13**	**64.1**
S/N Margin (assume throughput)					**6.68**	**1.35**
S/N Projected					**12.03**	**2.42**

Design Elements Impacted by System Model:

- Laser power output, pulses, rep rate
- Telescope Optics and Coatings
- Fiber optic cable material
- Complete development of Optical Bandpass Filter (demux)
- Body Unit FOC bundle
- Spectrometer slit design, Optic materials & coatings,
2-D CCD array
- Incorporation of CCD cryocooler & other thermal features
- Time of day for operation

System Engineering Challenges

- Extremely complex instrument and tough science requirements
- Short development time (~2 years from start to flight delivery) to conduct a qual level program
- Numerous mission and environmental requirements (science, mission assurance, planetary protection, environmental, Rover accommodation, etc)
- ChemCam made up of three teams (LANL & JPL in US, and CESR in France). Many different cultural aspects at all 3 institutions!

Mechanical Engineering
ChemCam

NASA/JPL/Cornell

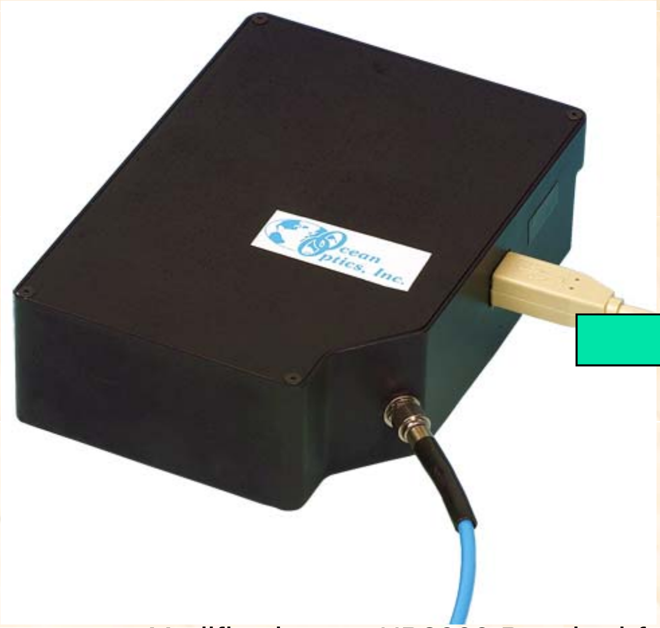
Many Unique Design Challenges

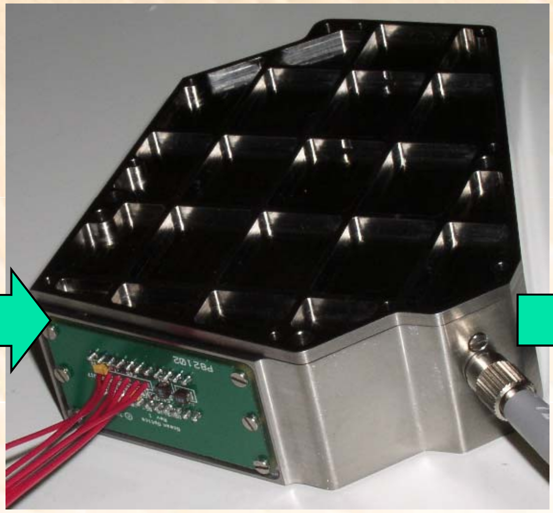
- Delicate high precision optics (position, alignment, stability)
- Sensitive electronics
- Lightweight materials (Be, Mg)
- Small Packaging Envelope
- Thermal dissipation, temperature & CTE control
- Mechanical strength & stability for vibration & shock
- Protection from EMI, dust, radiation

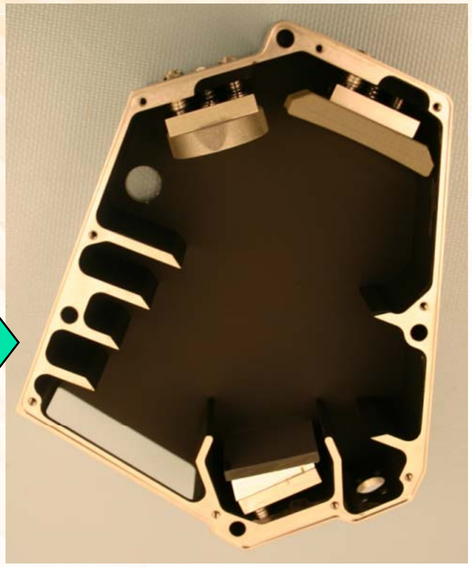
Mechanical Design Example

Spectrometer Evolution

Commercial Ocean Optics Aluminum HR2000 Spectrometer	ChemCam EDU Ti Spectrometer	ChemCam EM Ti Spectrometer (partial)



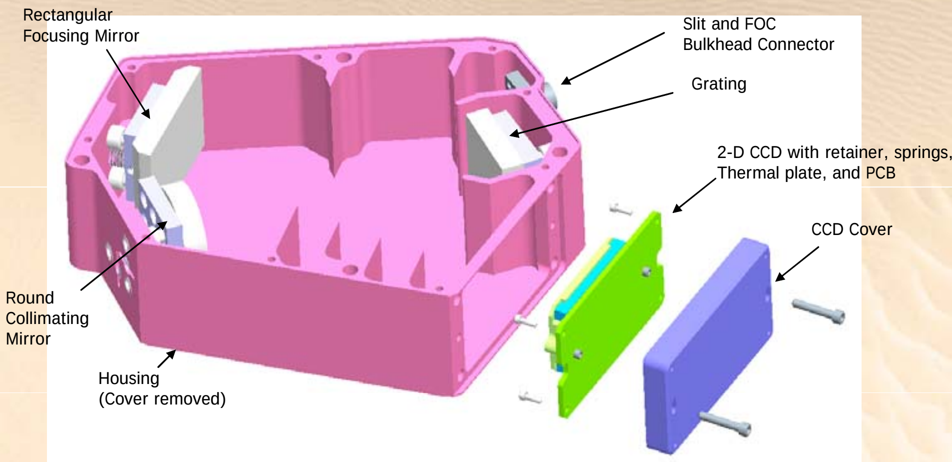




Modifications to HR2000 Required for MSL Flight Compatibility:

- Change housing material and geometry to reduce mass and minimize thermal expansion/contraction problems
- Change CCD for radiation survivability
- Change optics/mount materials for CTE compatibility
- Relocate spectrometer electronics to Ebox
- Reconfigure grating mount for stiffness and adjustability
- Change FOC mount for enhanced alignment and stability

Mechanical Design – Spectrometer Housing

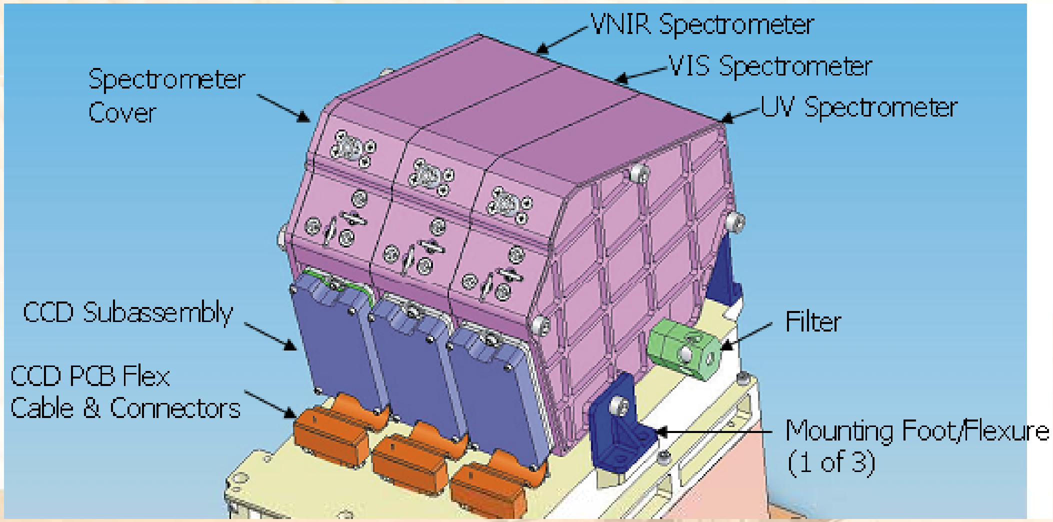


Individual Spectrometer Design Summary

- Be S200F housing: low mass, low CTE
- SFL57 Optics/Ti-6Al-4V mounts for CTE match
- Semi-kinematic mounts for mirrors and grating
- Thermal float mount for CCD with clocking adjustment
- Light baffles + Z306 black paint for scattered light suppression
- Outer Ni plating for low ε and Be containment
- Be-Cu slit, SS-FC bulkhead connector – CTE matched, ok on venting
- Hi tolerance machining for alignment reasons

Multiple Spectrometer Design Summary

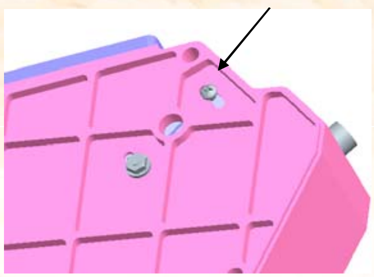
- Close
- Ti-6Al-4V bolts for cinching & CTE match
- 15 μm filter for venting, avoids icing and ΔP failure
- Three Al-6061-T6 mounting feet for CTE mismatch with Magnesium Ebox, good thermal conductivity
- Copper tape to seal screw holes and seams



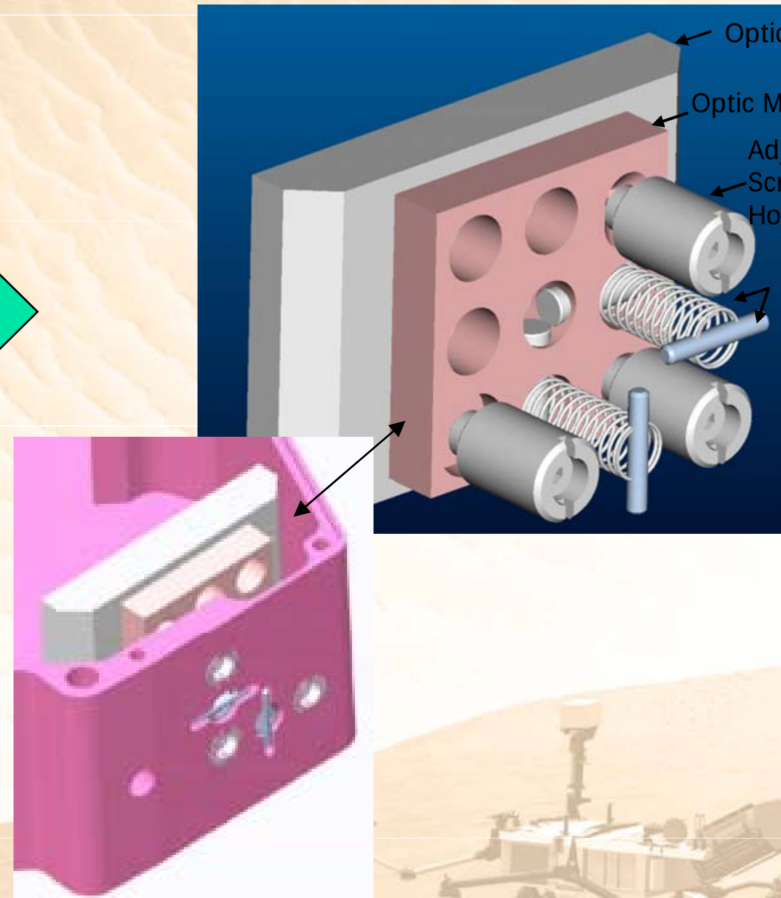
Mechanical Design – Grating Mount

Grating Mount changed to kinematic configuration for stiffness and alignment enhancement & stability

