Jet Propulsion Laboratory
California Institute of Technology

JPL Advanced Thermal Control Technology Roadmap

a presentation to

Spacecraft Thermal Control Workshop
The Aerospace Corporation, El Segundo California
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California Institute of Technology

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Thermal Technology Roadmap

- Driven by the institution's science and engineering-science objectives as well as cost reduction needs over the state-of-the-art

Top-level objectives	Areas enabled or enhanced by Thermal	Drivers on Thermal
In-situ science	Rovers, landers, EDL systems	Extreme environments, diurnals, regolith, random/roving orientations, closed config for atmospheric entry
Remote sensing science	Active/passive microwave, spectrometer, imaging, and ranging USO systems	Dimensional stability, instrument electronics stability, detector SNR (cryogenic cooling)
Low cost telescopes	Active optics	Optical wave-front error
Low cost spacecraft	Scalability, adaptability to different environments	Lower NRE costs for spacecraft to any planet

Thermal Technology Development:

In-Situ Science Missions

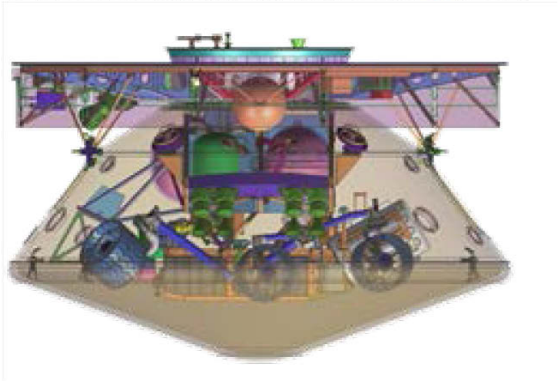
Key drivers on the thermal subsystem

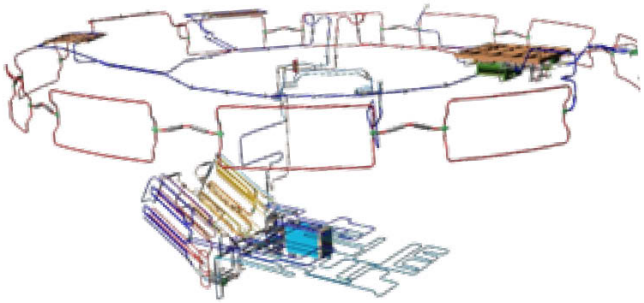
Rovers, Landers, EDL systems

Driving characteristics	Thermal system impact
Entry through atmosphere	Requires a thermally isolative aeroshell with lengthy paths between power dissipating components (Rover) and exterior
Dust	
Extreme landing latitudes and random orientations in a gravity environment	Drives the power system to a high waste-heat (2 kW_t) MMRTG architecture
Diurnals	

Thermal technology to meet demands

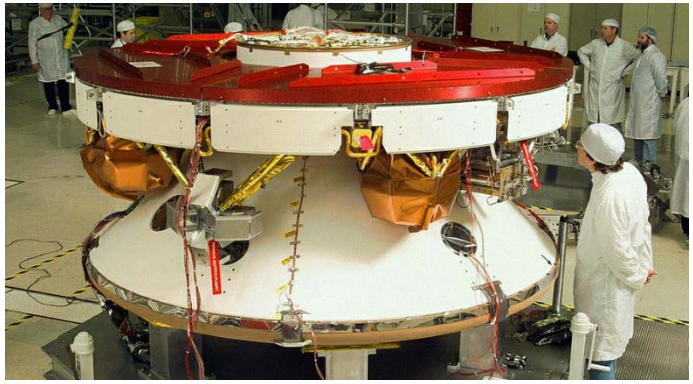
- JPL's thermal technology path is the single-phase, mechanically pumped fluid loop (1-ϕ MPFL)
  - Capable of transporting waste heat over long distances
  - Bypass and mixing valves allow for system turn-down and utilization of waste heat during cold conditions
  - Scalable and allows system design flexibility (thermal bus architecture)





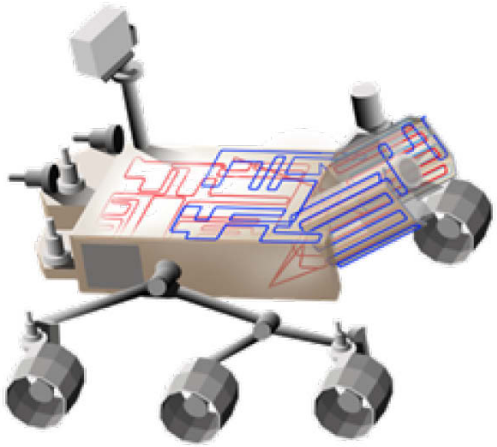
MPFL Flight Heritage at JPL

- Mars Pathfinder
  - JPL's MPFL technology development started in 1994 with the Mars Pathfinder mission
  - A centrifugal pump circulated liquid CFC-11 to remove excess waste heat from the lander inside the aeroshell during its Mars cruise
  - Similar system used on MER
- Mars Science Laboratory
  - In 2011, two MPFL systems using CFC-11 were flown on MSL
  - A loop similar to that of MER but twice the flow rate was used for removing waste heat from an RTG and the Rover embedded in the aeroshell during the 10 month Earth-Mars cruise
  - A new fluid loop system with mixing and splitting valves is used for the rover during the 3 years of cruise + surface operations



Mars Pathfinder Flight System

Mars Pathfinder MPFL pump



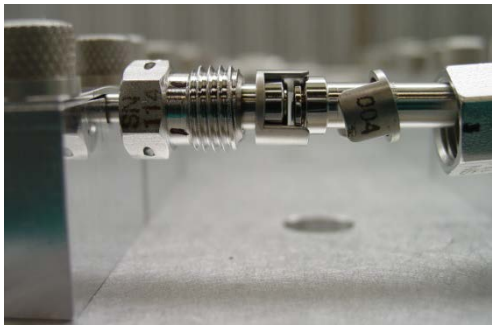
MSL Rover MPFL system

MPFL Technology Development at JPL

- Life testing
  - Life testing of pumps, valves, seals
  - Chemical compatibility of materials/working fluid
  - Chemical stability of the working fluid
  - Life testing mechanical joints, flex lines
- Technology roadmap
  - Alternate working fluids for higher temperature regimes
  - Advanced heat exchangers for lower mass and higher efficiency
  - Passive thermal control flow valves
  - Scalability and flexibility enhancers to reduce costs (e.g., reliable fittings and flex lines)

Life test panel

Passive flow control valve



Reliable fittings

NASA's Mars Exploration Missions

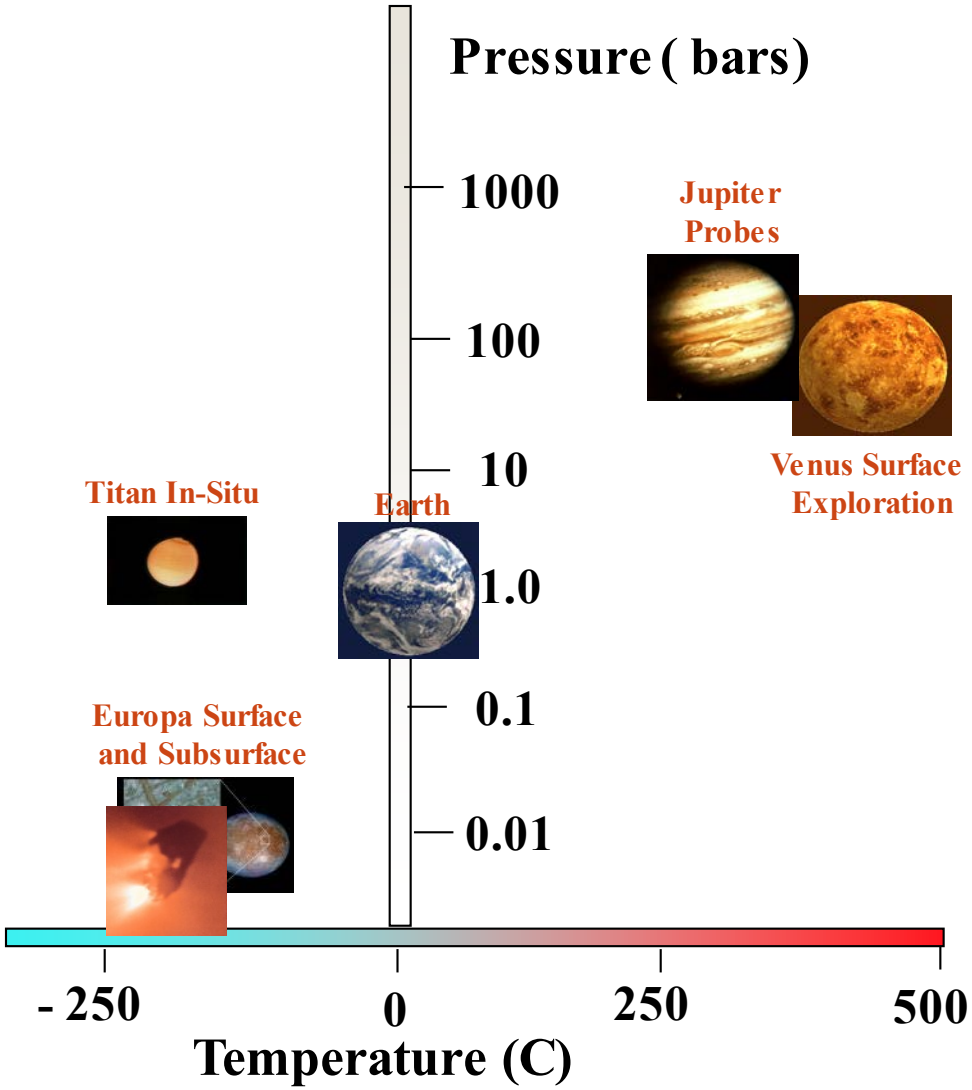
Launch Year

2000 to Present	2011	2013	2016	2018	2020
Odyssey, MRO, Mars Express (ESA)		MAVEN	ESA's TGO		2020 Rover

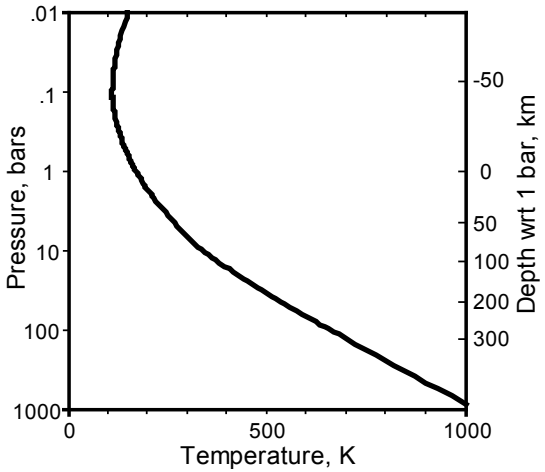
Recent missions have discovered that Mars' surface reveals a diverse and dynamic history, including evidence for sustained interactions with liquid water

Pre-Decisional--For Planning and Discussion Purposes Only

Planetary Extreme Environments



Lunar Diurnal: 100 to 400 K
Mars Diurnal: 150 to 300 K

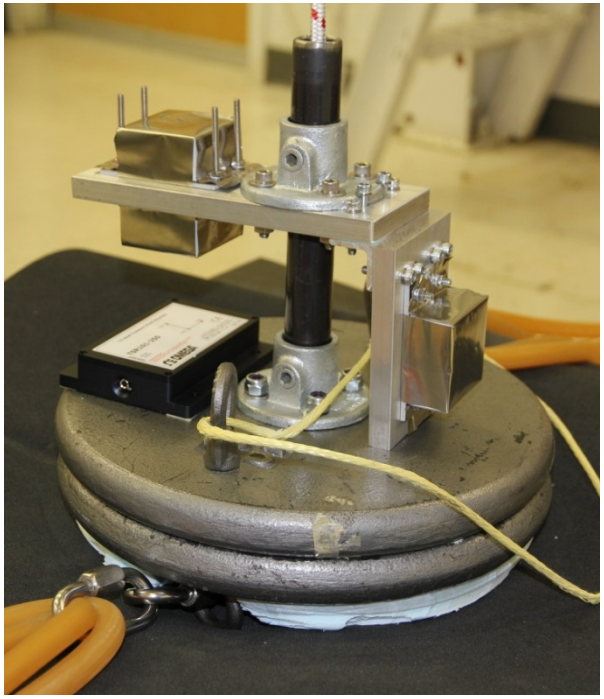


Jupiter Pressure Plot

Thermal technologies for a future Venus lander

- Develop a thermal control system enabling a Venus Lander Mission to survive for ~ 4 hours on surface at 92 bars and ~470ºC
  - Survive 2 times longer than previous missions with passive thermal control
  - Determine thermal and mechanical properties of external insulation materials
  - Quantify lifetime performance of thermal energy storage materials.

