Science Instruments and Sensors Capability
Roadmap
NRC Dialogue

NASA Co-Chair: Rich Barney, NASA
External Co-Chair: Maria Zuber, MIT

March 16, 2005
<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Presenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>7:30</td>
<td>Continental Breakfast</td>
<td></td>
</tr>
<tr>
<td>8:00</td>
<td>Welcome and Review Process, Panel Chair &amp; NRC Staff</td>
<td></td>
</tr>
<tr>
<td>8:15</td>
<td>NASA Capability Roadmap Activity</td>
<td>Perry Bankston, NASA</td>
</tr>
<tr>
<td>8:30</td>
<td>12.0 Science Instruments &amp; Sensors Overview</td>
<td>Rich Barney, NASA</td>
</tr>
</tbody>
</table>

-Sub-Team Presentations-

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Presenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>9:15</td>
<td>12.1 Microwave Instruments &amp; Sensors</td>
<td>Chris Ruf, UMich</td>
</tr>
<tr>
<td>9:45</td>
<td>12.2 Multi-Spectral Imaging/Spectroscopy (vis-IR-FarIR)</td>
<td>Craig McCreight, NASA</td>
</tr>
</tbody>
</table>

- Break -

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Presenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:45</td>
<td>12.3 Multi-Spectral Sensing (UV-Gamma)</td>
<td>Brian Ramsey, NASA</td>
</tr>
<tr>
<td>11:15</td>
<td>12.4 Lasers/LIDAR Remote Sensing</td>
<td>Maria Zuber, MIT</td>
</tr>
</tbody>
</table>

- Lunch -

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Presenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:45</td>
<td>12.5 Direct Sensing of Particles, Fields &amp; Waves</td>
<td>Dick McEntire, APL</td>
</tr>
<tr>
<td>1:15</td>
<td>12.6 In-Situ Instrumentation</td>
<td>Tim Krabach, NASA</td>
</tr>
<tr>
<td>1:45</td>
<td>Co-Chair Summary</td>
<td>Maria Zuber, MIT</td>
</tr>
</tbody>
</table>

-Break-

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Presenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:30</td>
<td>Open Discussion</td>
<td>NRC Panel</td>
</tr>
</tbody>
</table>

-Adjourn-
Capability Roadmap Team

**Co-Chairs**
NASA: Richard Barney, NASA/Goddard Space Flight Center
NASA Deputy: Juan Rivera, NASA/Goddard Space Flight Center
External: Dr. Maria Zuber, Massachusetts Institute of Technology

**NASA**
Brian Ramsey, MSFC
Bruce Spiering, Stennis
Tim Krabach, JPL
Soren Madsen, JPL
Paul Mahaffy, GSFC
Azita Valinia, GSFC
Craig McCreight, ARC

**Industry**
David Chenette, Lockheed Martin
Ron Polidan, Northrop Grumman
Rich Dissly, Ball Aerospace

**Academia**
Chris Ruf, Univ. Michigan
Steve Ackerman, Univ. Wisconsin
Suzanne Staggs, Princeton

**Other/Independent**
Richard McEntire, JHU/APL
David Glackin, Aerospace
Shyam Bajpai, NOAA

**Ex-Officio**
Carl Stahle (GSFC-Nano CRM)
Louis Barbier (NASA-SEU Technologist)
Thomas Black (National Reconnaissance Office)
Amy Walton (Earth Science and Technology Office)

**Coordinators**
Directorate: Harley Thronson, SMD
APIO: Perry Bankston, JPL
The Science Instruments and Sensors roadmaps include capabilities associated with the collection, detection, conversion, and processing of scientific data required to answer compelling science questions driven by the Vision for Space Exploration and The New Age of Exploration (NASA’s Direction for 2005 & Beyond).

- Driving design reference missions
- Science measurement
- Capability/technology gaps
- A description of the developments (including alternate paths and options) required to advance a priority capability to spaceflight

Specific science instrument and sensor groups include the following:
- Microwave Instruments and Sensors
- Multi-Spectral Imaging / Spectroscopy (Vis-IR-FIR)
- Multi-Spectral Sensing (UV-Gamma)
- Laser / LIDAR Remote Sensing
- Direct Sensing of Particles, Fields, and Waves
- In Situ Instrumentation

The Science Instruments and Sensors roadmaps will not include:
- Instruments and sensors performing “engineering” functions
- Instrument accommodations on a variety of platforms (orbiting, landers, rovers, probes, aerial vehicles)
- Astronaut tools required to use instruments and sensors
- Large sets of systems and associated technologies necessary to collect, concentrate and combine electromagnetic bands ranging from gamma-rays to radio waves, and including gravity-waves
Compelling Science Questions

Answers to questions as old as human curiosity have always seemed beyond the reach of science. 
UNTIL NOW!

• Understand the fundamental physical processes of the space environment – from the Sun to Earth, to other planets, and beyond to the interstellar medium.
• Observe, understand, and model the Earth system to discover how it is changing and to understand the consequences for life on Earth.
• Define the origins and societal impacts of variability in the Sun-Earth connection.

• How did the solar system form?
• How does life begin?
• How can Humans explore Mars?

• How did the Universe begin?
• Does time have a beginning and an end?
• Where did we come from?
• Are we alone?
Top Level Assumptions

• Design reference missions and strategic science measurement needs must be driven by the Vision for Space Exploration and the New Age of Exploration (NASA’s Direction for 2005 and Beyond).
  – Supplemental information was obtained (and documented) from science working group interactions, presentations to the Strategic Roadmap Teams, and science/engineering technical presentations.