Original Grating Mount Configuration

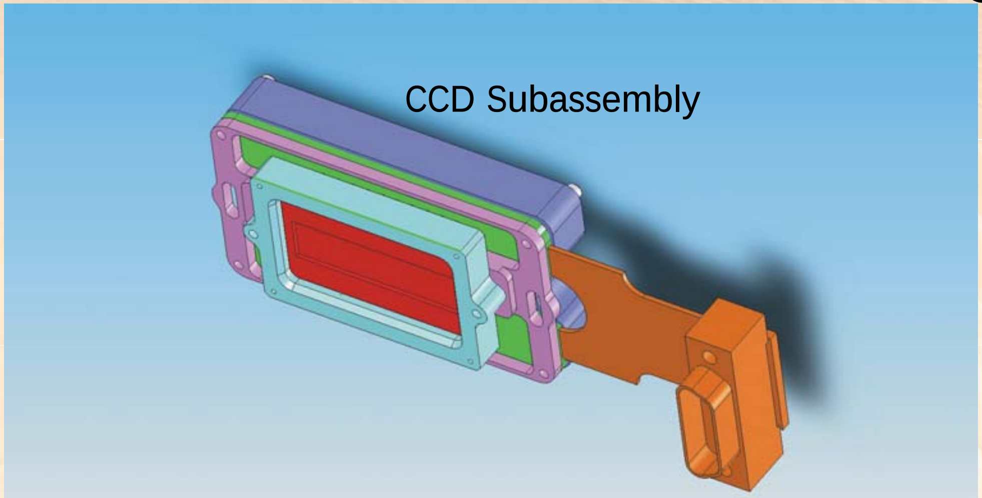


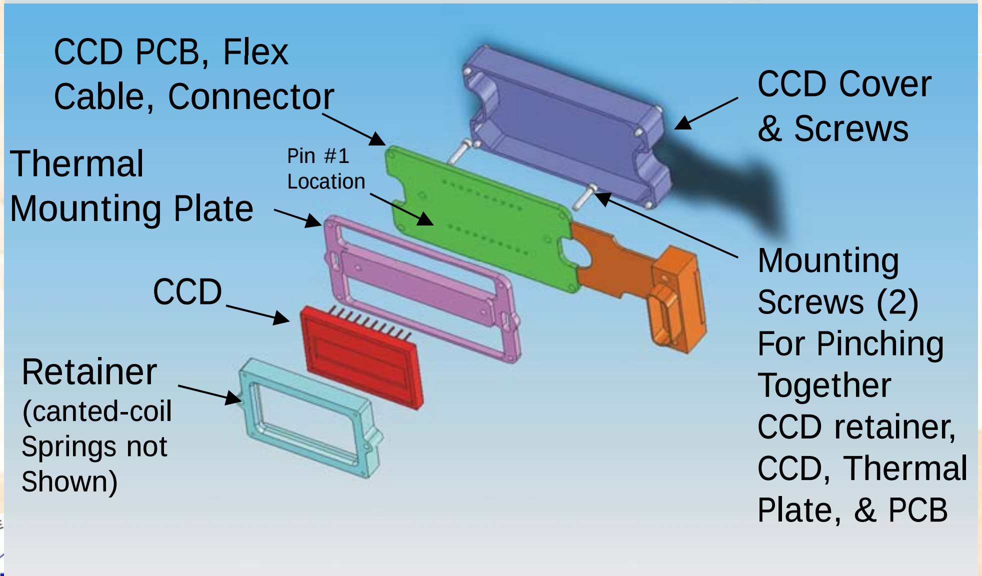
New Grating Mount Configuration



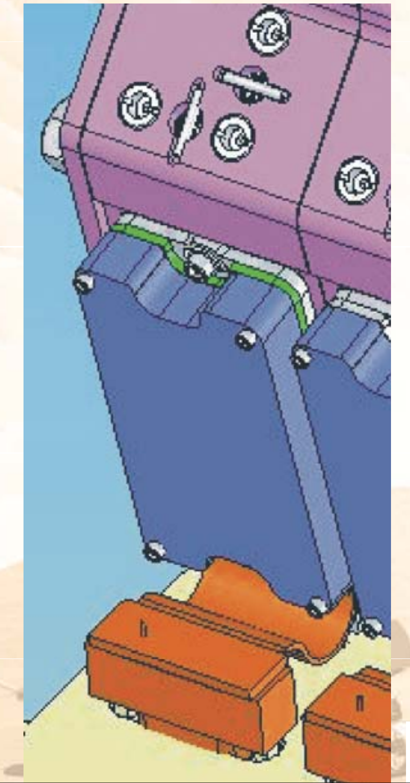
Mechanical Design - CCD

- 2-D CCD with new Mounting Hardware and PCB



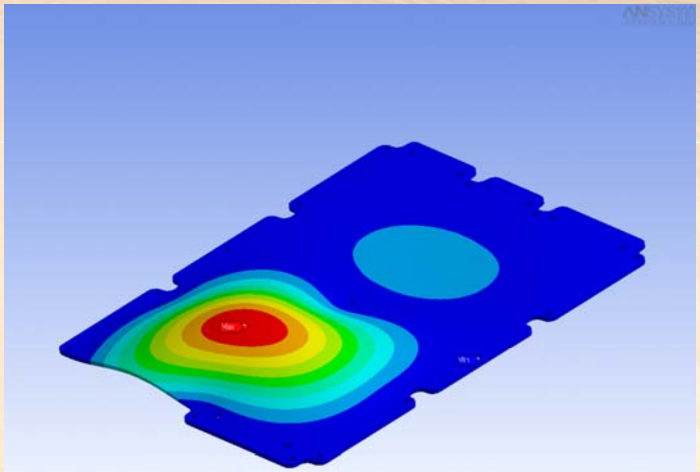


- CCD Subassembly on spectrometer and CCD PCB flex cable connected to Ebox spectrometer PCB
- Cover designed to allow +/-2.3 deg clocking rotation.

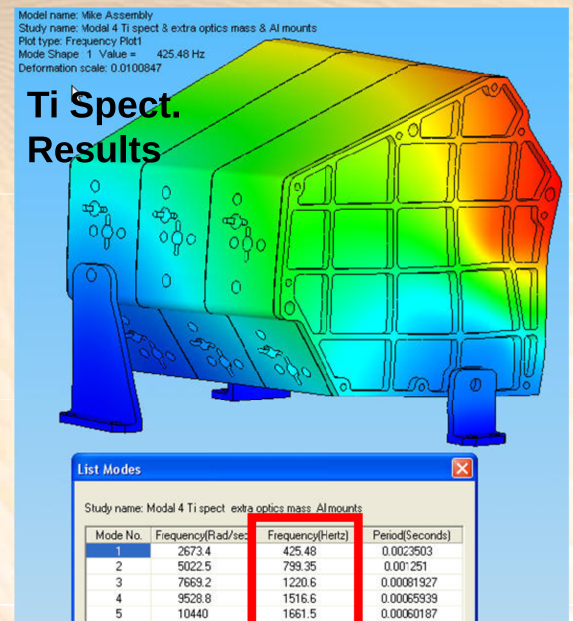


Modal Analyses

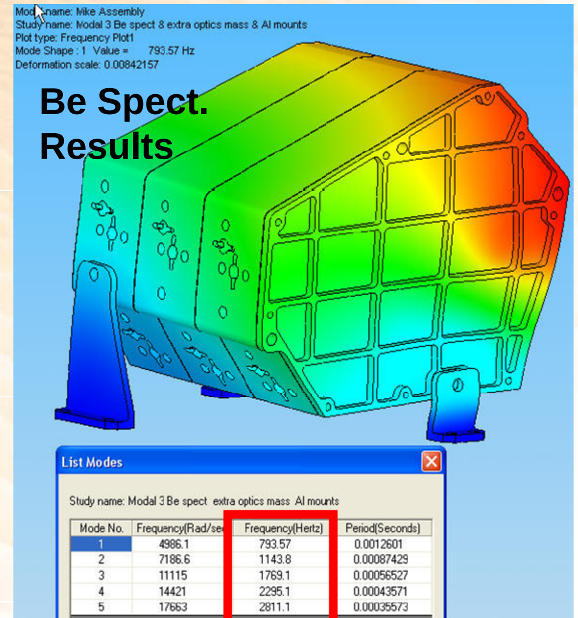
Los Alamos NATIONAL LABORATORY



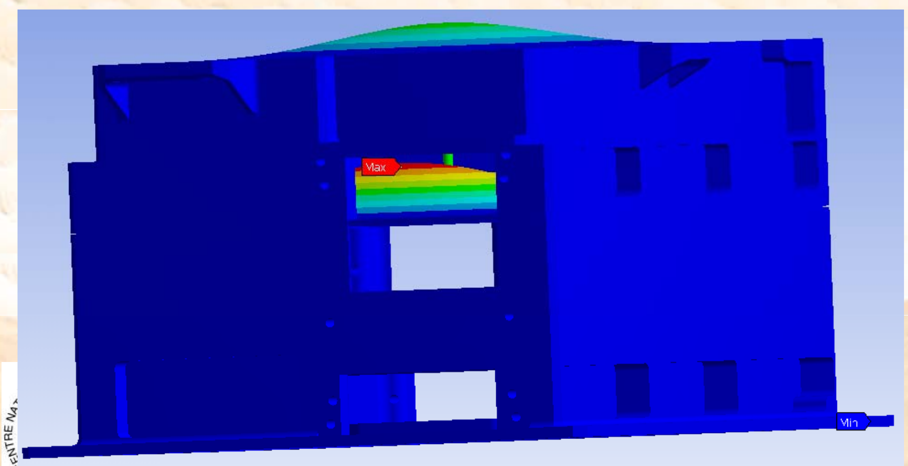
First mode: natural frequency of 555 Hz

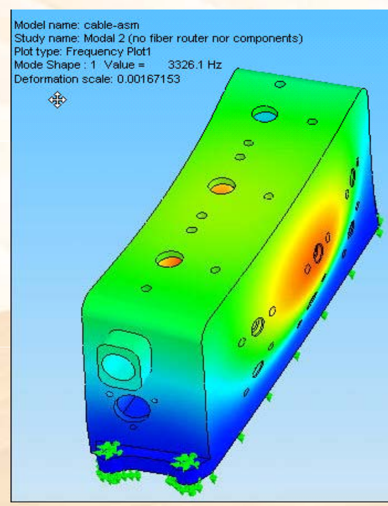


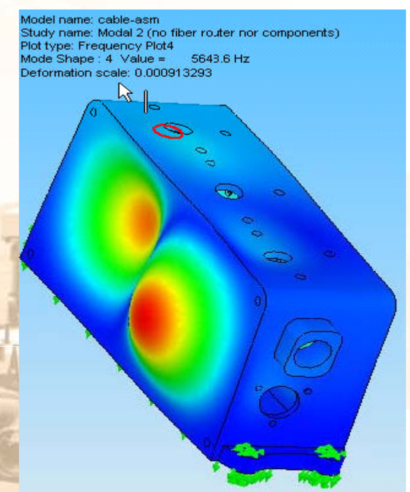
Mode No.	Frequency(Rad/se	Frequency(Hertz)	Period(Seconds)
1	2673.4	425.48	0.0023503
2	5022.5	799.35	0.001251
3	7669.2	1220.6	0.00081927
4	9528.8	1516.6	0.00065939
5	10440	1661.5	0.00060187