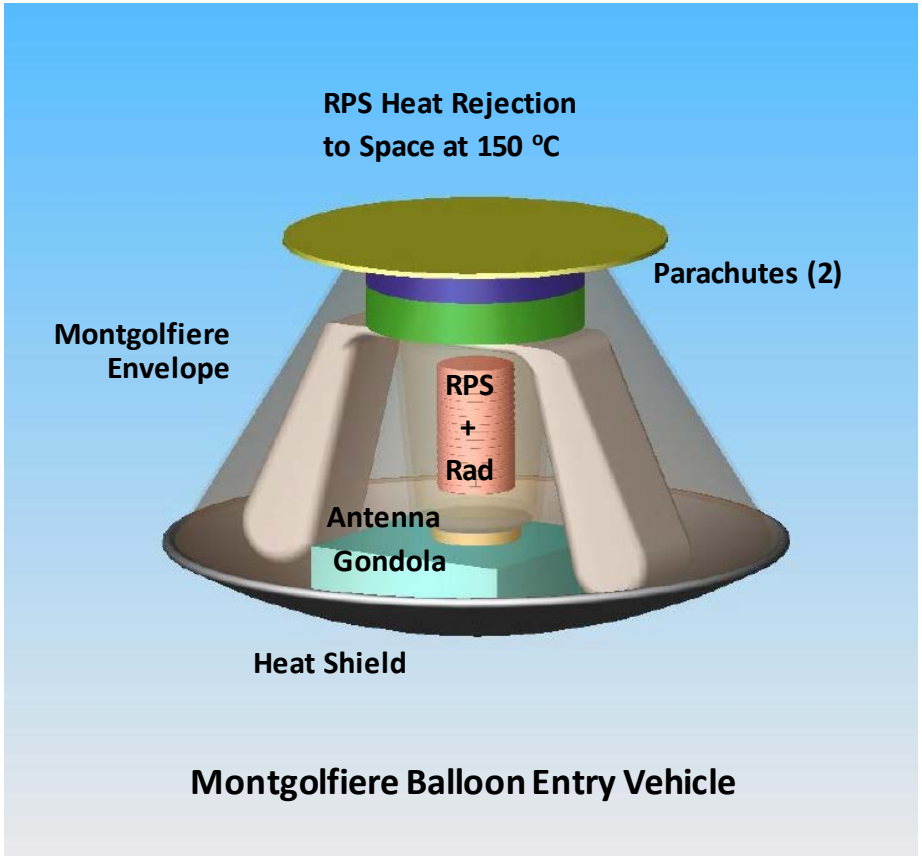
Insulation Testing in Venus Chamber



Acceleration Testing of Insulation

Life Testing of Energy Storage Materials

Conceptual Design of Future Titan Planetary Explorer



A packed balloon heated by RTG waste heat would be packaged in an entry vehicle, filled with cold ambient nitrogen gas, and could be controlled to float at any altitude between the Titan surface and about 10-km altitude.

Thermal Technology Development:

Remote Sensing Science Missions

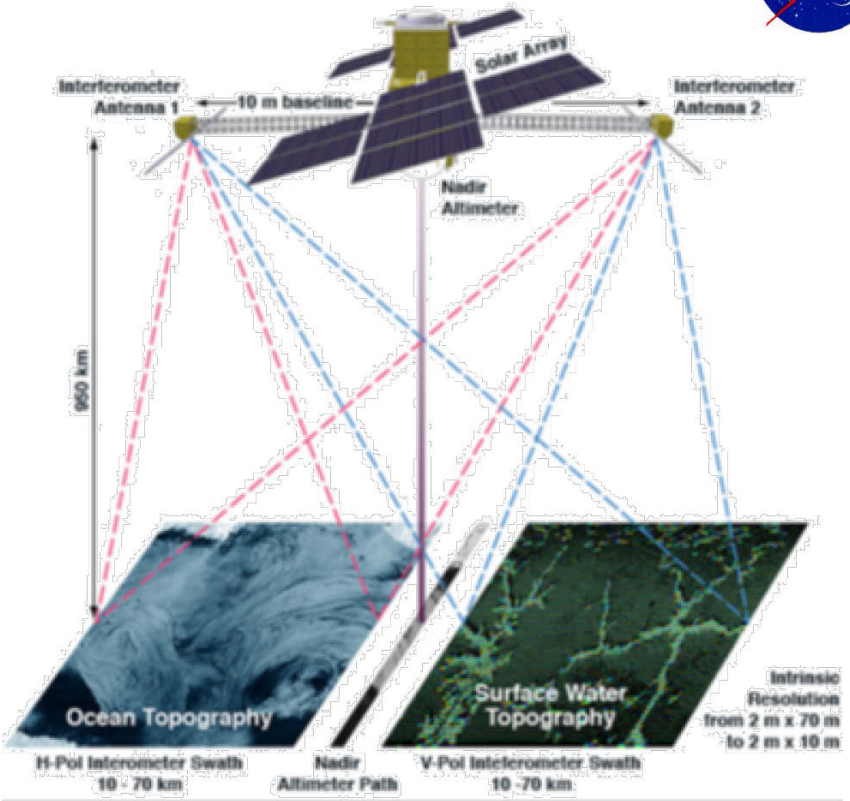
Key drivers on the thermal subsystem

The quest for higher resolution science products from active/passive microwave, optical, and imaging instruments will be enabled through advanced thermal technologies

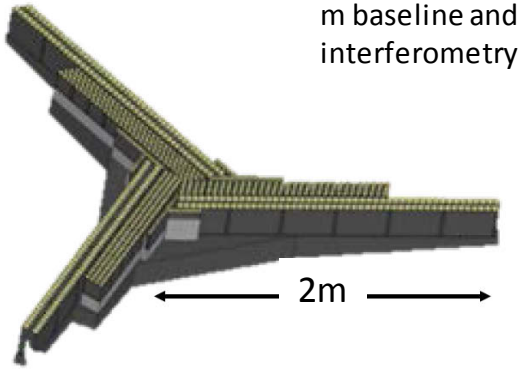
Driving characteristics	Thermal system impact
Advanced antennas/feeds on InSAR missions for higher resolution science products	Enabled by sub-micron thermo-elastic stability over large distances; requires specialized testbeds for design validation
Active/passive microwave electronics for higher resolution science	High spatial and temporal stability of co-located electronics
Optical system detectors toward longer IR wavelengths	Spectrometers and imagers require cryogenic temperatures

Thermal technologies for dimensional stability

- Advanced materials for lower CTE (reflectarray) and improved isothermalization (mast)
  - Frequency dependent requirements result in specific figures of merit
- 2-ϕ technologies for waveguide manifold isothermalization and stability
- Low cost, sub-micron testbeds for design characterization

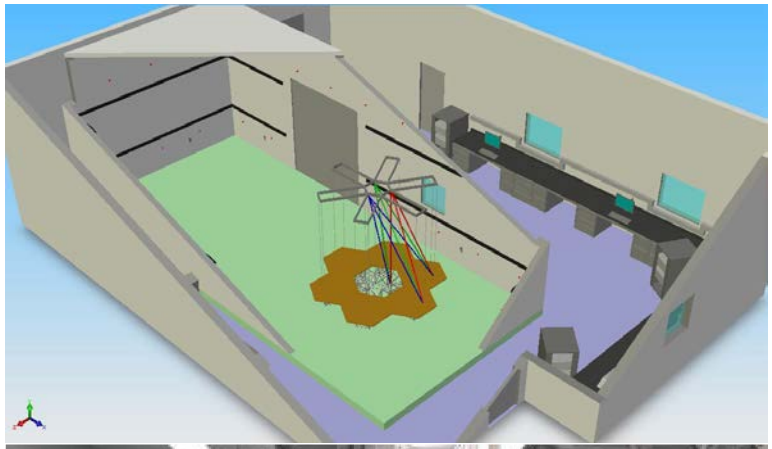


Surface Water Ocean Topography mission concept uses a 10-m baseline and reflectarray antennas for Ka-band radar interferometry



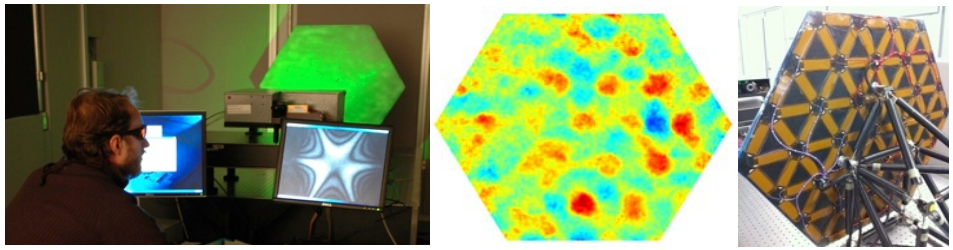
GeoSTAR instrument concept uses 2-m arms of waveguide manifolds requiring stringent temperature stability

Integrated thermo-mechanical testbed development



JPL Precision Environment Test Enclosure (PETE): CAD view of the PETE inside Building 299 cleanroom, photograph of PETE with 8m deployable structure (SABUR - JPL/ATK/AFRL/CSA).

- **Precision Environment Test Enclosure** (**PETE**) in ALPS clean room
  - 10m x 5m x 3m test enclosure, mounted on isolator bearings. The PETE has structural mount points on walls and ceiling suitable for gravity offload systems, with a reinforced floor grid.
  - Provides thermal (<0.01 deg C per hr) and seismic (< 0.0001 G rms) and acoustic (< 35 dBA) stability for precision testing.
  - Dedicated metrology systems for the characterization of test hardware, including a speckle laser holographic interferometer capable of measuring surface deformations (relative) to 25 nm over a 2 m field of view for both static and dynamic testing.

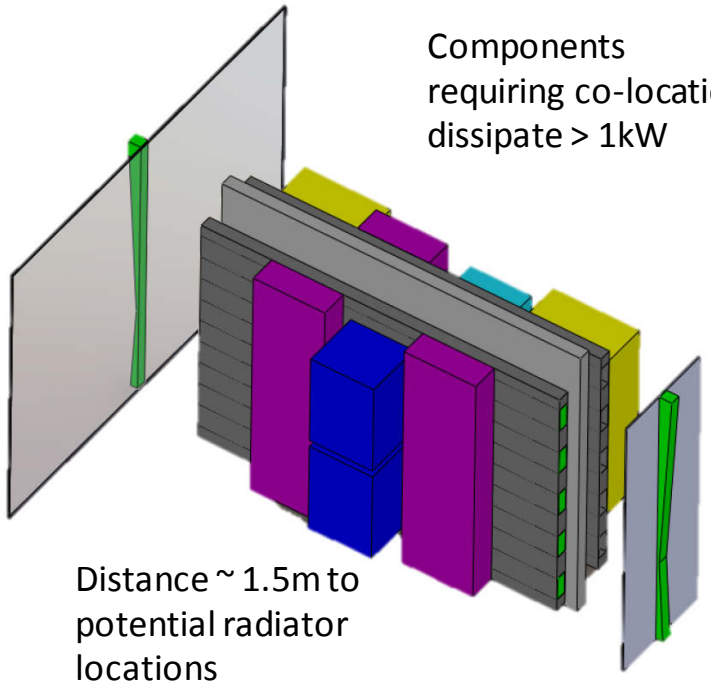


Speckle Interferometer, measuring the surface of a 0.8 m active panel. An array of flat piezoelectric actuators corrects thermally-induced deformations to better than 100 nm RMS.

PETE Contacts: Greg Agnes, 818.354.9317, Gregory.S.Agnes@jpl.nasa.gov and S Case Bradford, 818.393.2793, case@jpl.nasa.gov

Thermal technologies for remote sensing electronics stability

- Drivers
  - Co-location requirements of microwave interferometric electronics
  - High power voltage supplies and microwave amplifiers (Klystron) result in high waste heat dissipations
  - Frequency dependent temperature requirements
  - Missions with widely varying sink temperatures and orbital frequency
- Technologies to address the above include highly stable pallet structures using 2-ϕ passive and MPFL technology

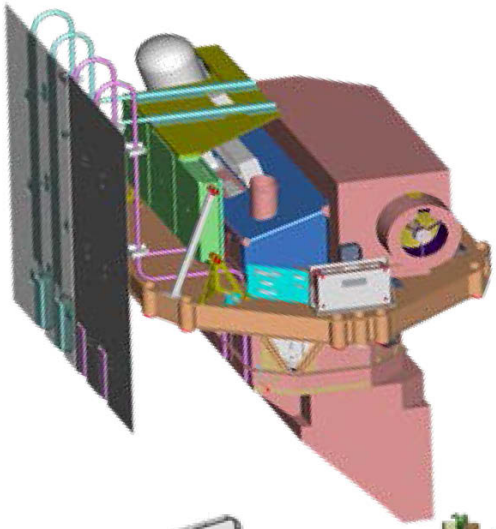


Temperature stability:
< 0.01 °C/5 minutes
< 0.1 °C/100 min.
< 1 °C/month

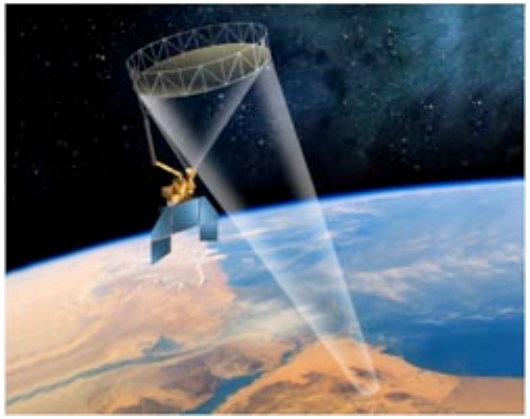
Remote Sensing Science Instruments

MIRI on JWST

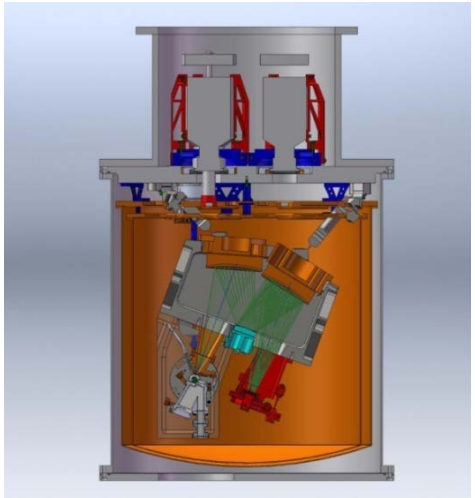
OCO-2, 2013

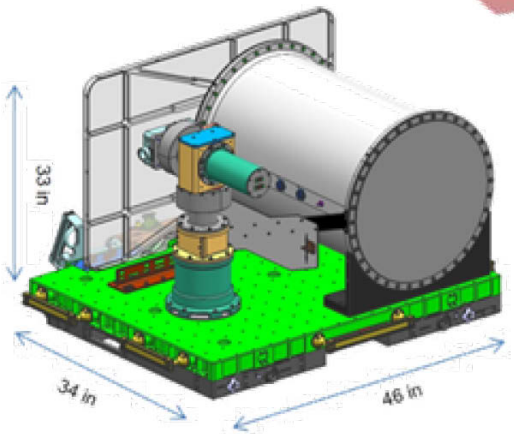


SMAP, 2015

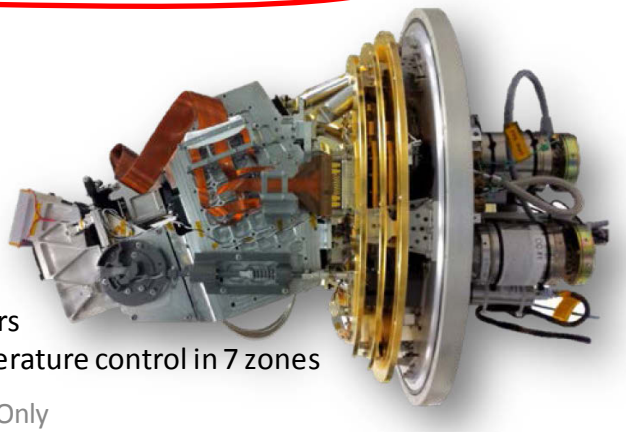


NEON/CAO/AVIRIS NG –based Airborne Spectrometers



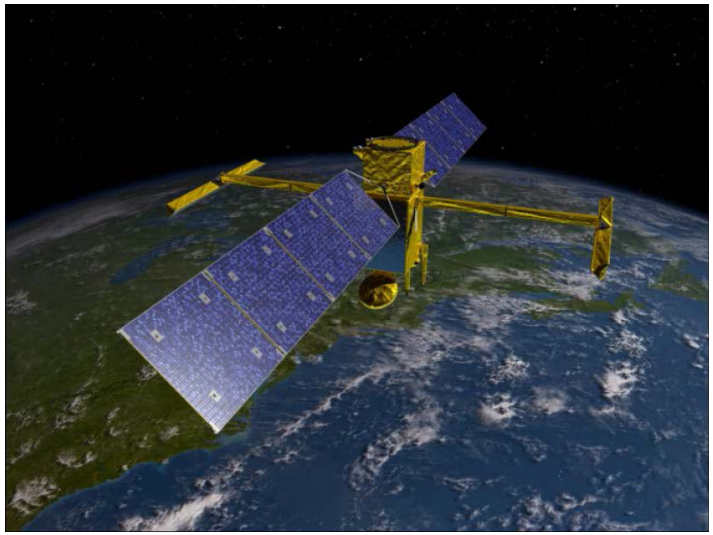


OPALS on ISS

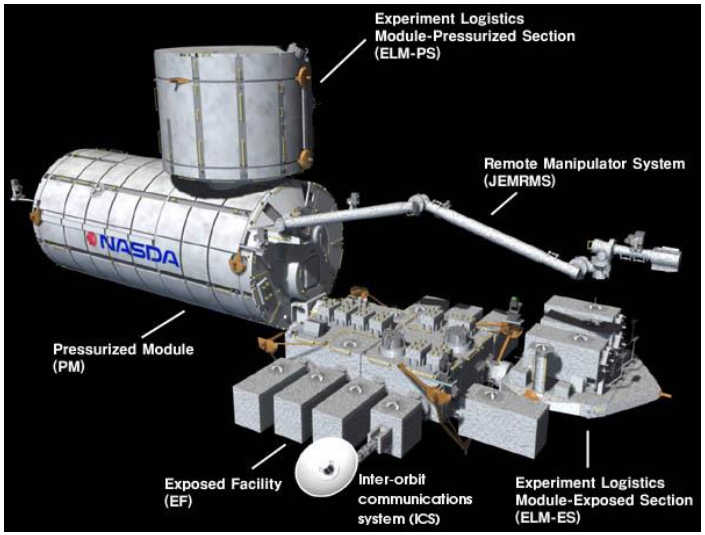


MaRSplus Sensor System (MSS)
Airborne imaging spectrometer
Two Sunpower Cryotel GT coolers
LabVIEW-based, mK-level temperature control in 7 zones

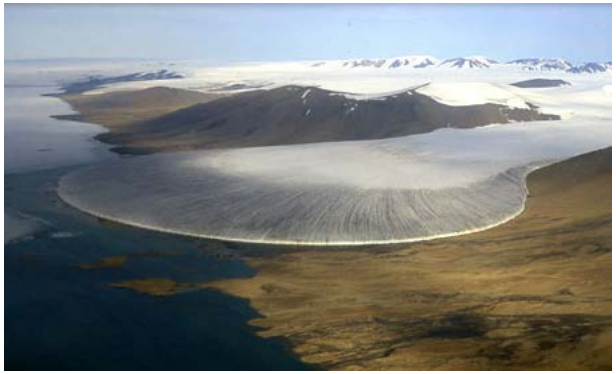
Instruments in pre-development



Proposed: Surface Water Ocean Topography (SWOT)



Proposed: OCO-3 on ISS JEMS EF



Proposed: Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI)

Thermal Technology Development:

Low Cost Telescopes

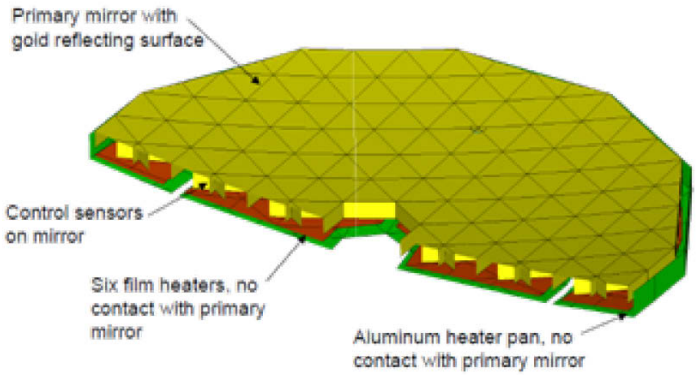
Key drivers on the thermal subsystem

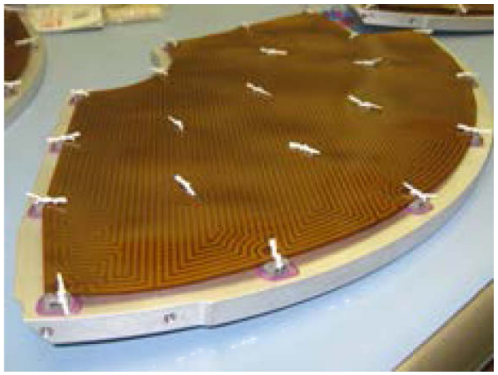
Low-cost, advanced telescopes using active optics

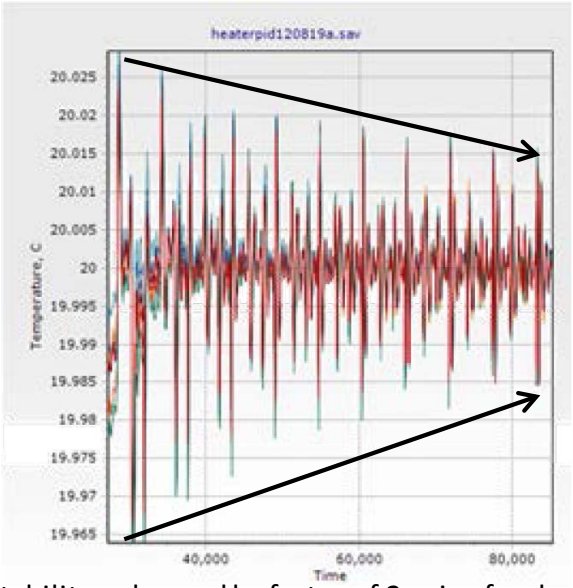
Driving characteristics	Thermal system impact
Telescopes using deformable SiC mirrors for on-orbit SFE removal to achieve diffraction-limited imaging	Thermal control system needs to provide mK-level temporal temperature stability due to high CTE and low frequency of WFS&C
Telescopes using laser metrology for on-orbit rigid body error removal	Laser metrology system needs mK-level temporal temperature stability to due laser wavelength sensitivity
Push to remove integrated thermo-optical testing for telescope validation due to high costs	More reliance on design validation via analysis

Thermal technologies for low-cost telescopes

- Advanced optics materials for higher figures of merit, $\frac{k}{\rho Cp * \alpha}$
- Advanced cold-biased/heater designs
- Feed-forward controllers
- Integrated, multi-threaded modeling tools





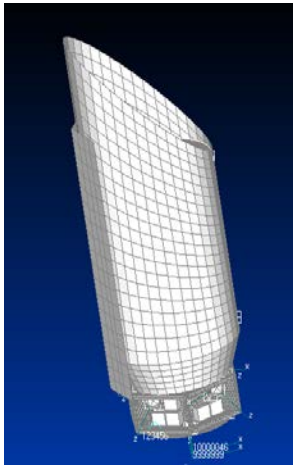


Temperature stability enhanced by factor of 2 using feed-forward control for external ISS environment

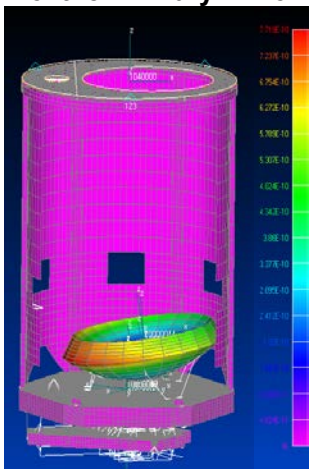
Integrated Thermal-Structural Modeling with Cielo

- Cielo is a general-purpose finite element-based code for advanced thermal, structural and optical aberration analysis.
- Replaces traditional "STOP" analysis with a truly integrated system-level capability
- Highly configurable to project needs
- Motivated by extreme challenges in precision
- Deployable structure analysis and design.
- Cielo consists of a MATLAB-hosted client and a parallel compute server.
- Performance limited only by parallel hardware availability—makes uncertainty quantification practical for large models

Coronagraph Common Model



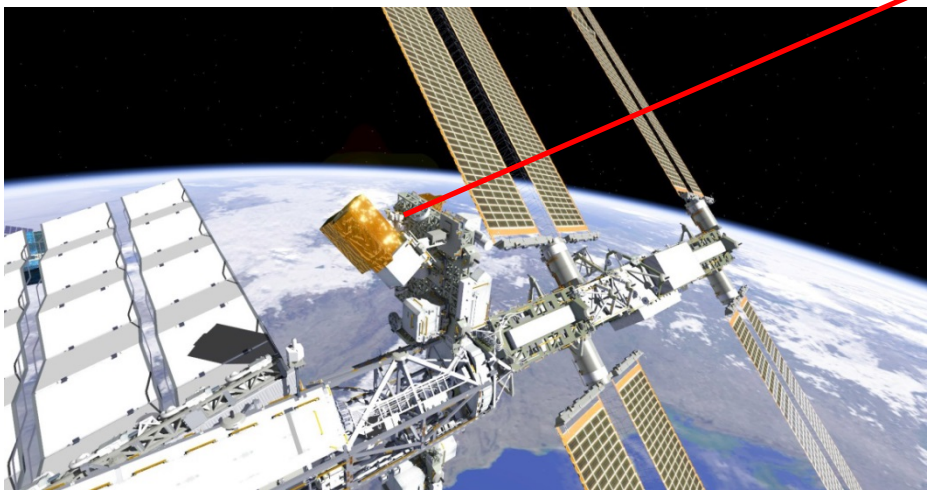
Thermal Deformation of the Primary Mirror



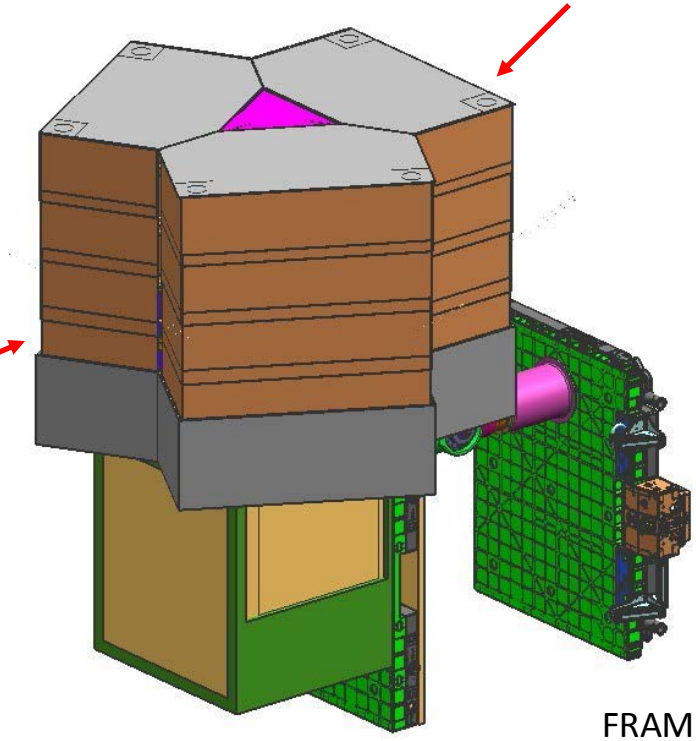
JPL Supercomputing facility. The Zodiac cluster has 1824 nodes. http://supercomputing.jpl.nasa.gov/zodiac.php

Low cost telescopes in pre-development

- Optical Testbed and Integration on ISS eXperiment (OpTIIX) is a NASA technology demonstration to robotically assembly a six segment, 1.5 m telescope on the ISS with active co-phasing and figure control to achieve performance like a single large telescope