Mode No.	Frequency(Rad/se	Frequency(Hertz)	Period(Seconds)
1	4986.1	793.57	0.0012601
2	7186.6	1143.8	0.00087429
3	11115	1769.1	0.00056527
4	14421	2295.1	0.00043571
5	17663	2811.1	0.00035573







First mode: natural frequency of 802 Hz

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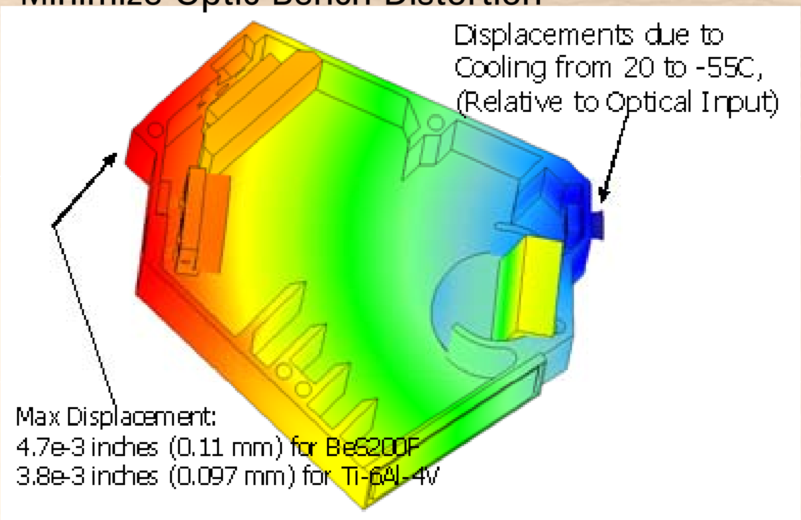
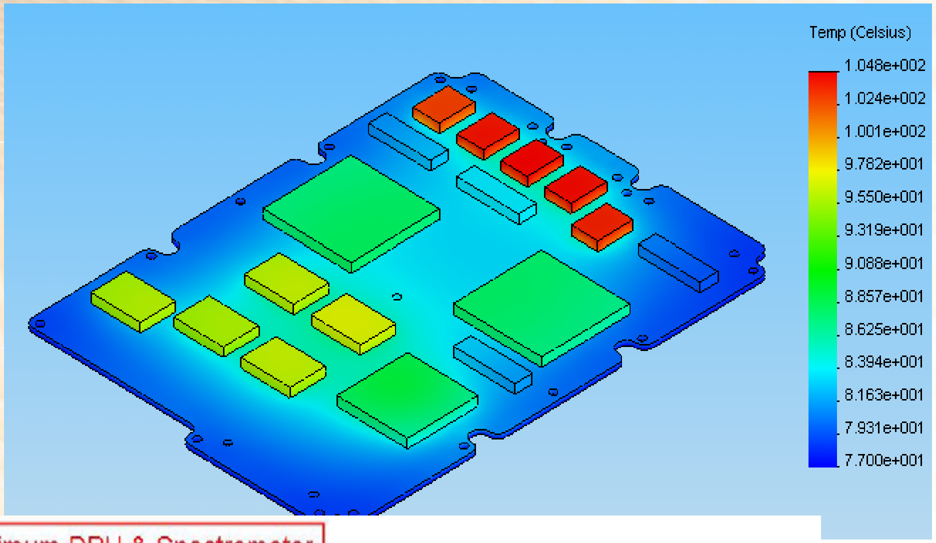
Thermal Analyses

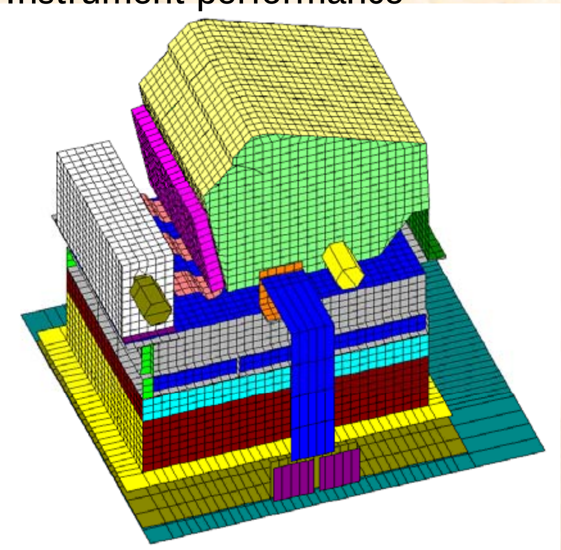
Minimize Optic Bench Distortion

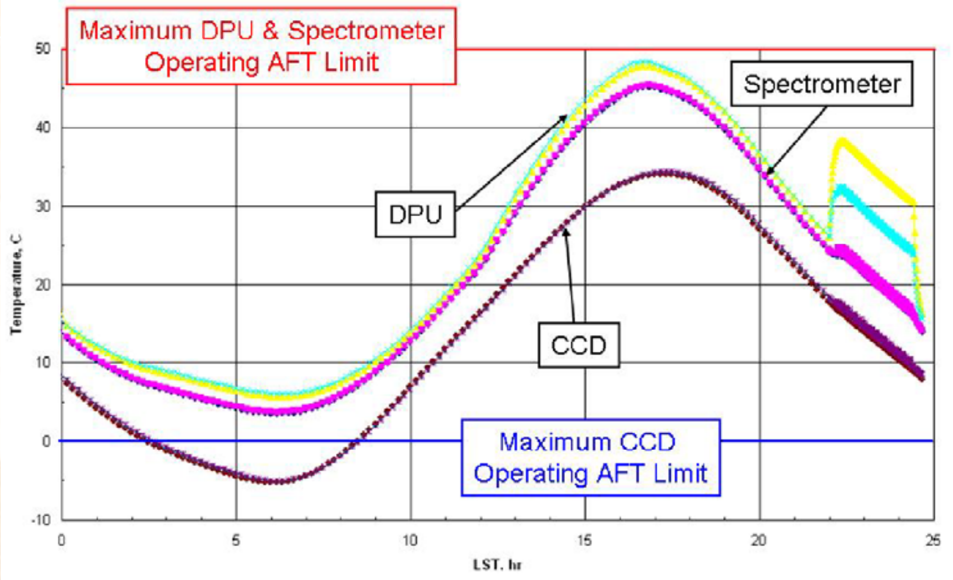


Cool electronics below de-rated temperature limit



Optimize thermal control system for Instrument performance

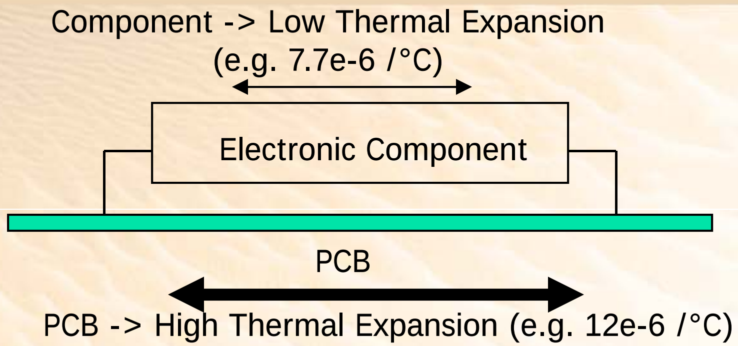


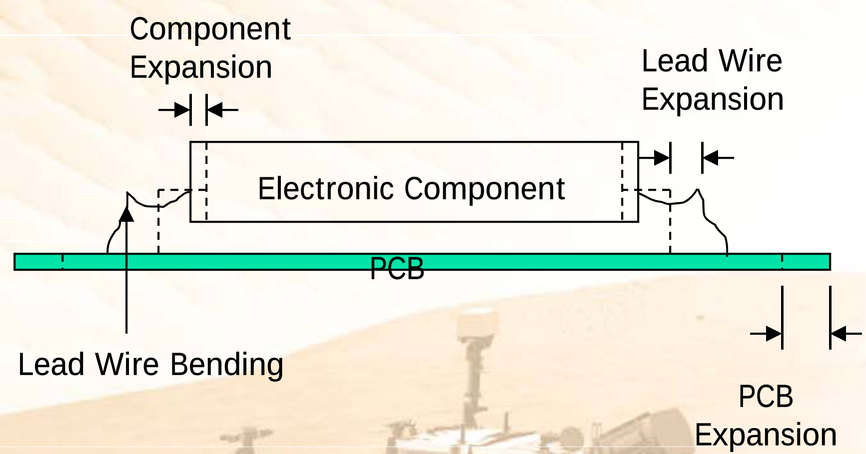


- *Assumptions:*
  - *PCB Fixed at center*
  - *1-D Analysis*
- Thermal expansion difference:

$$\Delta l = \left(\alpha_{PCB} - \alpha_{Component} \right) d \Delta T$$

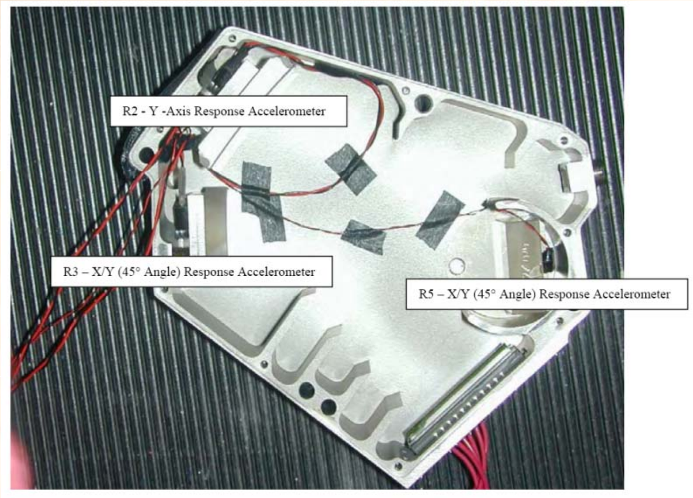
where d is the diagonal length of the component