Each of 3 bays contain 2 segments of the PM. Launched separately and assembled robotically



FRAM

Thermal Technology Development:

Low Cost Spacecraft

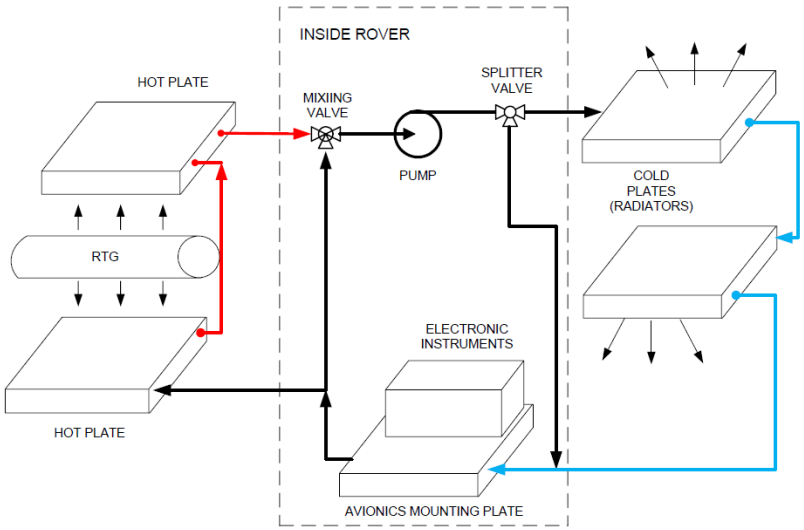
Key drivers on the thermal subsystem

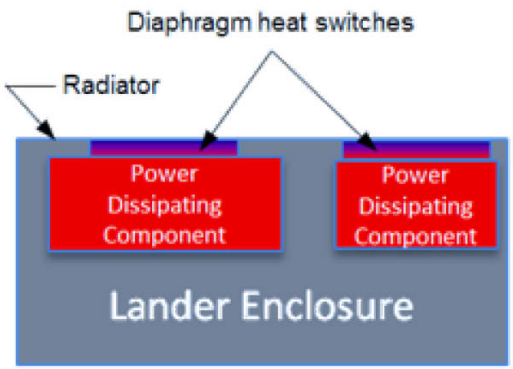
Low-cost spacecraft

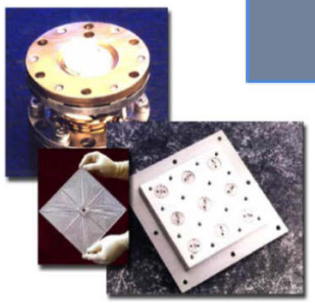
Driving characteristics	Thermal system impact
Desire for lower NRE costs for spacecraft	JPL's solar system exploration focus imposes diverse thermal environments, yet spacecraft need to be scalable, configurable, and robust
Micro- and nano-spacecraft	Minimal power for thermal control

Thermal technologies for low cost spacecraft

- Low-cost MPFLs with variable heat rejection radiators
  - Overall mission costs are reduced with a "thermal bus" architecture
- Turn-down devices for Cubesats and low-cost landers

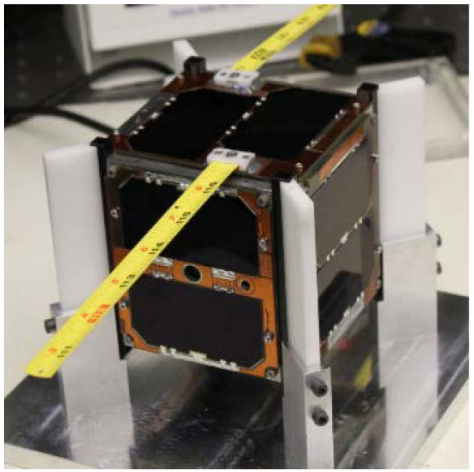




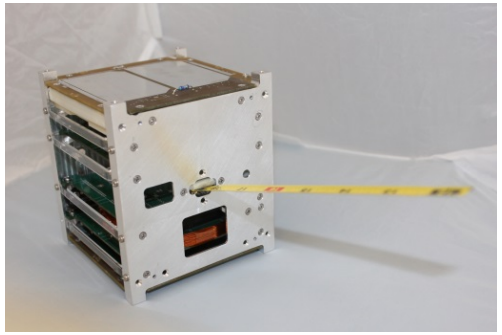


Heat switch photos courtesy of Sierra Nevada Corporation

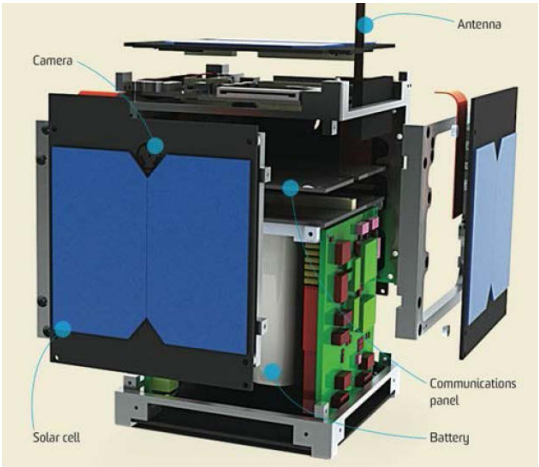
Active JPL Cubesat Projects



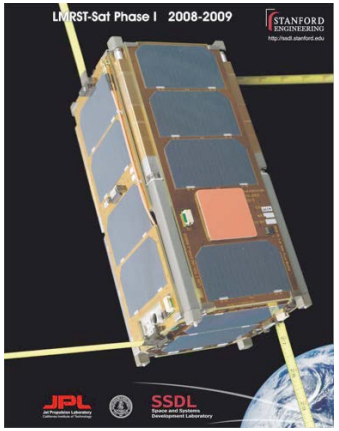
M-Cubed/COVE (NASA ESTO, 1U)
High data-rate on-board processing
P. Pingree: JPL, U. Michigan
Launched VAFB: Oct 2011 (NASA CLI)



M-Cubed/COVE-2 (NASA ESTO, 1U)
High data-rate on-board processing, Reflight
P. Pingree: JPL, U. Michigan
Launched VAFB: Dec 2013 (NASA CLI)



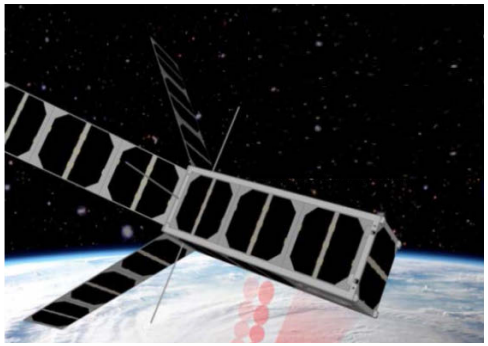
IPEX (NASA ESTO, 1U)
Autonomous low-latency product generation
S. Chien: JPL, GSFC, Cal Poly SLO
Launch Manifest: Sep 2013 (NASA CLI)



Proposed: LMRSaT (3U)
Low Mass Radio Transponder
C. Duncan: JPL, Stanford
Launch Awarded (NASA CLI)

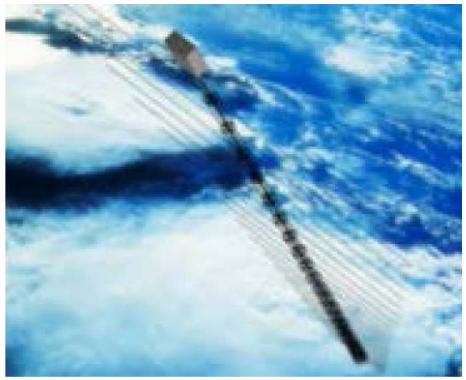
Active JPL Cubesat Projects (Cont'd)

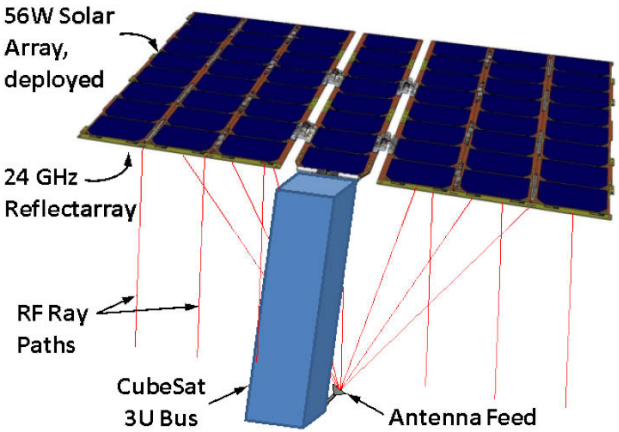
GRIFEX (NASA ESTO, 3U)
Unprecedented frame-rate ROIC/FPA
D. Rider JPL, U. Michigan
Launch Awarded (NASA CLI)



Proposed: RACE/CHARM (HOPE, 3U)
Hydrometric Atmospheric Radiometer
B. Lim: JPL, ARC
Launch Manifest: 2014 (NASA CLI)

Proposed: CHIRP (NASA JPL, 6U)
VHF transmitter to study Ionospheric dispersion of Radio Pulses
A. Romero-Wolf JPL, U. Michigan
Launch TBD





ISARA (EDISON, 3U)
Integrated Solar Array & Reflectarray Antenna
R. Hodges: JPL, Pumpkin Inc.
Launch TBD

Proposed: INSPIRE (NASA JPL, 3U)
Tech demo for deep space Telecom with magnetometer on-board
A. Klesh JPL, U. Michigan, Cal Poly SLO, UT Austin
Launch TBD

NASA Exploration Program – Beyond Low Earth Orbit Missions

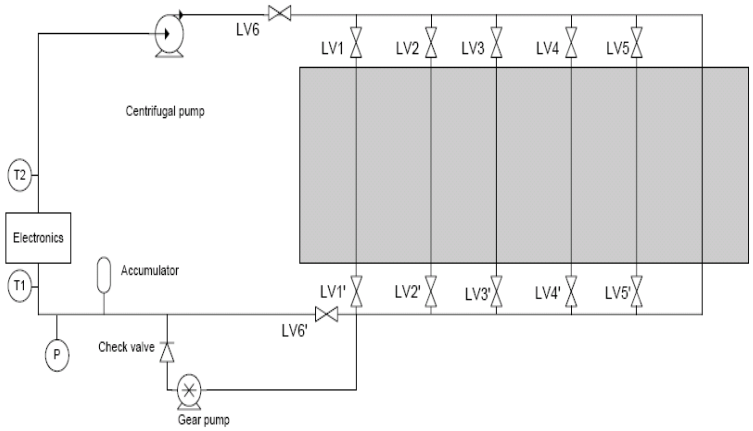
Thermal Control Challenges

- Thermal control of human-rated and robotic missions near-Earth missions
- Challenging thermal environment and thermal control requirements (dust, extreme cold/hot environment, etc)
- Thermal management of large thermal loads (both equipment and human); Passive and active thermal control technologies for heat collection, rejection, and transport

Thermal Technologies Investigated at JPL

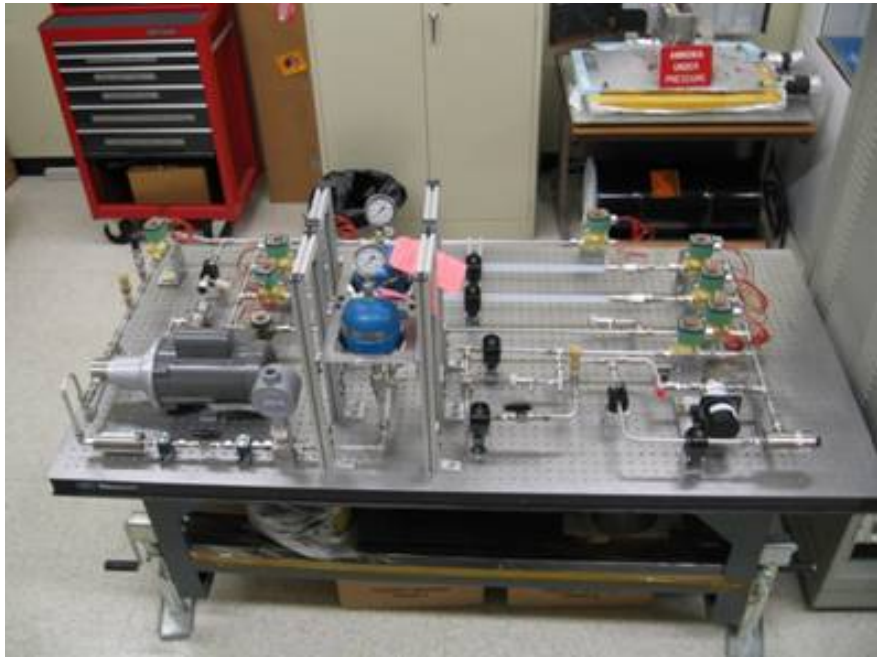
- Lightweight, variable heat rejection radiators

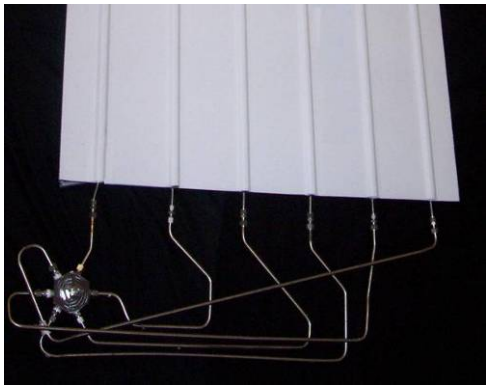
Thermal Control Technologies for Exploration



Variable Heat Rejection Radiator (Digital Radiator)

Digital Radiator Test Set up (JPL)





Stagnation Radiator (Apollo Mission)

Cryogenic Systems Technology

Brian Carroll

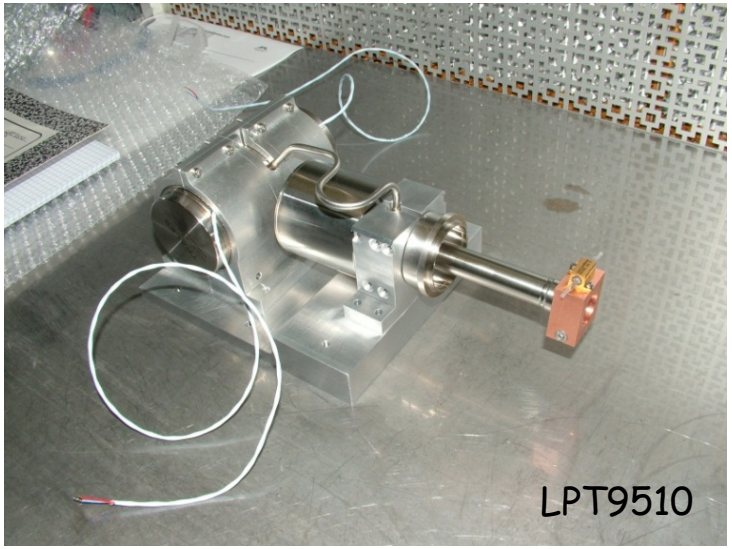
Cryogenic Instrument Technology Development

- Long-life low cost tactical cryocoolers for space
- Low cost cryocooler drive electronics
- Microcoolers for space and Mars landed missions
- Passive coolers
- Long-life space cryocoolers on-going experience

Long-Life Tactical Cryocoolers for Space Use

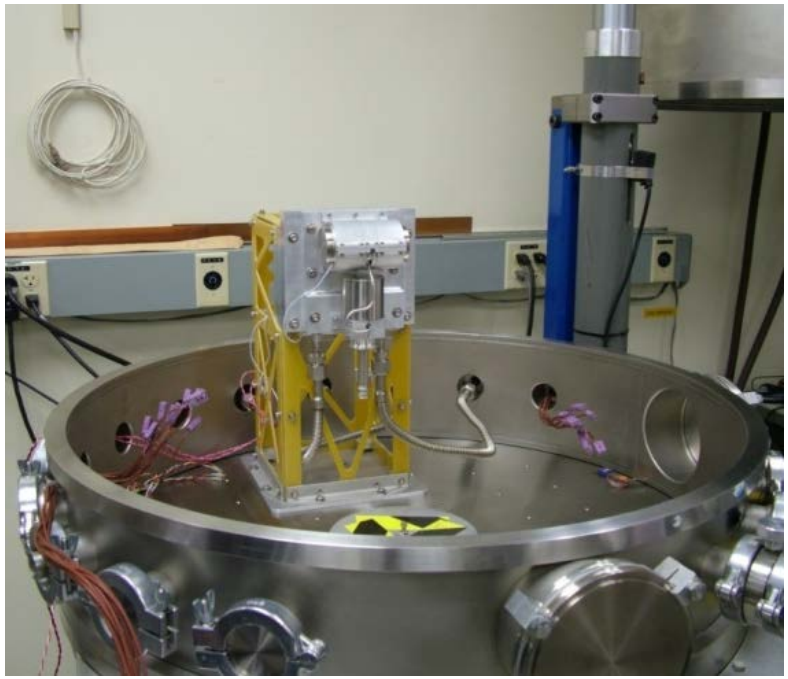
- NASA's cost-cap missions are driving instrument costs down by a ~5X from 10 years ago
- Reduced instrument costs require similar cost reductions across all subsystems including cryogenic subsystems
- NASA/JPL is investing resources to address these needs in the near term
- Low-cost tactical pulse tube cryocoolers offer significant advantages over other existing technologies including the needed cost reductions
- Thales pulse tube cryocoolers with flexure bearing technology are being considered to meet JPL's immediate needs for cryogenic cooling of spacescience instruments

Thales Tactical Pulse Tube Cryocoolers

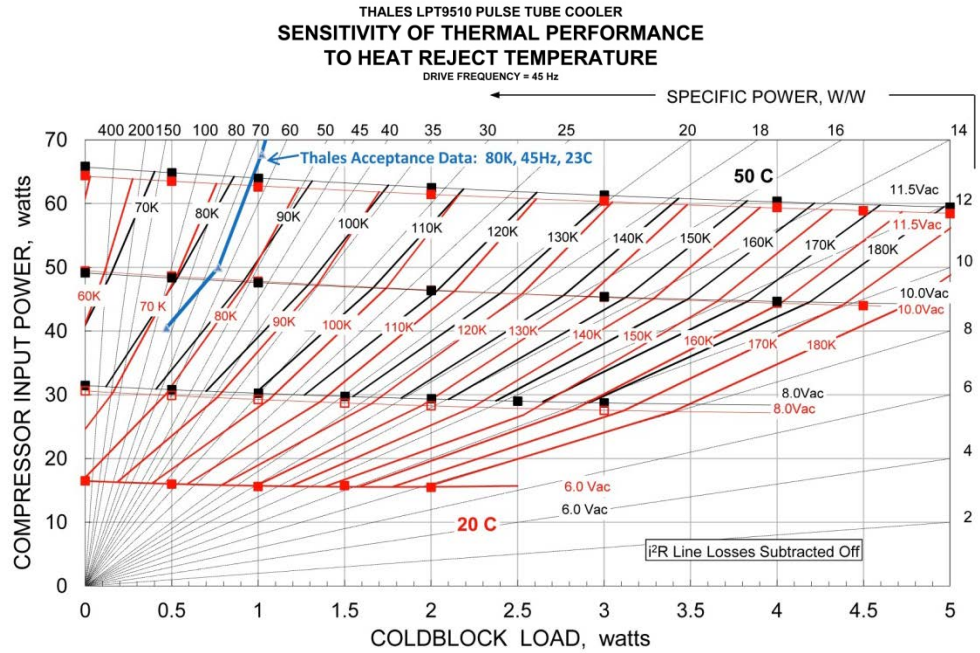


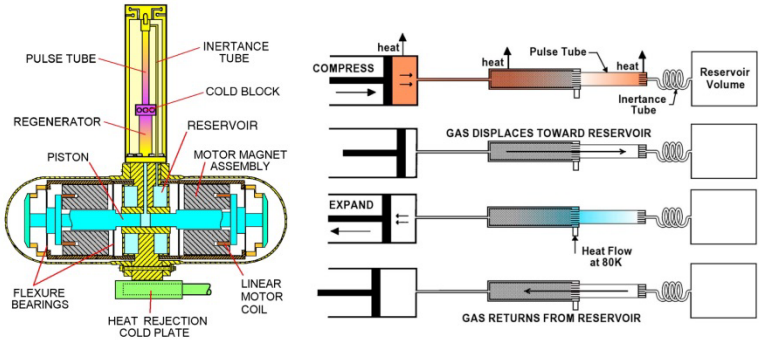
Flexure bearing technology is used on all 3 pulse tube cryocoolers

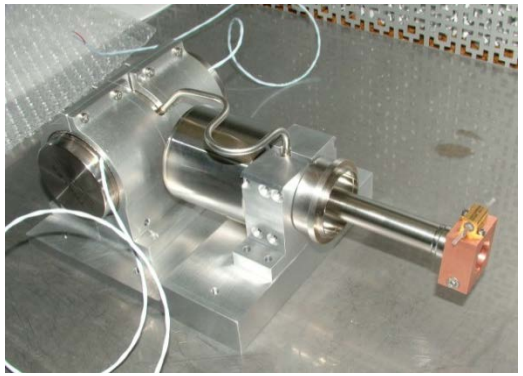
Thales LPT9510 Cryocooler Performance

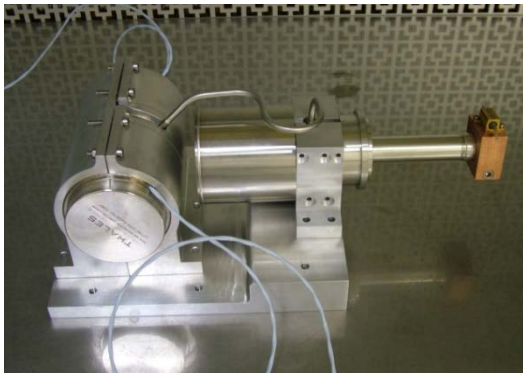


JPL clam-shell interface requires clamping entire compressor to provide sufficient heat transfer area