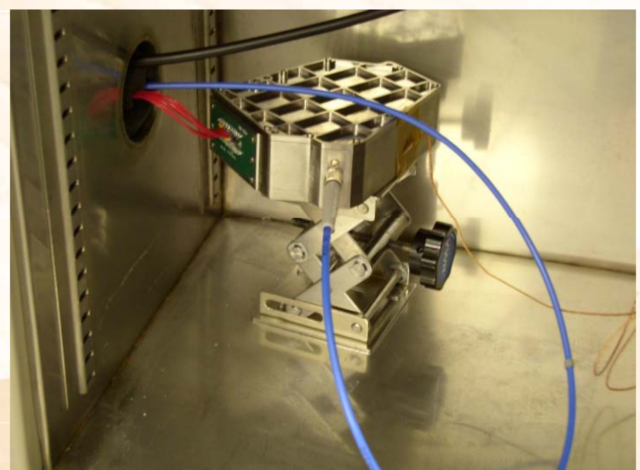




EDU Test Results

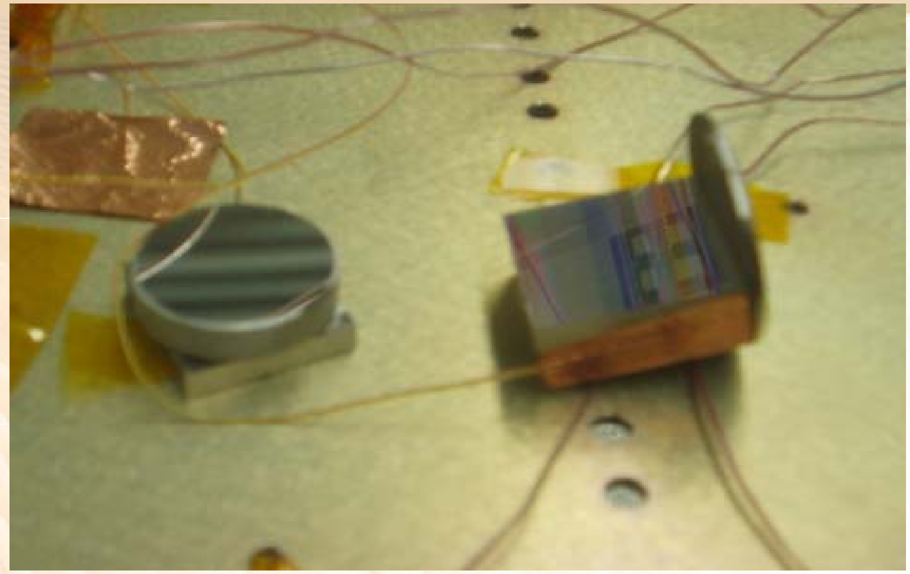
- Titanium EDU Spectrometer with SFL Optics on Ti Mounts and old Sony 1-D CCD put through Qualification Vibration and Thermal-atmosphere tests
- Test results lead to
  - Redesign of grating mount
  - Choice of material for optics and their mounts
  - Flatness specification of Spectrometer housing

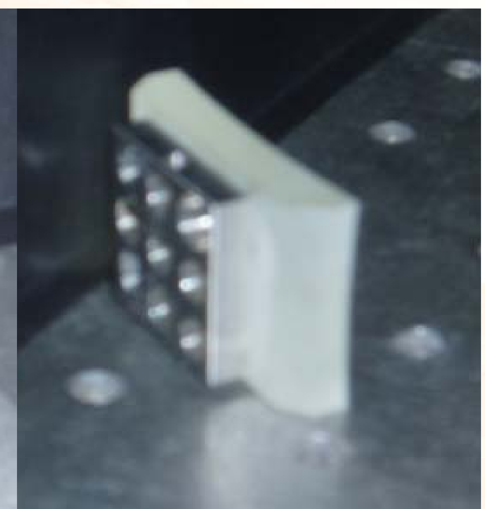




PQV Testing - Optics

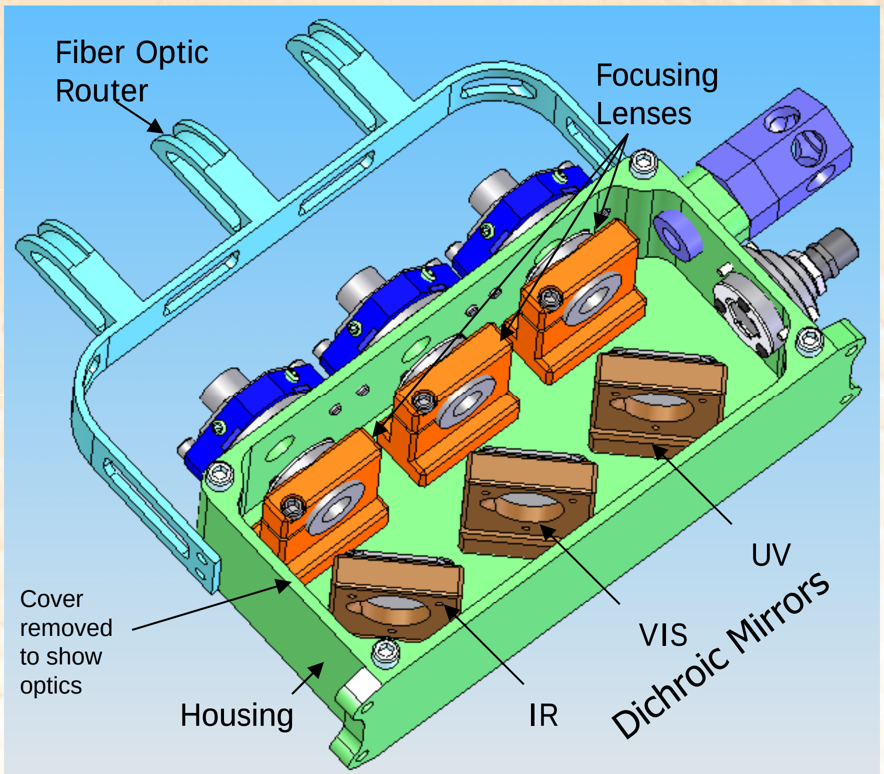
- Spectrometer Optics
  - 900 LPM Zerodor grating on a Ti-6Al-4V mount
  - Round and Rectangular SFL57 mirrors on Ti-6Al-4V mounts
  - All mounted with Dymax 602 Rev A series bonding adhesive (no activator used)
- No damage nor releasing of the epoxy noticed throughout the 2000 cycles

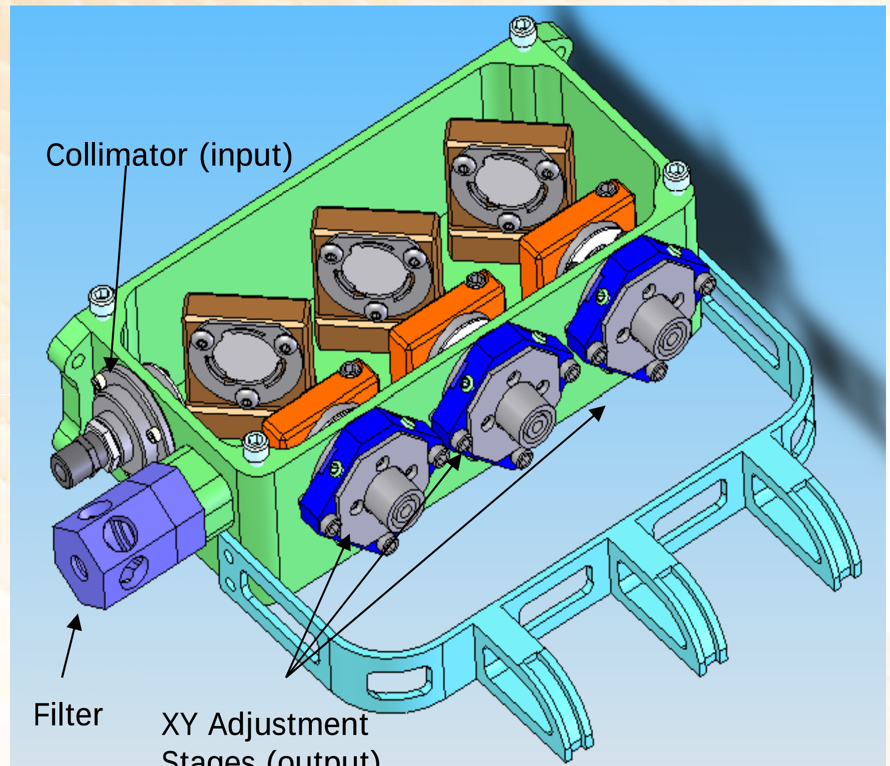




Demux Design

Demux Overview

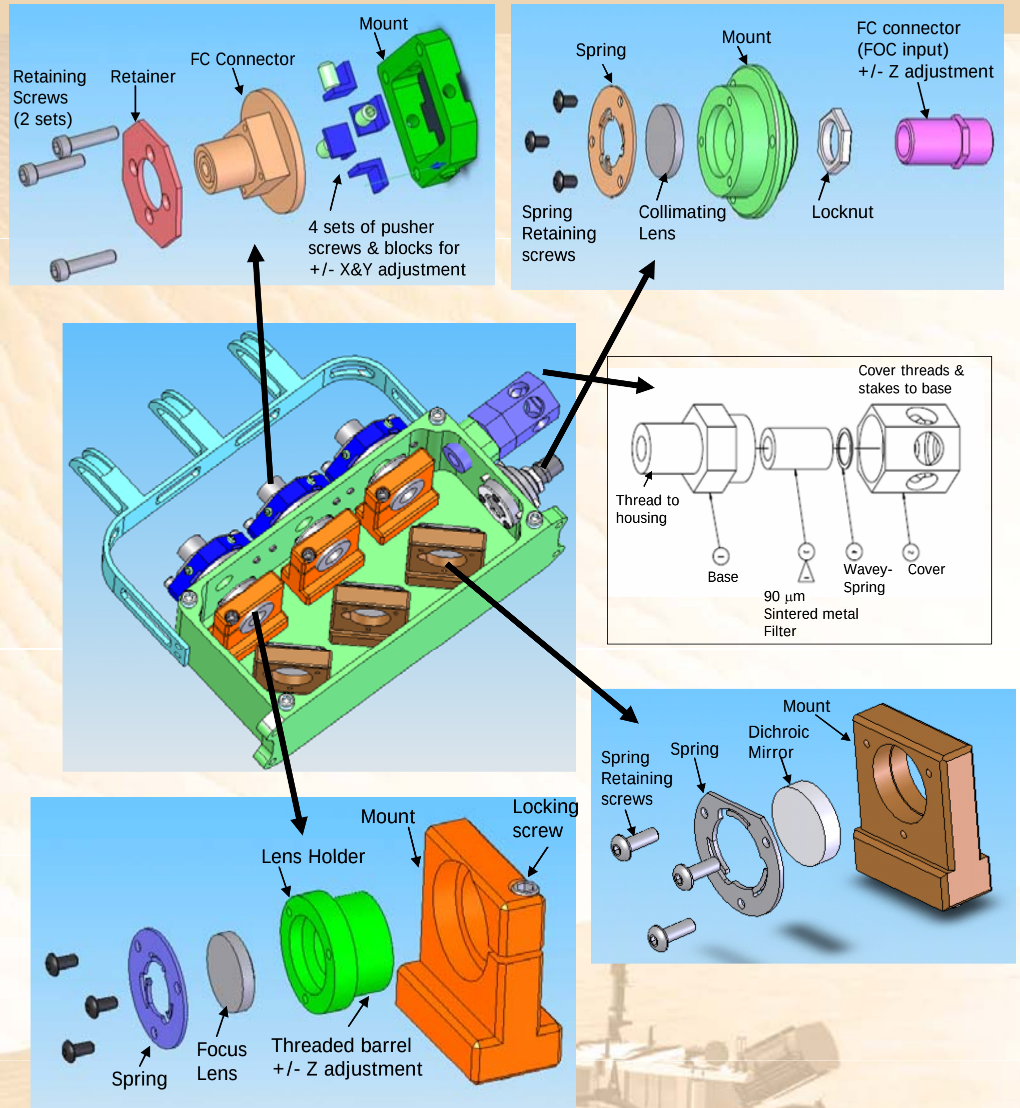




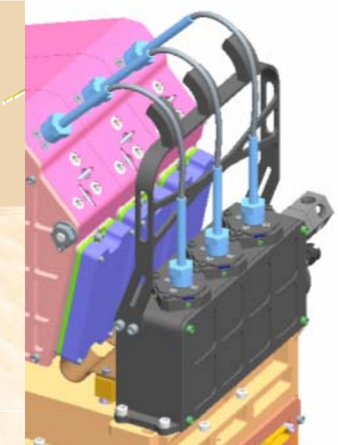
Optical/Mechanical Design

Optic mounting:

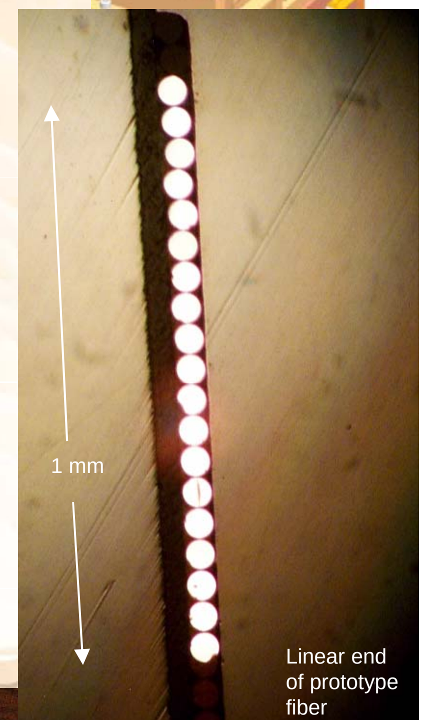
- Adjustability limited for mass, envelope, and vibe slip reasons. Adjustments in Z of lenses and XY for FOC output connector
- High precision machining on flatness & positioning
- Spring mounts designed for CTE mismatch & vibration levels



Fiber Bundle Design



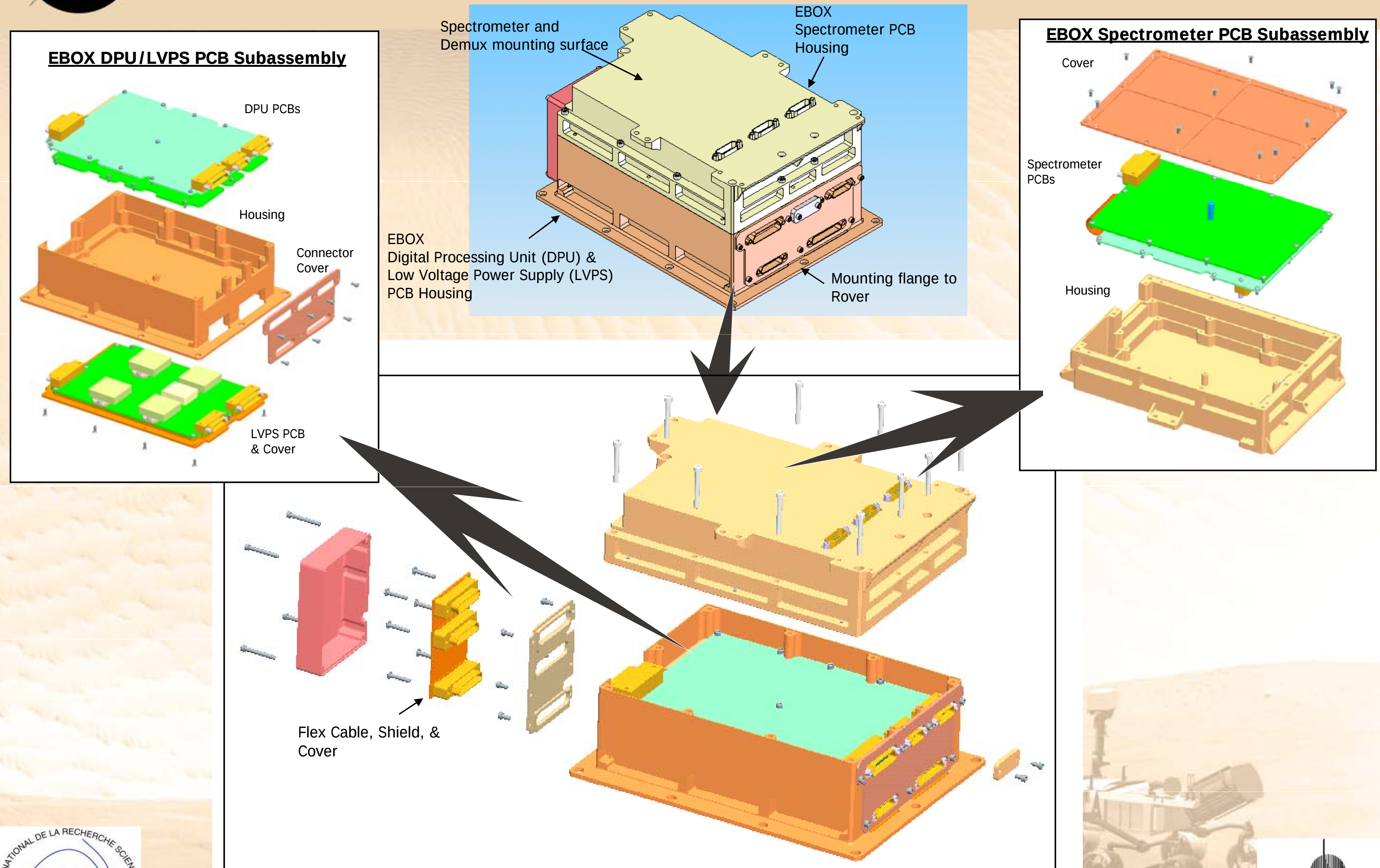
- Fiber needed to transport LIBS plasma light from demux to spectrographs
- Fiber Optic Cable Vendor: CeramOptec
- History:
  - New CCD opened the possibility of using fiber bundle to increase throughput into spectrometer (round bundle on demux end, linear array on spectrometer slit end)
  - Discussed and ordered prototype in Aug. ’06
  - Received and optically tested Oct. ’06
  - Thermally cycled Nov. ’06 to Jan. ’07
  - SOW negotiated Nov. to Feb., visited CeramOptec in Feb.
    - Inputs from C. Hays & M. Ott
    - Includes vacuum bake, pull tests, inspections
- Design Features:
  - FC-FC 19-fibers, 50-55-66 µm core+cladding+buffer
  - Matching of key to linear feature on spectrometer end
  - PTFE jackets



Linear end of prototype fiber

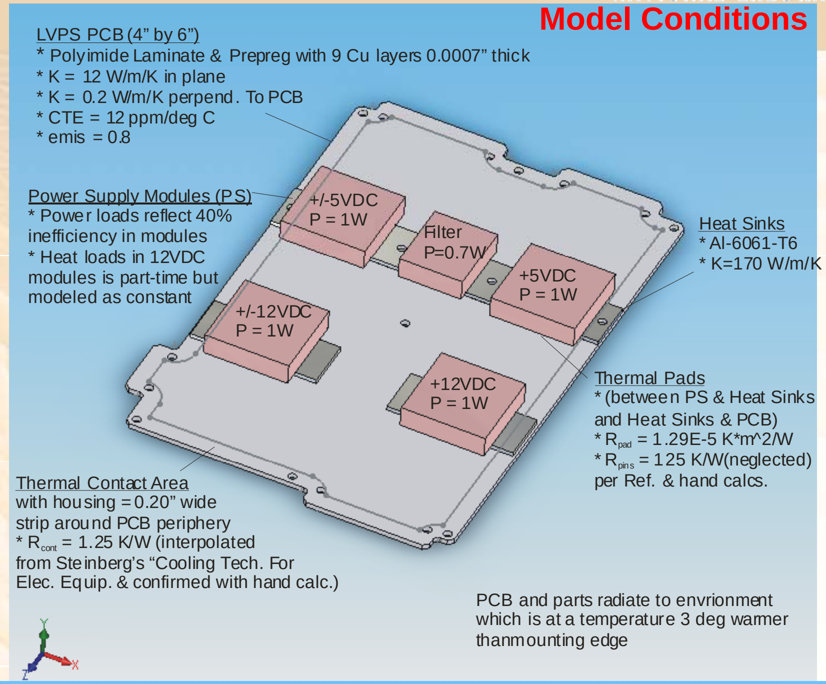
Sample

Ebox Description



LVPS PCB Thermal Analyses

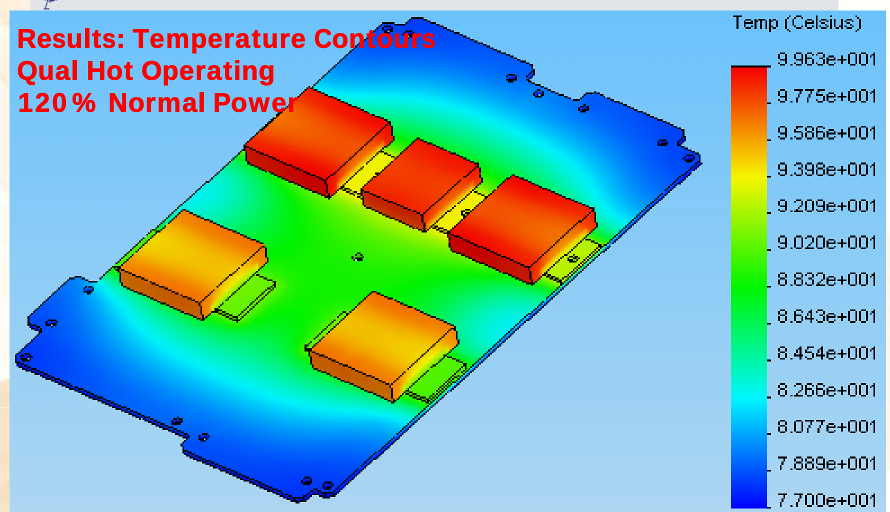
- Materials:
  - Polyimide PCB
  - Ceramic Power Supplies
  - Al-6061-T6 heat sinks
  - Micro-Faze A thermal pads
- Thermal Conditions
  - Steady-state analysis
  - Total power (nominal for all BU functions) = 4.7 W
  - Max power = 5.6 W (120% for uncertainty)
  - Thermal contact resistance modeled for PCB to housing and thermal pad mounts
  - PCB edge temperature determined from Ebox temperature (Ebox thermal model) and PCB thermal contact resistance
  - Thermal path of pins neglected
  - Qual. Operating, Hot & Cold temperature conditions
  - AFT Operating Hot & Cold temperature conditions



120% Nominal Power Results (no limits exceeded)

LVPS Board Thermal Results
Polyimide board with copper layers

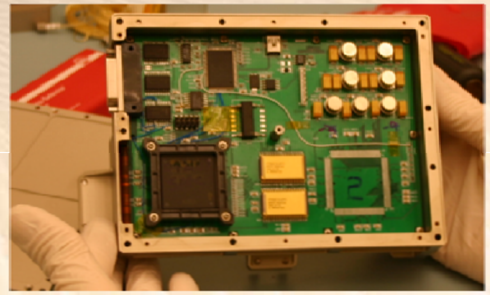
Temp of EBOX mounting	70C		50				
Temp of board at mount	77C		57				
Condition Modeled	Qual Hot Operating		AFT Hot Operating				
Component ID	Temp top of case (deg C)	Temp of Junction (deg C)	Temp top of case (deg C)	Temp of Junction (deg C)	Nominal recom-mended Op Case Temp Range (deg C)	Max Rated Op Junction Temp (deg C)	JPL derated Op Allowable max Junction temp (deg C)
+/-12VDC converter	96.9	99.3	77.5	79.9	-55 to 125'	135	110
-12VDC converter	96.9	99.3	77.5	79.9	-55 to 125'	135	110
Filter	99.1	NA	79.7	NA	-55 to 120'	130	105
+/-5VDC converter	99.6	102.0	80.3	82.7	-55 to 125'	135	110
+5VDC converter	99.6	102.0	80.3	82.7	-55 to 125'	135	110