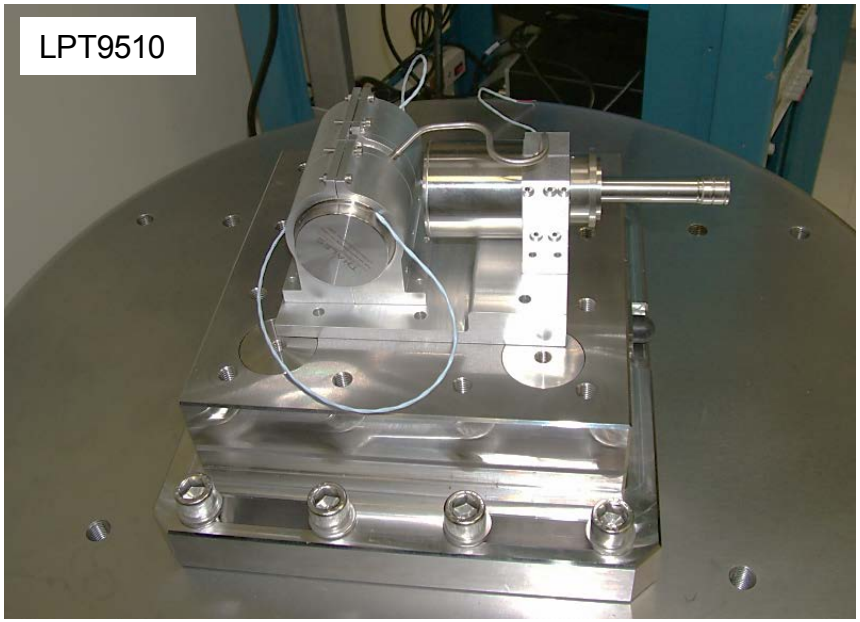


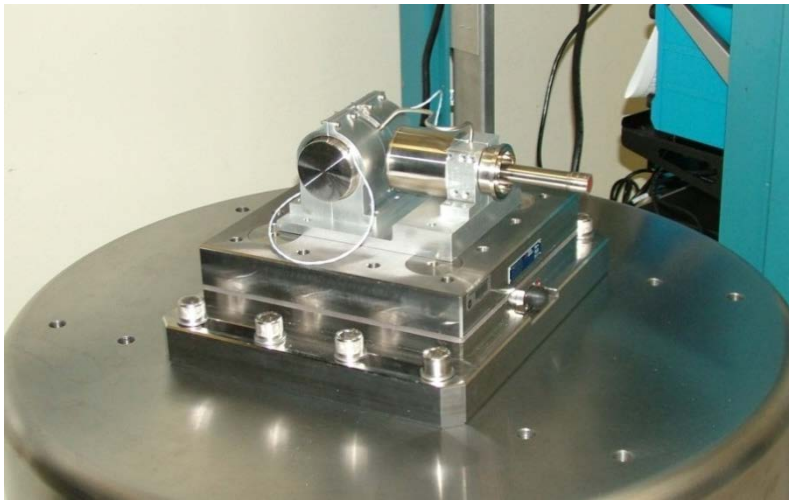


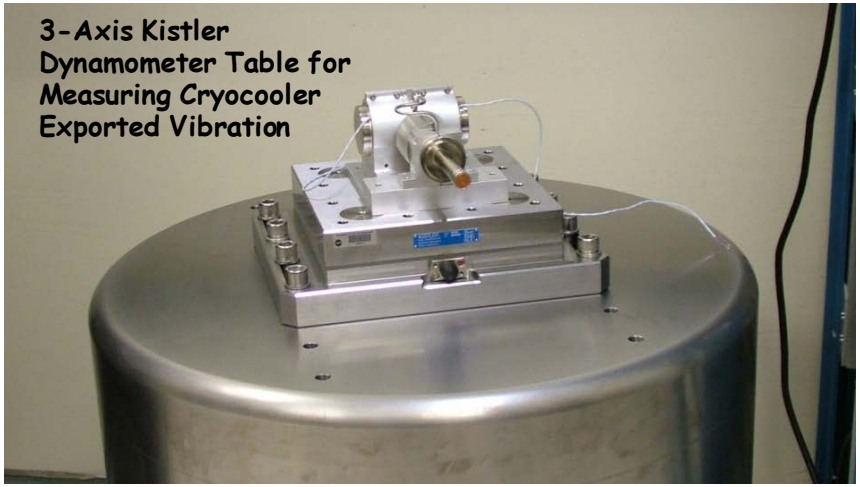


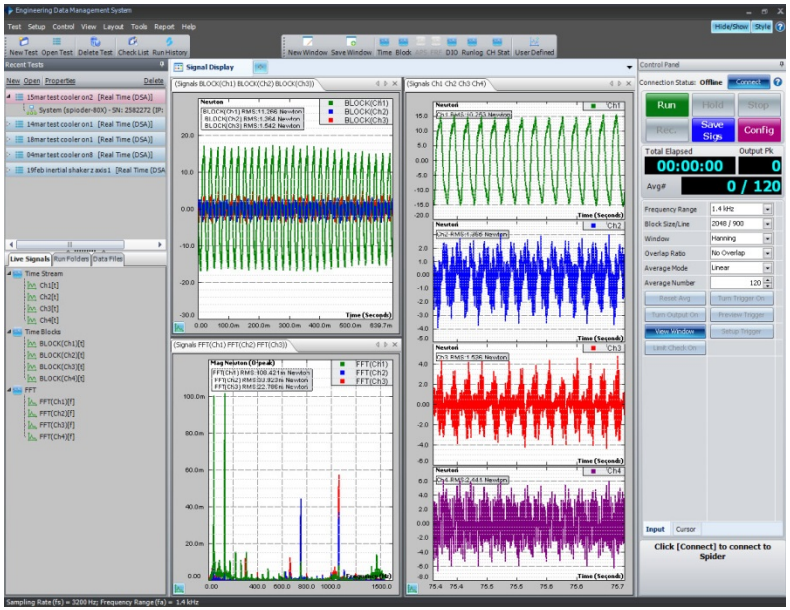


Cryocooler Exported Vibration Facility

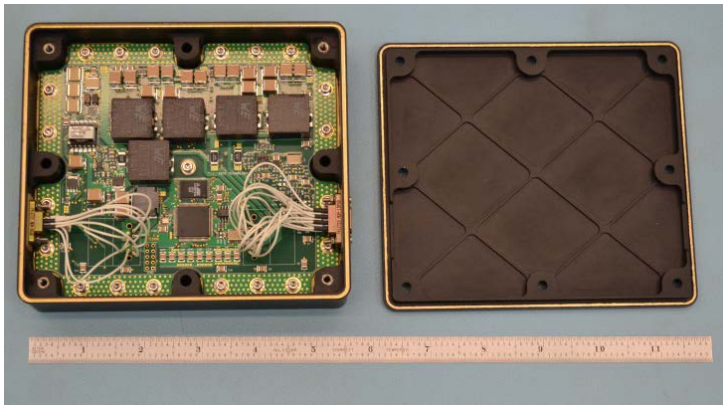


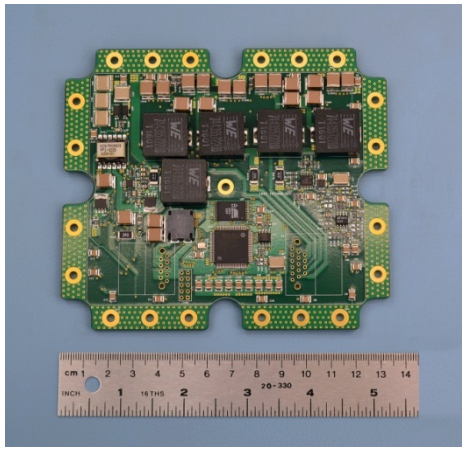


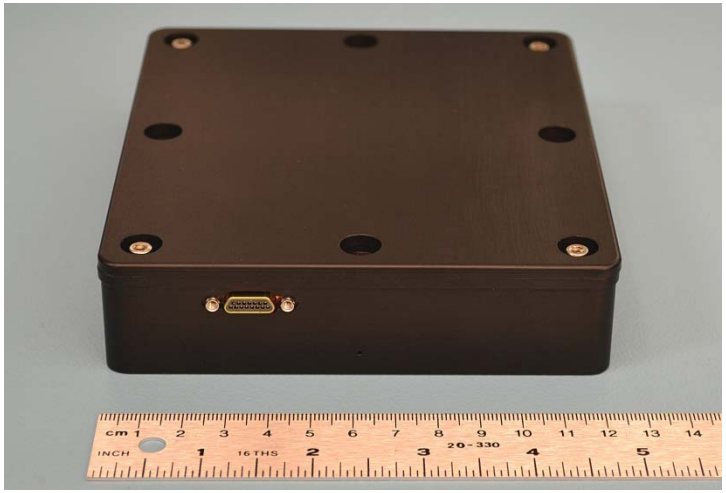


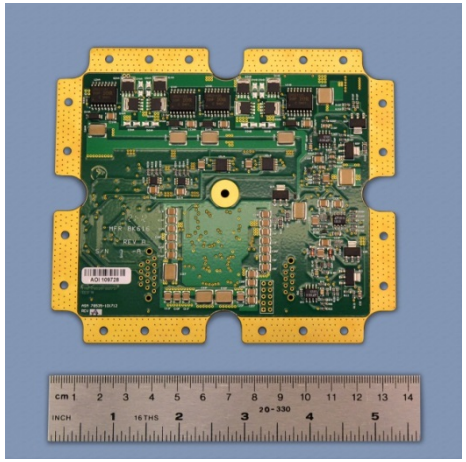


Low Cost Cryocooler Electronics (LCCE)







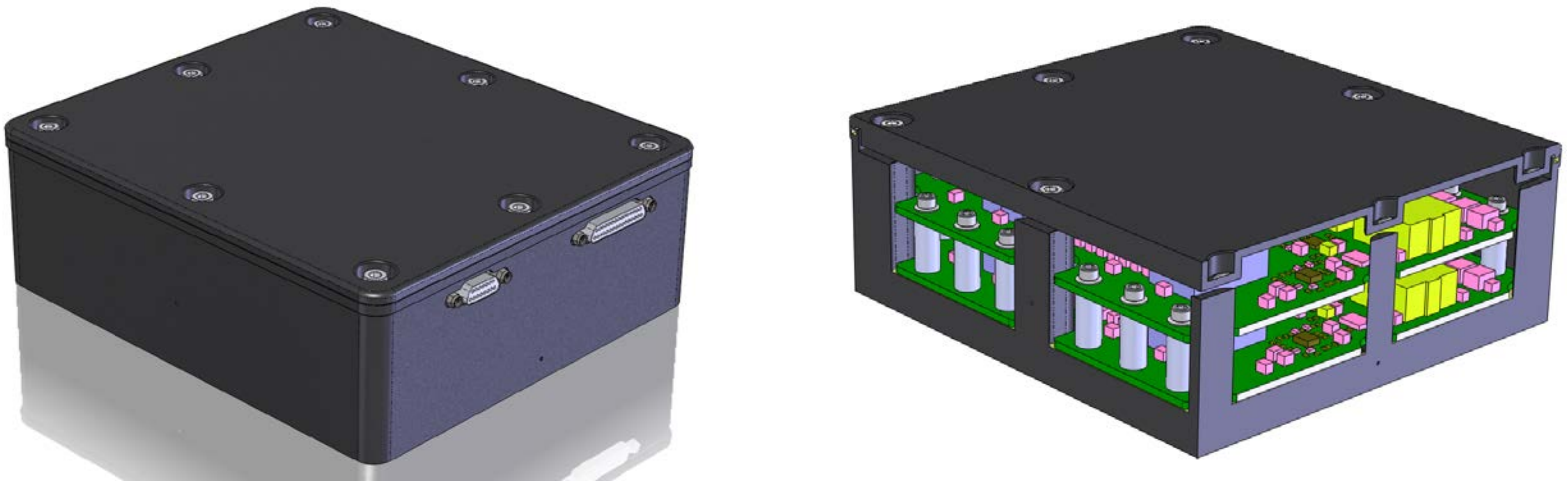


Iris Technology LCCE	
Input Voltage	22 - 37 V_{dc}
Max Output Current	6 A_{ac}
Max Output Voltage	15.2 V_{ac}
Mass	725 gr Total (<225 gr PCB)
Operating Temperature	-50 to 65°C
Non-operating Temperature	-60 to 75°C
Efficiency	>90% @ 40W >85% @ 70W
Output Frequency	50-150 Hz

LCCE is matched to operate the Thales LPT9510 cryocooler

LCCE Two-Board High Power Version

Two-Board LCCE is matched to operate the Thales LPT9310 cryocooler

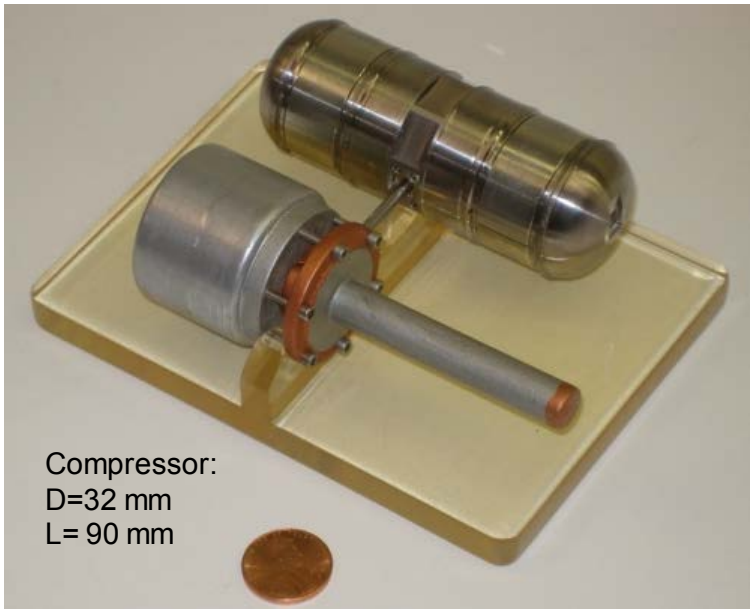


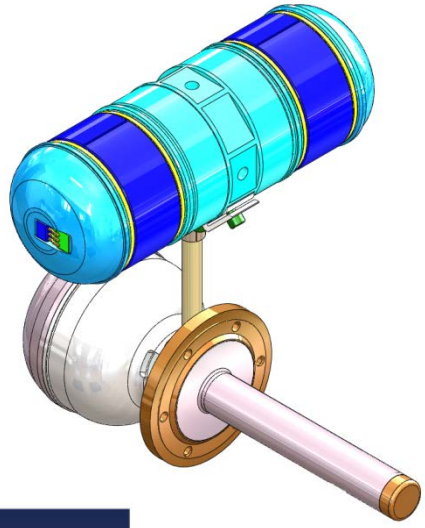
(a) (b)

Preliminary Two-Board / High Power LCCE Physical Design. Overall dimensions are 14.2 cm x 12.6 cm x 4.8 cm with an estimated mass of 990 g. (a) Solid Model. (b) Cutaway to display two board stack.

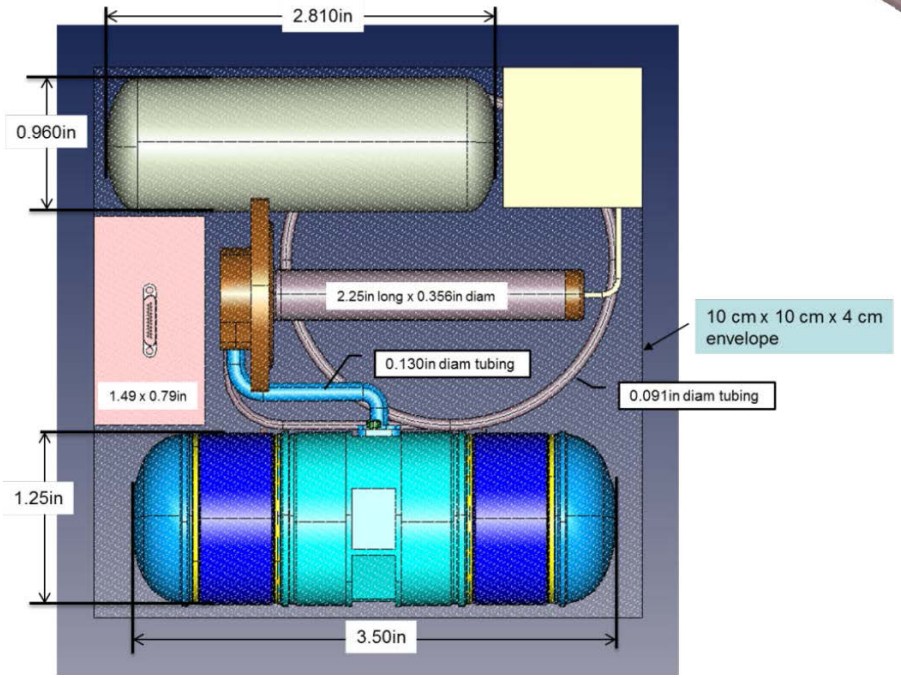
Linear Pulse Tube Microcooler

Mass: Compressor=187gm, Cold Head Assembly=78gm, Complete System=265gms





CubeSat Dimensions (10cm X 10cm)



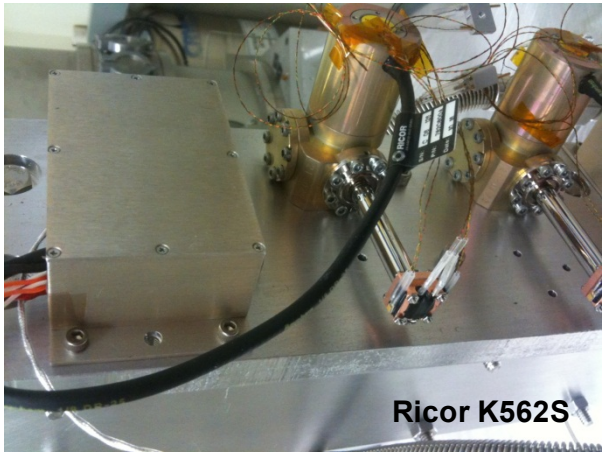
Initial developments by Lockheed Martin Space Systems, Advanced Technology Center (LMSS ATC) for tactical applications to cool M&FC Santa Barbara Focal Plane n-type-Barrier-n-type (nBn) IR sensors

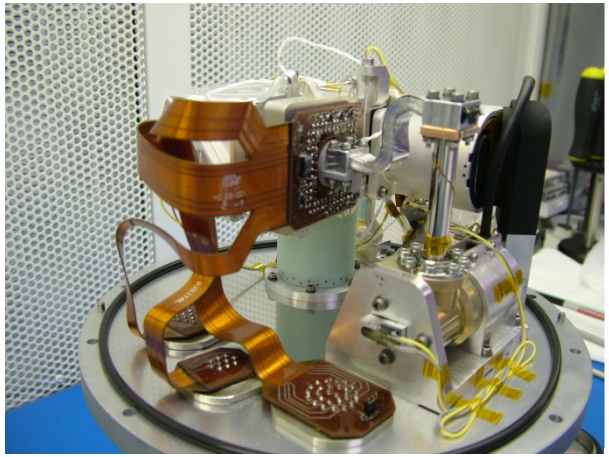
Predicted performance: 1.5W @ 150K with 6-10 Welec/Wref Specific Power

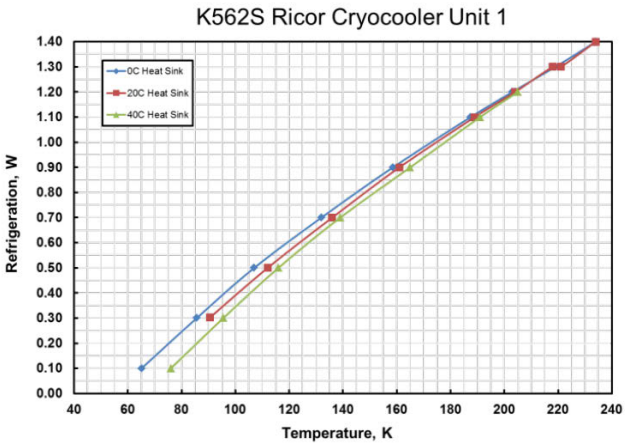
Primary features: Flexure bearing technology with no wear mechanisms to limit life or degrade performance (10 years), balanced compressor to minimize vibration

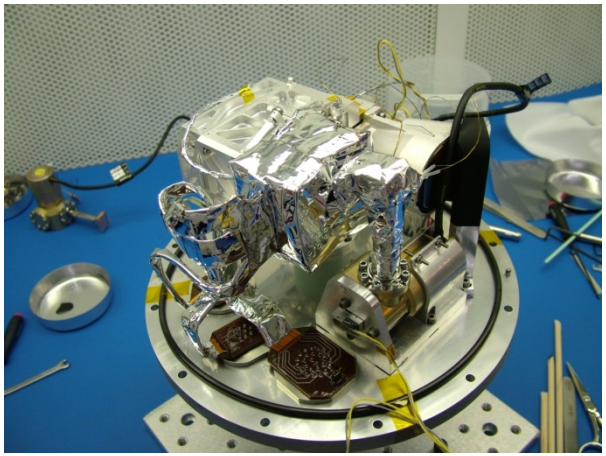
Status: Design complete for 150K operation, compressor motor built and tested, laboratory cold head tested

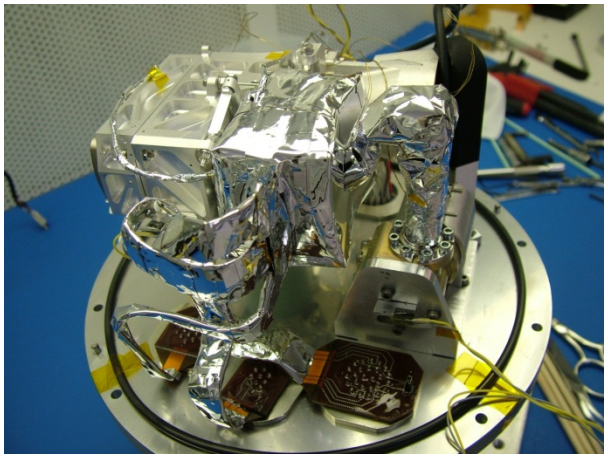
Rotorary Ricor Stirling Microcooler

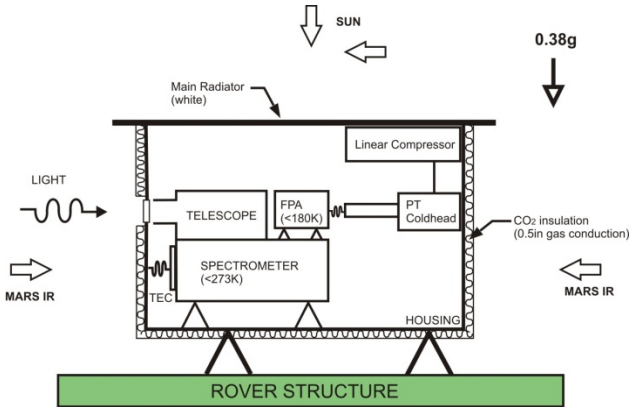




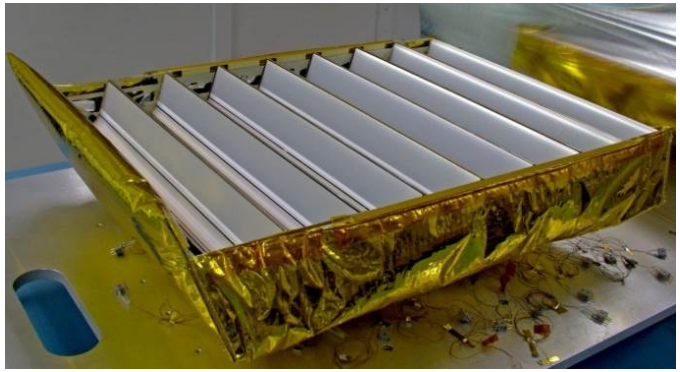


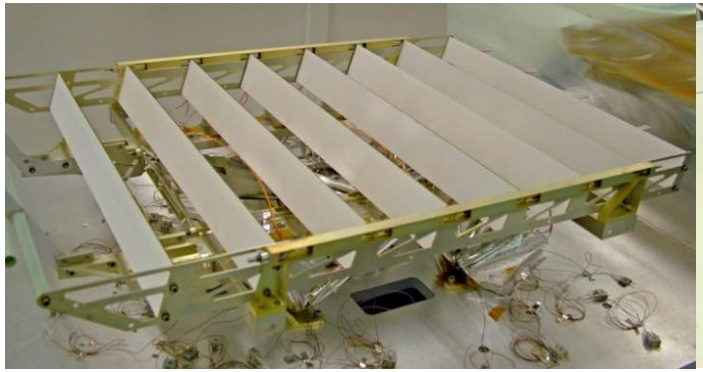


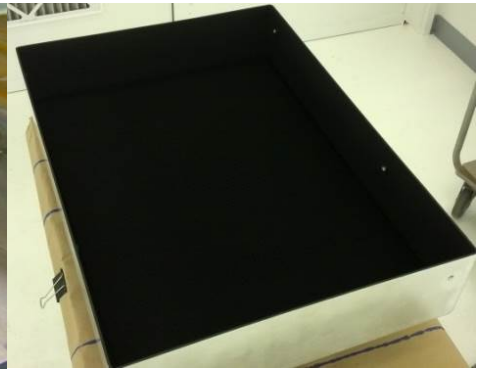


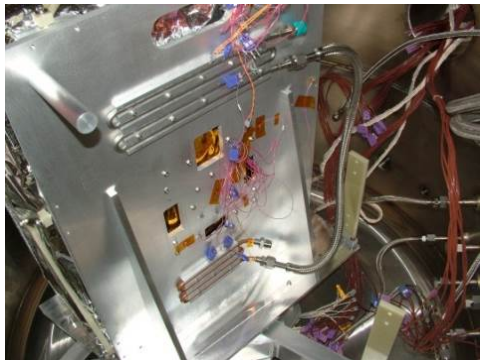


MATMOS Prototype Passive Cooler Development and Testing









Recent Long-life Space Cryocooler Flight Operating Experience as of June 2011

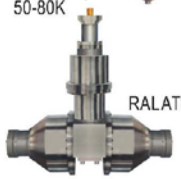
Cooler / Mission	Hours/Unit	Comments
Air Liquide Turbo Brayton (ISS MELFI 190K)	43,000	Turn on 7/06, Ongoing, No degradation
Ball Aerospace Stirling (60K HIRDLS)	60,000	Turn on 8/04, Ongoing, No degradation
Creare Turbo Brayton (77K NICMOS)	57,000	3/02 thru 10/09, Off, Coupling to Load failed
Fujitsu Stirling (ASTER 80K TIR system)	99,000	Turn on 3/00, Ongoing, No degradation
JPL Sorption (PLANCK 18K JT (Prime & Bkup))	7,300	Bkup on 8/10, Ongoing; Prm failed at 10,200 h
Mitsubishi Stirling (ASTER 77K SWIR system)	95,000	Turn on 3/00, Ongoing, Load off at 71,000 h
NGAS (TRW) Coolers		
CX (150K Mini PT (2 units))	119,000	Turn on 2/98, Ongoing, No degradation
HTSSE-2 (80K mini Stirling)	24,000	3/99 thru 3/02, Mission end, No degrad.
MTI (60K 6020 10cc PT)	99,000	Turn on 3/00, Ongoing, No degradation
Hyperion (110K Mini PT)	91,000	Turn on 12/00, Ongoing, No degradation
SABER (75K Mini PT)	87,000	Turn on 1/02, Ongoing, No degradation
AIRS (55K 10cc PT (2 units))	79,000	Turn on 6/02, Ongoing, No degradation
TES (60K 10cc PT (2 units))	60,000	Turn on 8/04, Ongoing, No degradation
JAMI (65K HEC PT (2 units))	52,000	Turn on 4/05, Ongoing, No degradation
GOSAT/IBUKI (60K HEC PT)	20,700	Turn on 2/09, Ongoing, No degradation
STSS (Mini PT (4 units))	10,200	Turn on 4/10, Ongoing, No degradation
Oxford/BAe/MMS/Astrium Stirling		
ISAMS (80 K Oxford)	15,800	10/91 thru 7/92, Instrument failed
HTSSE-2 (80K BAe)	24,000	3/99 thru 3/02, Mission end, No degrad.
MOPITT (50-80K BAe (2 units))	94,000	Turn on 3/00, one disp. failed at 10,300 h
ODIN (50-80K Astrium (1 unit))	90,000	Turn on 3/01, Ongoing, No degradation
AATSR on ERS-1 (50-80K Astrium (2 units))	81,300	Turn on 4/02, Ongoing, No degradation
MIPAS (50-80K Astrium (2 units))	81,300	Turn on 4/02, Ongoing, No degradation
INTEGRAL (50-80K Astrium (4 units))	76,200	Turn on 11/02, Ongoing, No degradation
Helios 2A (50-80K Astrium (2 units))	56,500	Turn on 1/05, Ongoing, No degradation
Helios 2B (50-80K Astrium (2 units))	12,000	Turn on 2/10, Ongoing, No degradation
Raytheon ISSC Stirling (STSS (2 units))	10,200	Turn on 4/10, Ongoing, No degradation
Rutherford Appleton Lab (RAL)		
ATSR 1 on ERS-1 (80K Integral Stirling)	75,300	7/91 thru 3/00, Satellite failed
ATSR 2 on ERS-2 (80K Integral Stirling)	112,000	4/95 thru 2/08, Instrument failed
Planck (4K JT)	17,800	Turn on 6/09, Ongoing, No degradation
Sumitomo Stirling Coolers		
Suzaku (100K 1-stg)	52,000	Turn on 7/05, Ongoing, No degradation
Akari (20K 2-stg (2 units))	35,000	Turn on 2/06, 2nd Degraded, 1st failed at 13,000 h
Kaguya GRS (70K 1-stg)	14,600	10/07- 6/09, Mission end, No degradation
JEM/SMILES on ISS (4.5K JT)	4,500	Turn on 10/09, Could not restart at 4,500 h
Sunpower Stirling (75K RHESSI)	82,000	Turn on 2/02, Ongoing, No degradation