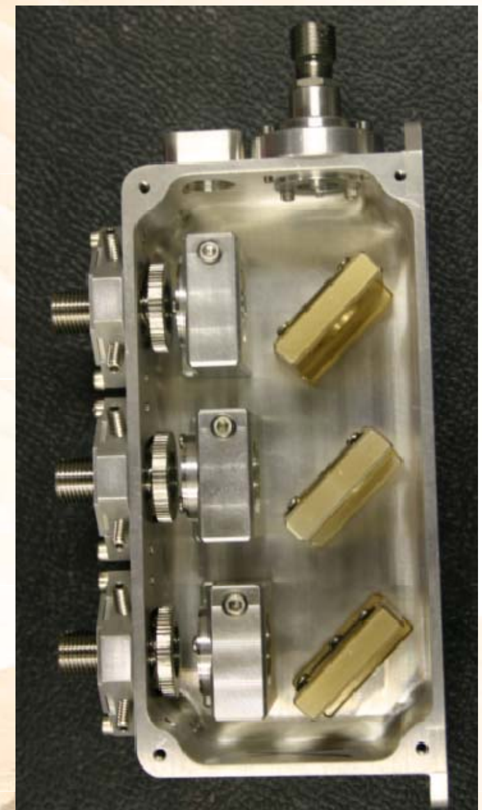
Procurements / Manufacturing / Assembly

Machining, Plating & Painting Be & Mg

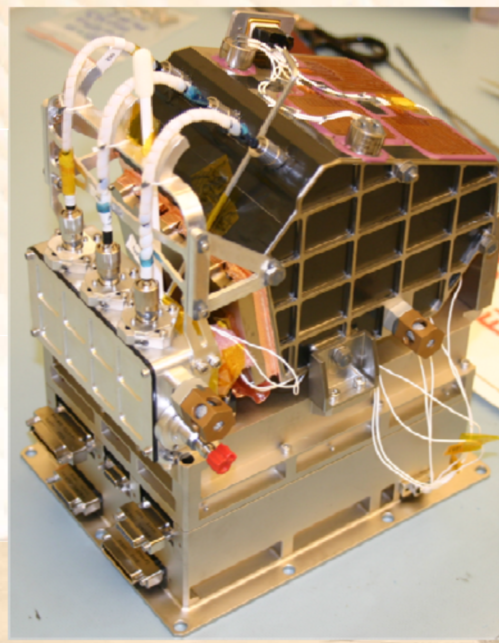
Electronics Integration



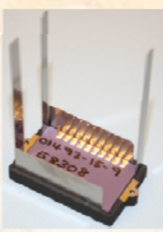
Demux Assembly & Alignment

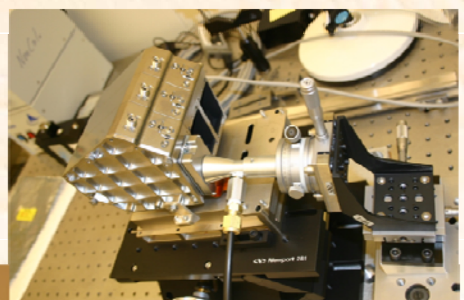


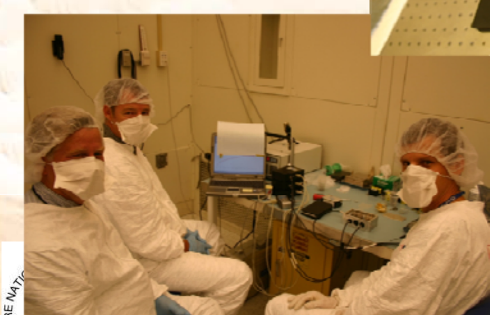
CCBU FM#1 Assembly

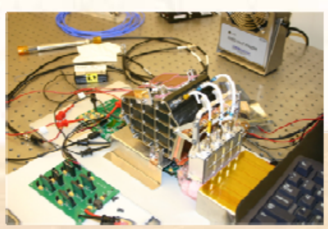


Custom Alignment & Test Tools

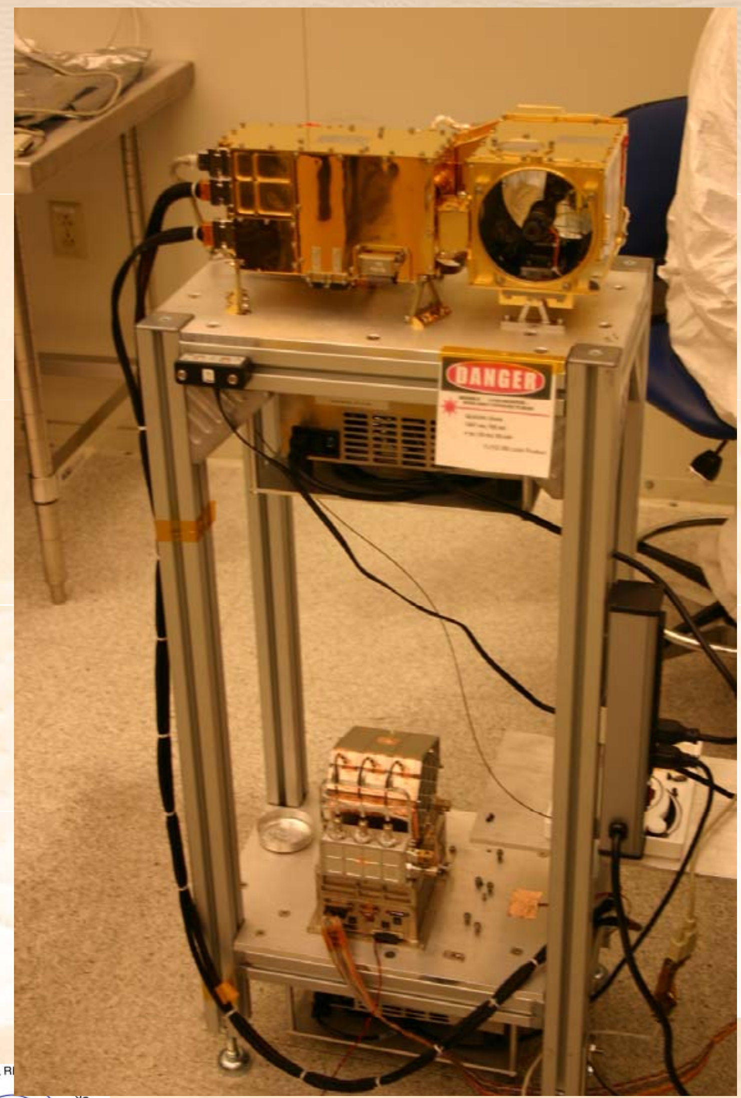


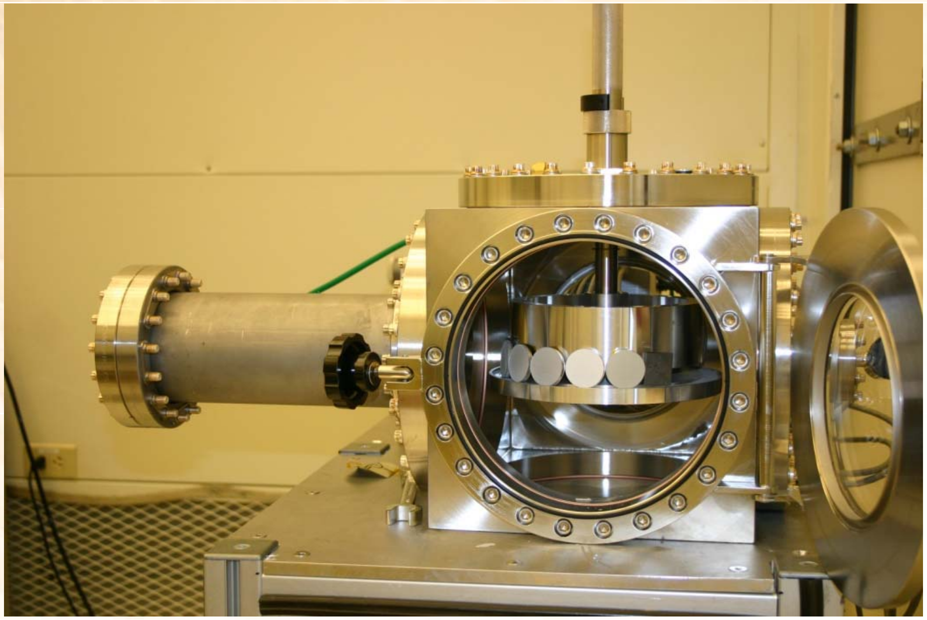






Functional Testing

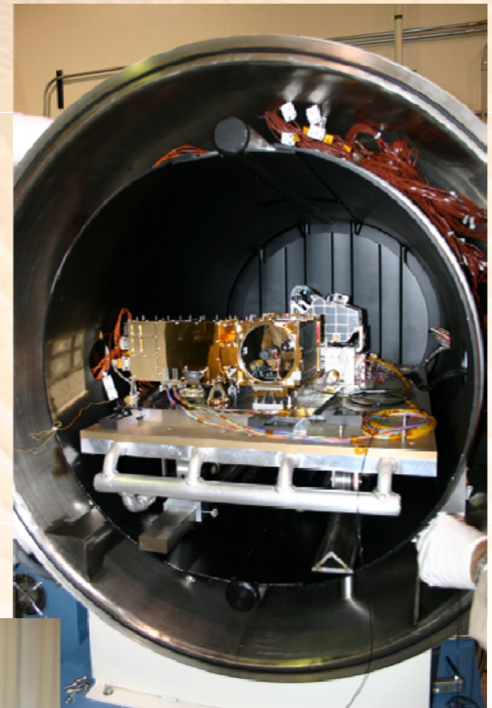




Environmental Testing

Random Vibration