Creare NICMOS

NGAS (TRW) Mini PT

NGAS (TRW) AIRS PT

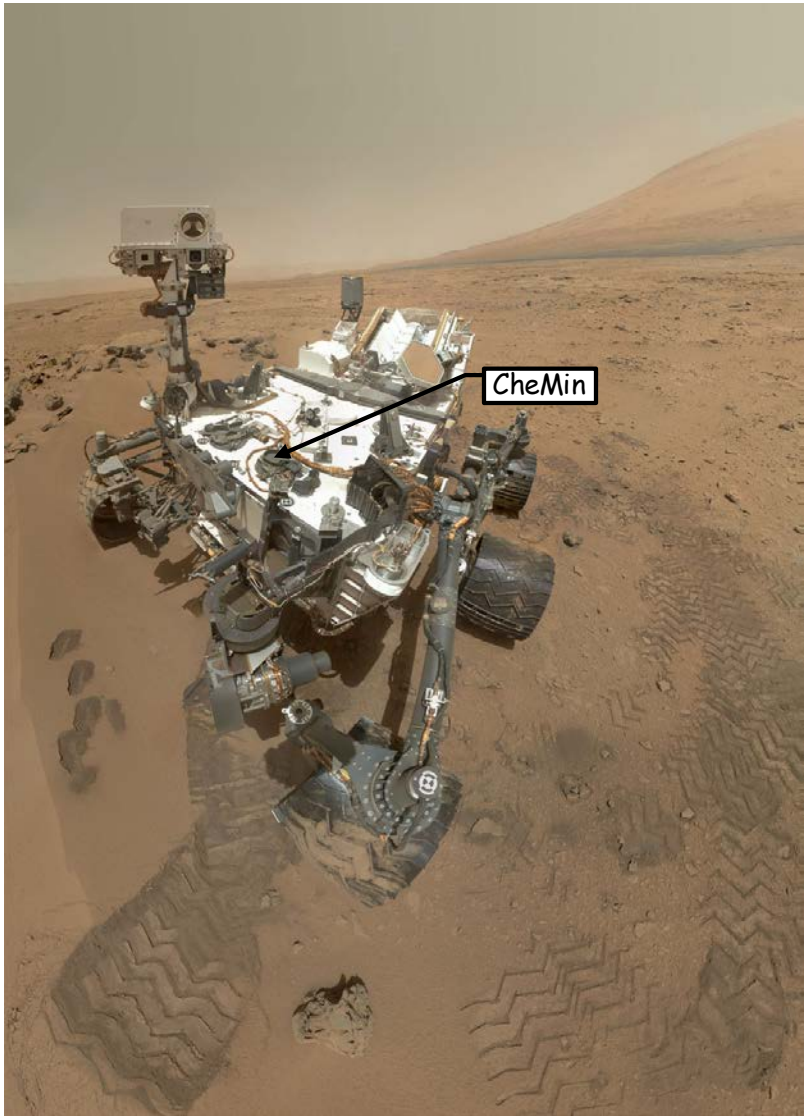
Astrium (BAe) 50-80K

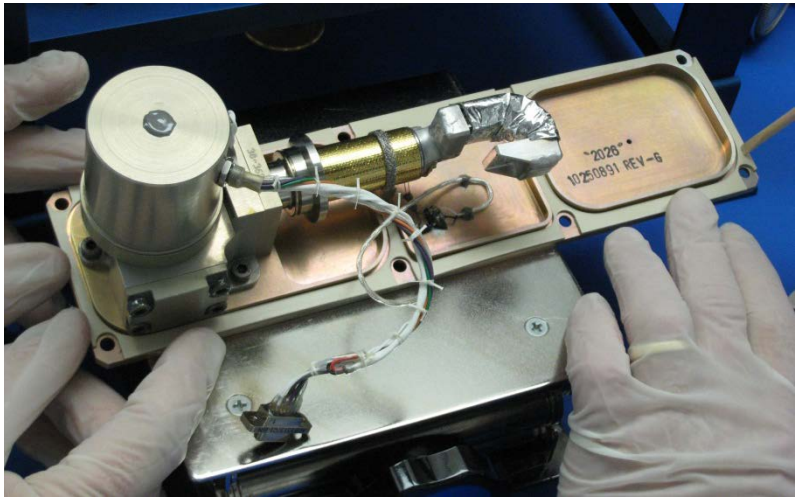

RALATSR

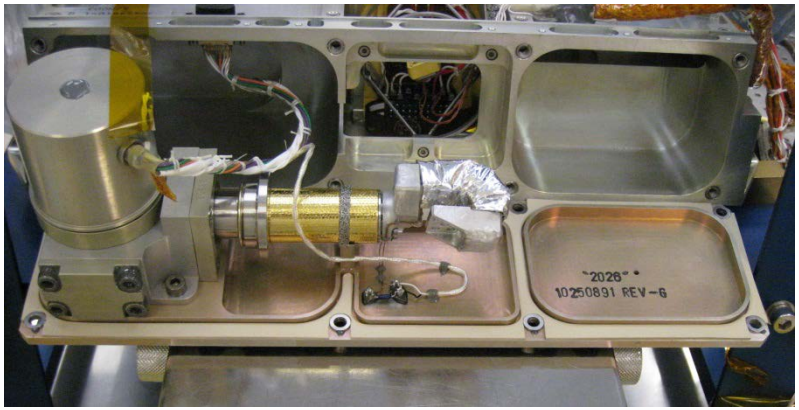
Sunpower

Ross 6/11

CheMin Mechanical Cooler (Ricor K508)

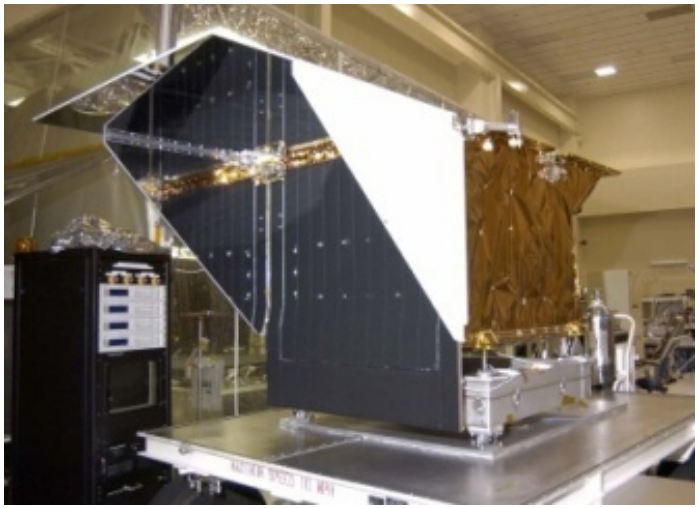


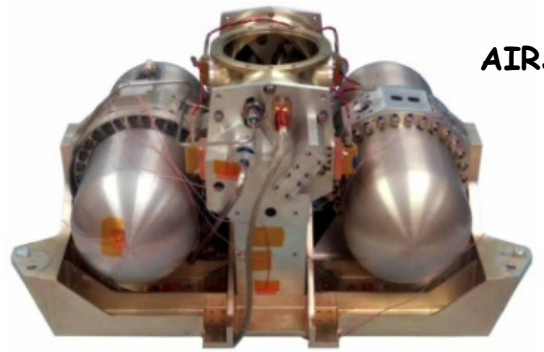




Chemistry and Mineralogy (CheMin): CheMin is a mineralogy instrument, onboard MSL, that will identify and quantify the minerals present in rocks and soil delivered to it by the Sample Acquisition, Sample Processing and Handling (SA/SPaH) system.
The Ricor K508 rotary cooler provides cooling to CCD at 200K with a lifetime requirement of 1100hrs for surface operations.

AIRS and TES Cryocoolers

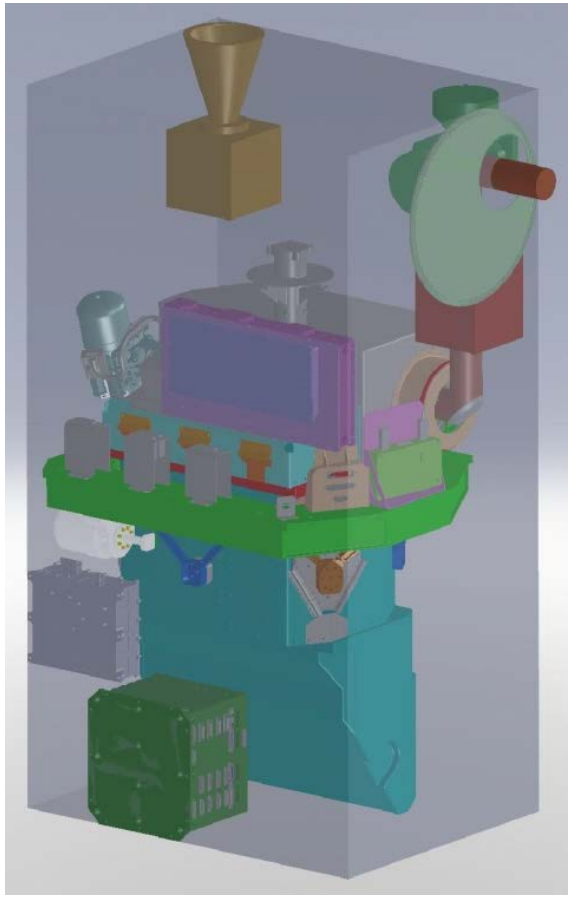




Performance:
The AIRS pulse tube coolers provide cooling to a focal plane at 55K and have been operating in space without degradation for over 10 years. The TES pulse tube coolers cool the focal planes to 65K and have been operating in space without degradation for over 8 years. This class of cooler technology has proven successful and has been operating flawlessly in space since launch.

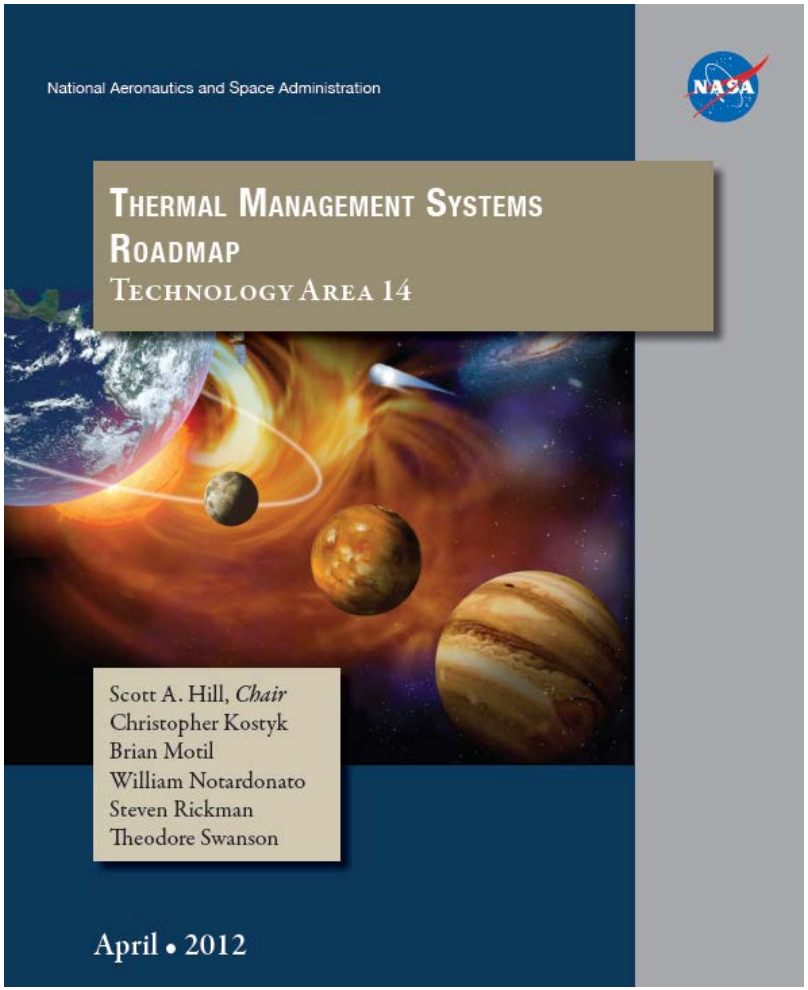
Future Cryogenic Instruments under Development

Commercial Humanitarian and Earth Science Spectrometer (CHESS), Instrument to Fly on the ISS Multiple User System for Earth Sensing (MUSES)



OCO-3, Instrument to Fly on the ISS Japanese Experiment Module (JEM)

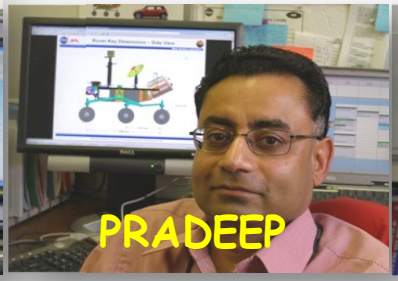
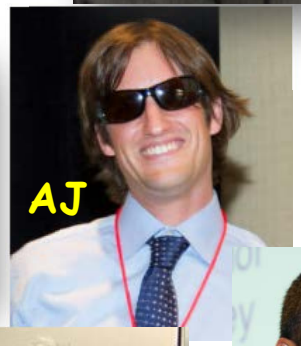
Alignment with NASA's technology roadmap



- JPL's technology roadmap is consistent and synergistic with the NASA Thermal Management Systems Roadmap

Technology	Motivation	Focus Areas	NASA Road-map x-ref	Who
1-φ MPFL	Flagship missions; In-house spacecraft; reference bus	• Long life pumps • Alternate working fluids and mat'l compatibility • Advanced HXs • Architecture & flow control	• TA-14.2.2 • TA-14.2.2 • TA-14.2.1 • TA-14.2.2	• Gaj Birur • Dave Bame • AJ Mastropietro • Pradeep Bhandari
Variable Heat Rej Radiators	Human exploration	• Digital radiator	• TA-14.2.3	• Gaj Birur/D. Berisford/J. Miller
2-φ MPFL	Instruments requiring temperature stability	• HX and subcooler design • Working fluids • Vapor tolerant pump (fault cond)	• TA-14.2.3 • TA-14.2.2 • TA-14.2.2	• Gaj Birur • Gani Ganapathi
Instrument Cryocoolers	Trend toward low-cost payloads	• Tactical coolers, pulse-tube	• TA-14.1.2	• Jose Rodriguez • Dean Johnson • Brian Carroll
Passive Coolers	Low-cost detector cooling	• Low profile, low cost coolers	• TA-14.1.1	• Jose Rodriguez
Temperature stability for remote sensing electronics	Active and passive microwave systems	• Loop heat pipes • Phase change systems	• TA-14.2.2 • TA-14.2.3	• Juan Cepeda-Rizo • Ruwan Somawardhana • Mike Pauken
Thermal control in extreme environments	Venus landers; Titan balloons	• Phase change systems • Advanced insulation • Balloon technology	• TA-14.2.3 • TA-14.2.2	• Mike Pauken • Jack Jones
Small spacecraft turn-down devices	Low power missions; Cubesats; Low cost landers	• Heat switches	• TA-14.2.2	• Ruwan Somawardhana
Enhancements to SOA	Benefit to all projects	• High temperature, flexible heaters • Solid-state thermostats	• TA-14.2.1	• Gordy Cucullu
Thermo-elastic stability for optical system WFE control	Active optics; low cost telescopes	• Primary mirror active thermal control • Advanced controllers		• Bob Krylo
Integrated modeling	Adaptive optics; low cost telescopes	• Multi-physics modeling		• Chuck Phillips • Mike Chainyk • Lee Peterson

Summary

- NASA's new emphasis on Human Exploration program for missions beyond LEO requires development of innovative & revolutionary technologies
- NASA's cost-cap missions are forcing instrument developers to re-evaluate existing technologies in an effort to reduce instrument costs
- Thermal control requirements of future NASA science instruments and missions are very challenging and require advances in existing technologies
- Limited resources requires organizations to cooperate & collaborate; government, industry, universities all need work together for the successful development of these technologies

JPL Advanced Thermal Technology Team