Thermal-Vacuum

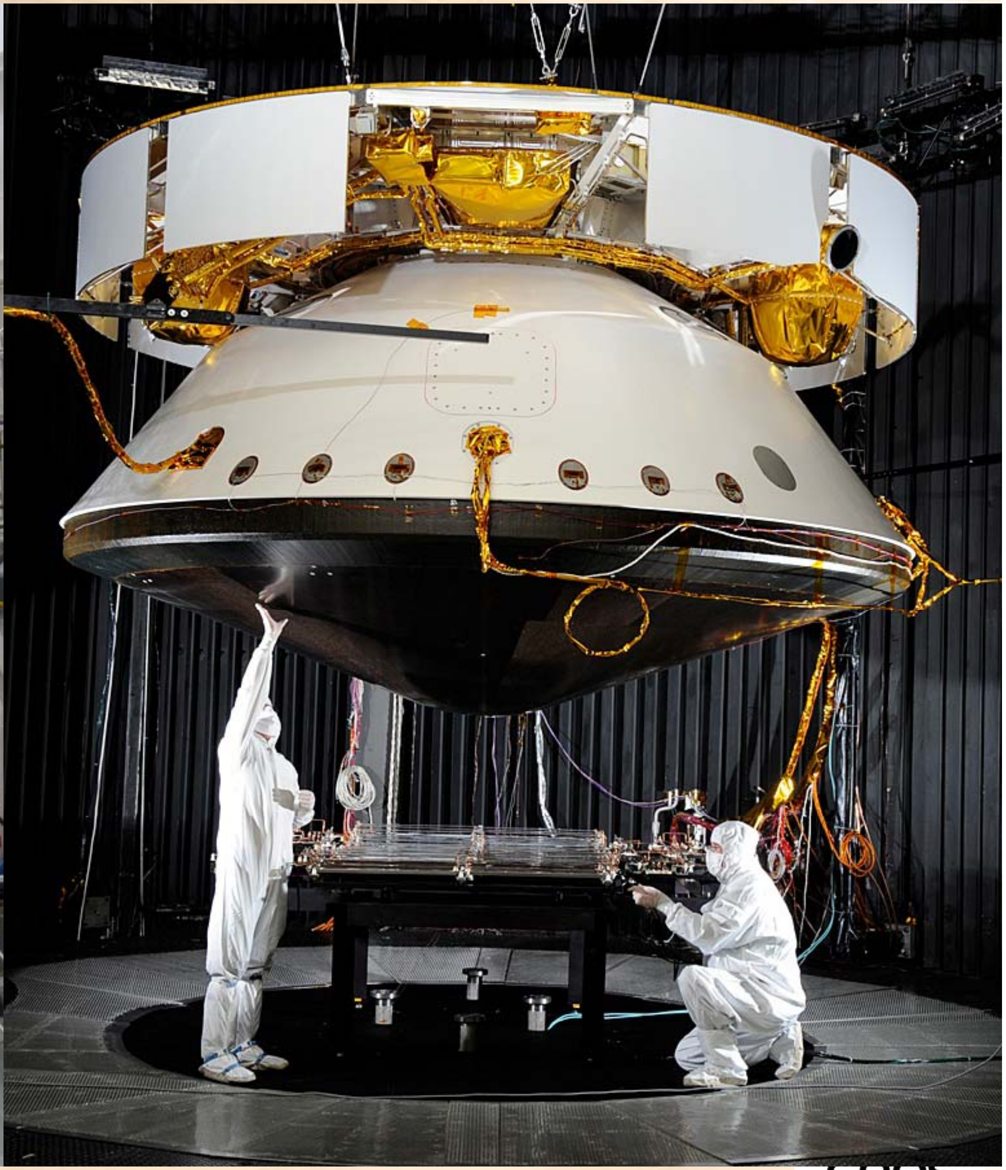


Mechanical Shock

Launch & the Future Mission

NASA/JPL/Cornell

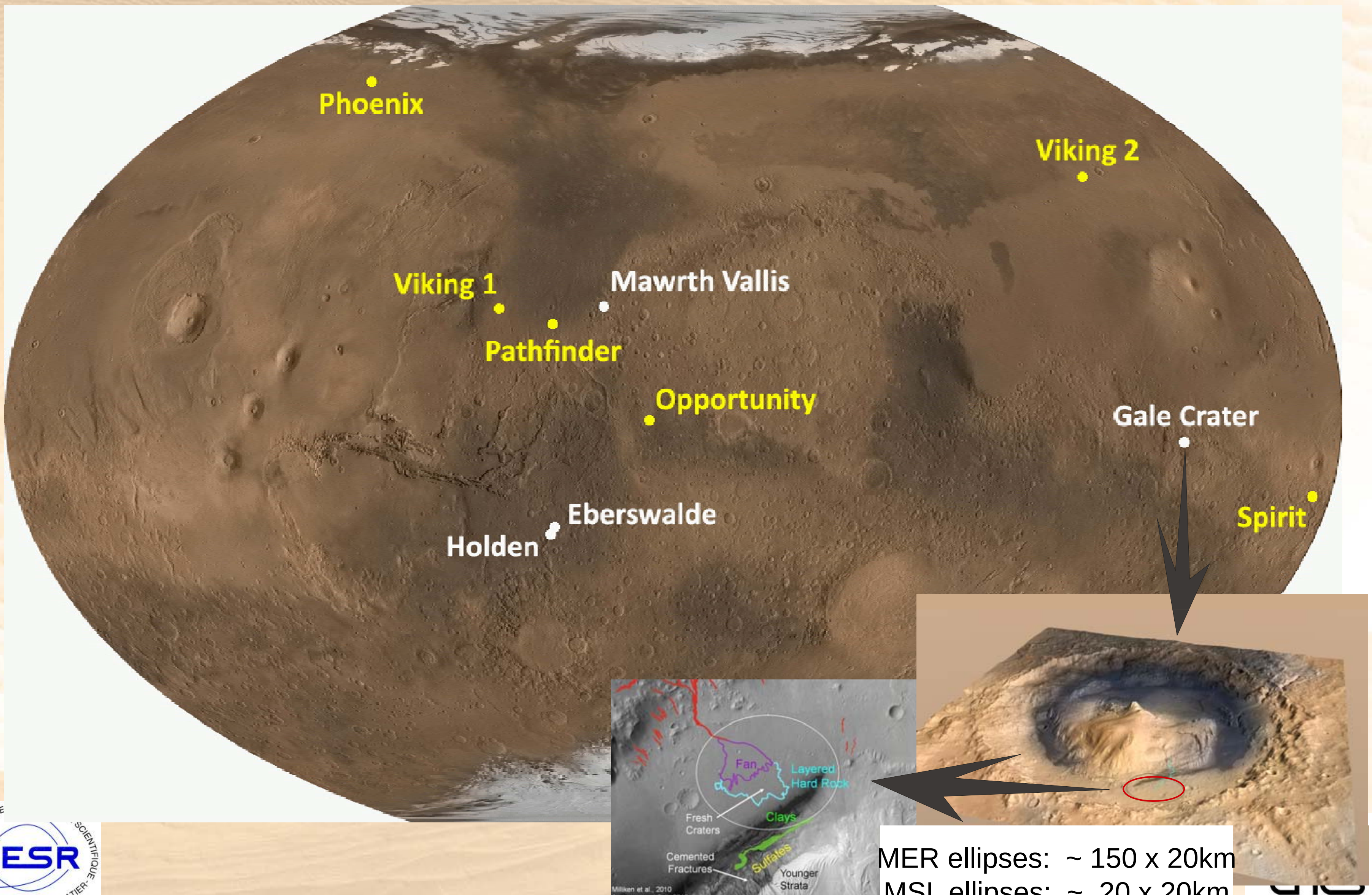
Assembled Spacecraft



LAUNCH!!!

Mars Landing Sites

(Previous Missions and MSL Final Candidates)

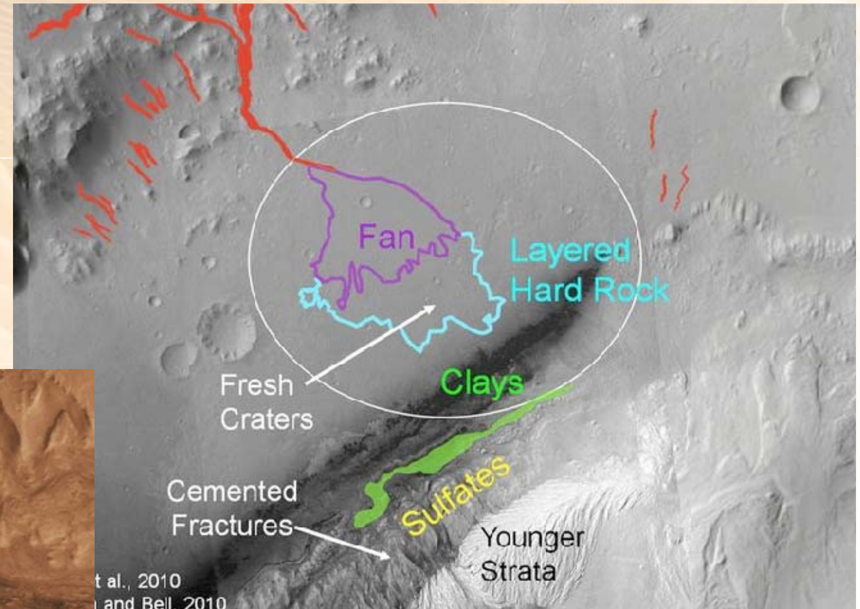


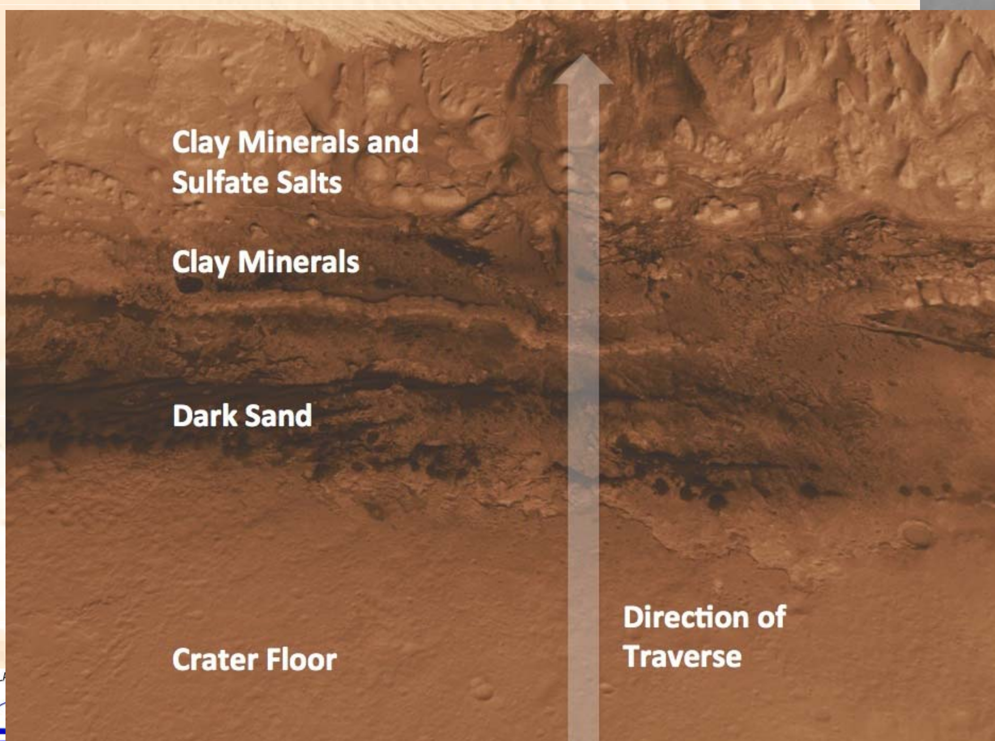
MER ellipses: ~ 150 x 20km
MSL ellipses: ~ 20 x 20km

Gale Crater

The landing ellipse allows access to a fan at the base of a fluvial channel that begins on the crater wall.

Other science targets include fresh craters that expose bedrock, and small channel features.

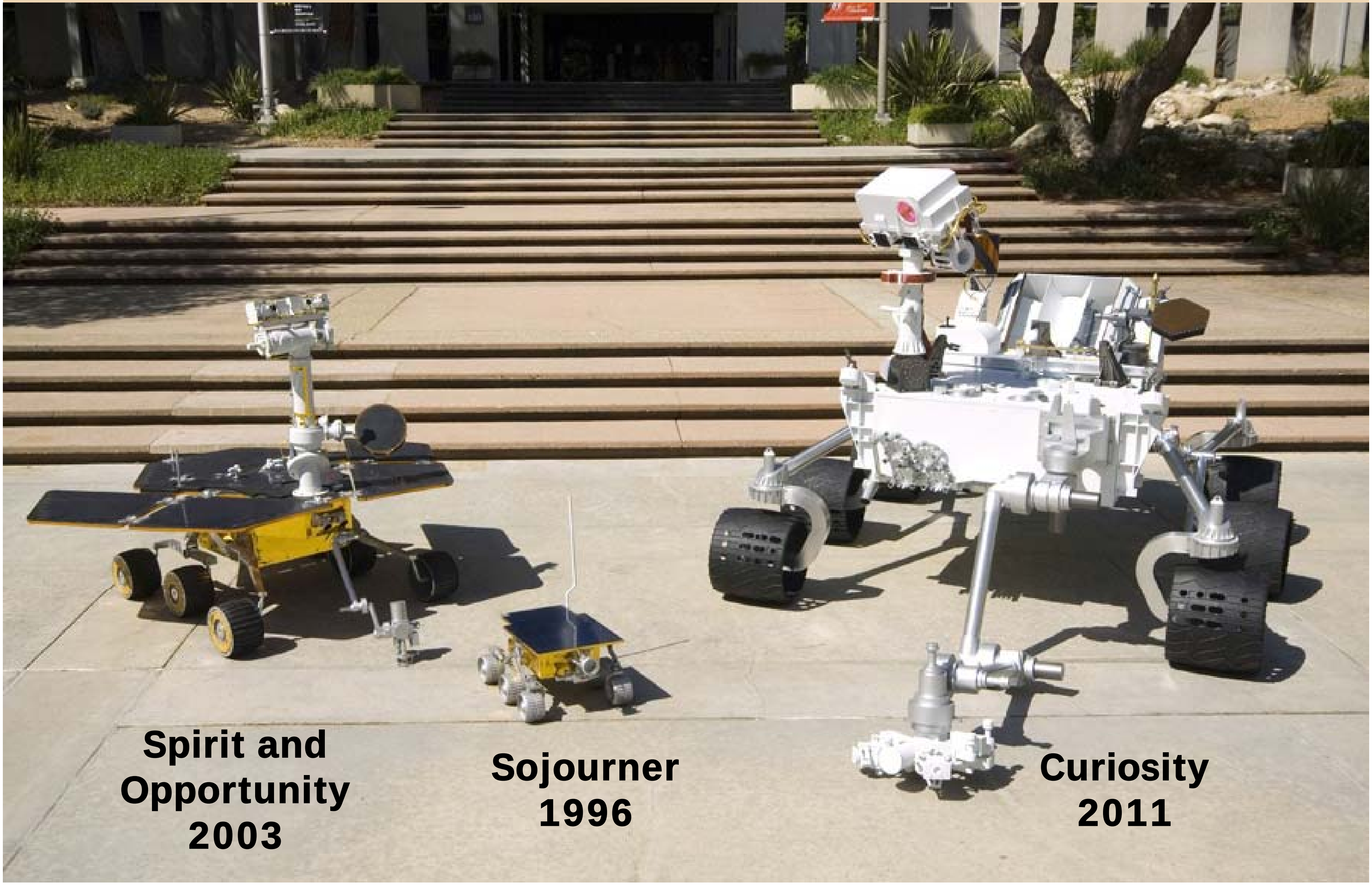




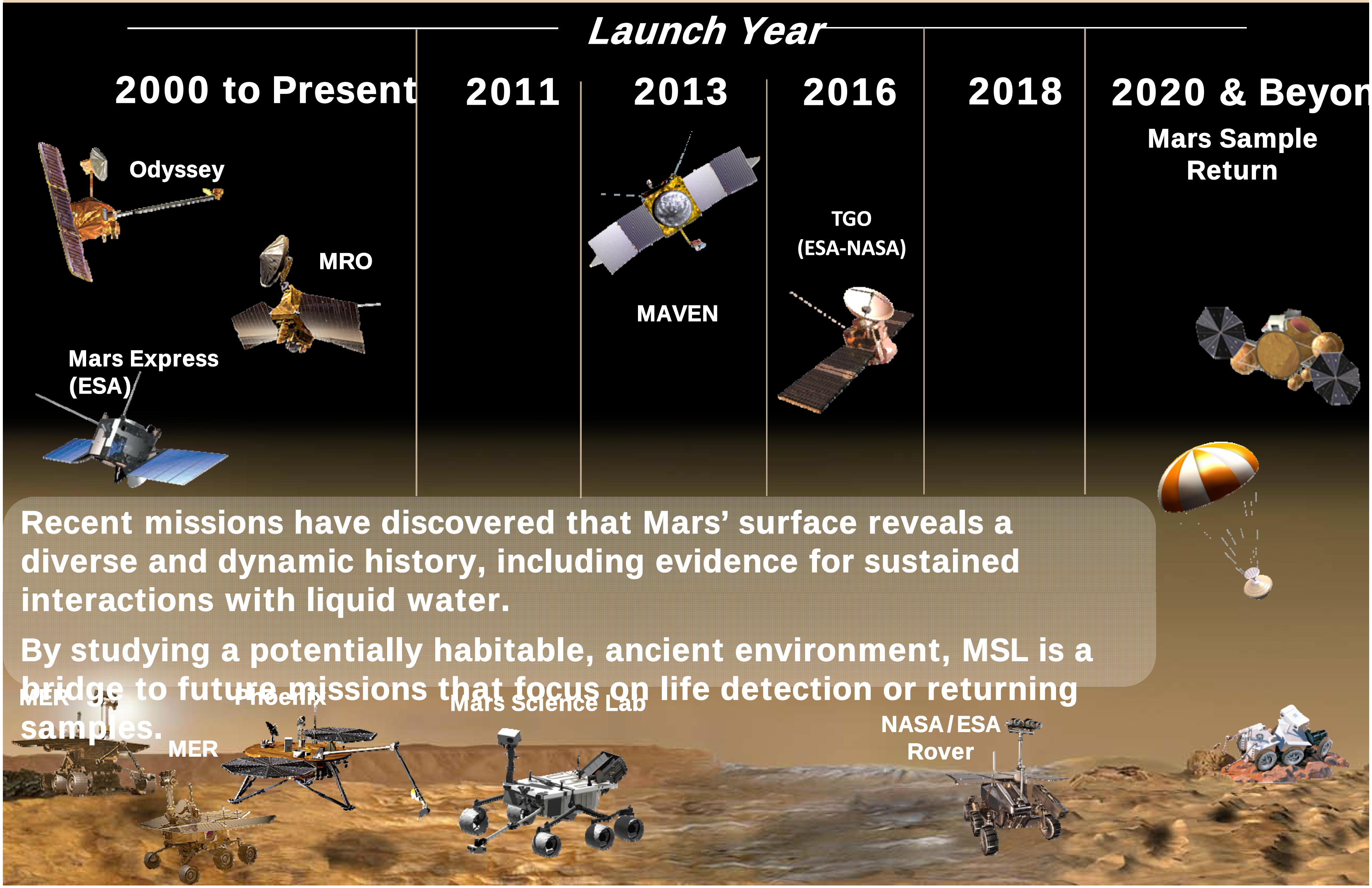
The primary science targets are the lower strata of the central mound, where orbital mapping indicates the presence of phyllosilicate minerals (clays) near the base of the section, transitioning to sulfates higher up.

Additional Slides

Rover Family Portrait



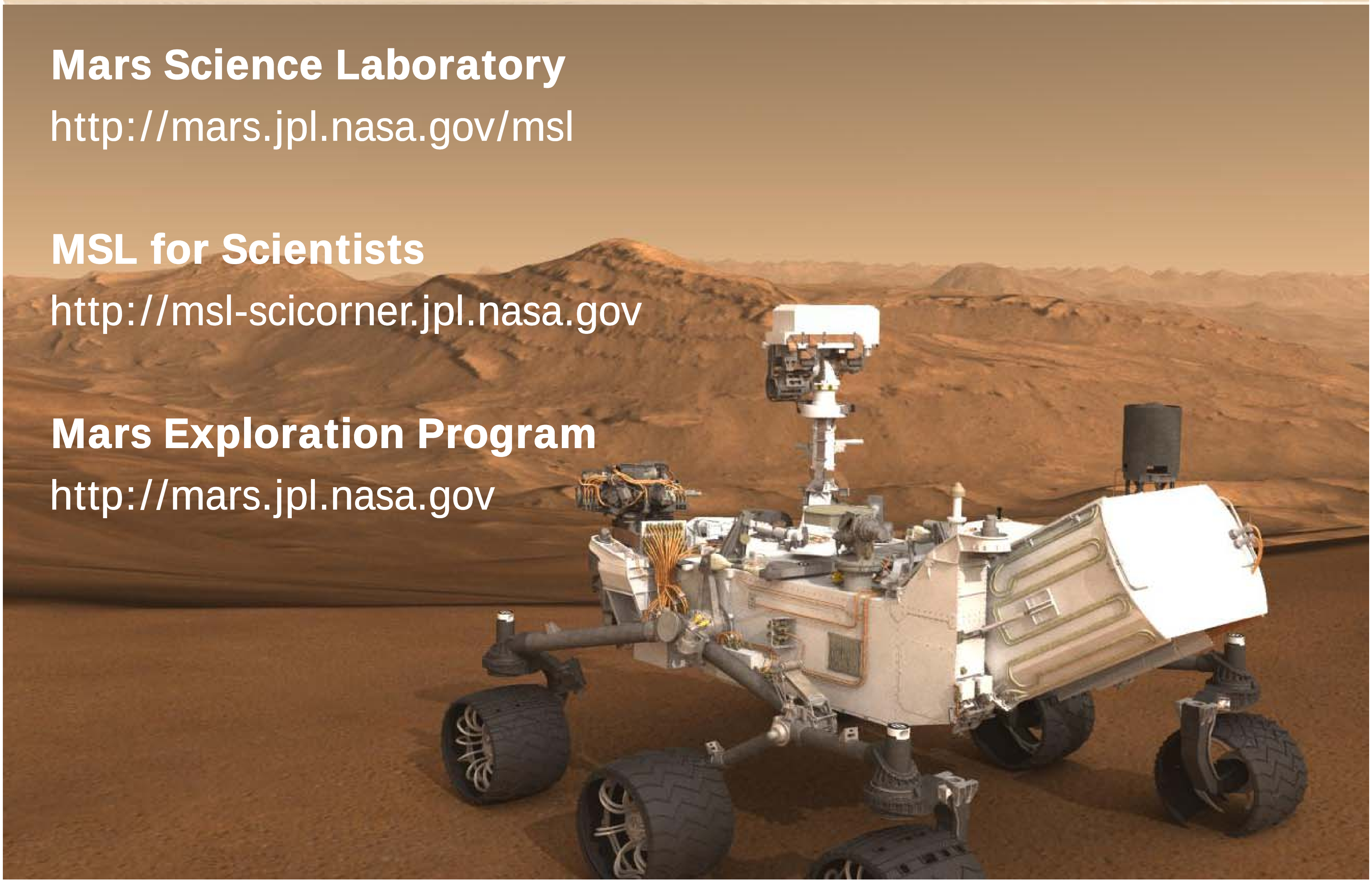
NASA's Mars Exploration Program



Recent missions have discovered that Mars' surface reveals a diverse and dynamic history, including evidence for sustained interactions with liquid water.

By studying a potentially habitable, ancient environment, MSL is a bridge to future missions that focus on life detection or returning samples.

Learn More about Curiosity



Mars Science Laboratory

http://mars.jpl.nasa.gov/msl

MSL for Scientists

http://msl-scicorner.jpl.nasa.gov

Mars Exploration Program

http://mars.jpl.nasa.gov

Fini