• Development of realistic Science Instrument and Sensor roadmaps is dependent upon many CRM team development activities. Dual membership occurs within the following CRM teams:
  – Advanced Telescopes and Observatories
  – In Situ Resource Utilization
  – Nanotechnology

• Roadmap Format:
  – Capability needs are shown in the timeline to be met 3-5 years before mission launch.
  – Missions timelines were provided by APIO/SMD via design reference missions or the strategic mission framework.
  – Missions listed with an * are not traceable to a currently defined design reference mission, however, the science measurement is dependent upon significant instrument and sensor capability development.
12. Capability Breakdown Structure

Science Instruments and Sensors
12.0

Co-Chair: Richard Barney, NASA/GSFC
Co-Chair: Maria Zuber, MIT
Deputy: Juan Rivera, NASA/GSFC

Microwave Instruments and Sensors
12.1
Chair: Soren Madsen, JPL
Co-Chair: Chris Ruf, UM

- 12.1.1 Radar Altimetry
- 12.1.2 Real Aperture Radar
- 12.1.3 Synthetic Aperture Radar
- 12.1.4 Interferometric SAR
- 12.1.5 Radar Subsurface Sounding

Multi-Spectral Imaging/Spectroscopy (vis-IR-FIR)
12.2
Chair: Craig McCort and ARC
Co-Chair: Ron Pollidan, NGST

- 12.2.1 Visible Imagers, Photometers, Radiometers, Sounders
- 12.2.2 Visible Imagers, Photometers, Radiometers, Sounders
- 12.2.3 Visible Spectral (visible-hyperspectral) Imagers
- 12.2.4 IR/FIR Imagers, Photometers, Radiometers, Sounders
- 12.2.5 IR/FIR Spectrometers/Interferometers
- 12.2.6 IR/FIR Spectral (visible-hyperspectral) Imagers

Multi-Spectral Sensing (UV-Gamma)
12.3
Chair: Brian Ramsey, MSFC
Co-Chair: David Chenette, LM

- 12.3.1 UV Imaging and Spectrometry
- 12.3.2 UV Interferometry
- 12.3.3 X-Ray Imaging and Spectrometry
- 12.3.4 X-Ray Timing and Polarimetry
- 12.3.5 X-Ray Interferometry
- 12.3.6 Gamma Ray Imaging and Spectrometry

Remote Sensing
12.4
Chair: Maria Zuber, MIT
Co-Chair: Richard Barney, GSFC

- 12.4.1 Allimeters
- 12.4.2 Transponders
- 12.4.3 X-Ray Imaging and Spectrometry
- 12.4.4 Spectrometers
- 12.4.5 Interferometers

Direct Sensing of Particles, Fields and Waves
12.5
Chair: Dick McEntire, APL
Co-Chair: Carl Stahle, GSFC

- 12.5.1 Energetic Particle and Plasma Imagers and Spectrometers
- 12.5.2 High Energy Particle Detector Systems
- 12.5.3 Magnetometers
- 12.5.4 Electric Fields and Wave Instruments
- 12.5.5 Gravitational Waves and Fields Instruments

In Situ Instrumentation
12.6
Chair: Tim Krabach, JPL
Co-Chair: Rich Dossy, BATC

- 12.6.1 Imaging/Microscopy
- 12.6.2 Mineralogical/Elemental Analysis
- 12.6.3 Chemical Detection and Identification
- 12.6.4 Isotope Analysis/ Age Dating
- 12.6.5 Biological Detection and Identification
- 12.6.6 Geophysical Measurements
- 12.6.7 Sample Handling and Preparation
- 12.6.8 In Situ Instrument Engineering
Science Instruments and Sensors is a broad and diverse roadmapping topic with significant science measurement application challenges.

- Previous instrument and sensor roadmapping efforts were limited to specific science measurement priorities (Earth Science, Universe, Solar System, etc.).
- Emphasis was placed on identifying instrument and sensor capabilities that would enable multiple design reference missions.

Extensive participation from past, present, and future Principal Investigators was encouraged at public meetings and workshops.

- Development of science instruments and sensors is a competed, peer reviewed process where lessons learned can influence future missions.
- Specific technology implementation strategies are the outcome of the proposal process and not the science instruments and sensors roadmap strategic planning activity.

Sub-Capability elements were prioritized by the degree of cross-cutting applicability to multiple design reference missions.

- Do they enable or enhance scientific discovery?
- Do they have broad application across instrument and sensor capabilities?
- Do they meet the needs of multiple design reference missions?
Roadmapping Process

Capability Roadmap Team Kickoff 9/28/04

Establish Team
* Collect team member recommendations from NASA, academia and industry

Preliminary Planning Activities
* Develop Capability Breakdown Structure, Roadmap Development Plan, Budget, and Schedule

Public Workshop 11/30/04
* 112 People Registered for the Science Instruments and Sensors Session
* 67 White Papers Submitted
* 23 Capability Presentations
* Follow-up Activity with Presenters

First Team Workshop @ JPL 12/8-9, 2004
* Review Planning Documents
* Capability Breakdown Structure
* Science and Technology Presentations
* Roadmap Development Process

Sub-Team Activities
* Define Capability Breakdown Structure: Level 2
* Develop Science Traceability Spreadsheets
* Review Strategic Reference Documents

GSFC Workshop Jan. 4-6, 2005
* Science Vision, Science Capability & Technology Presentations
* Science Traceability
* CRM Connection points

MIT Workshop Feb. 2-4, 2005
* Capability Breakdown Structure: Level 4
* NRC Presentation
* Review Science Traceability
* Identification of High Priority Capabilities

Deliver NRC Products 3/7/05
* HQ Team Dry Run (3/1/05)

NRC Dialogue 3/16/05
* A Clear Pathway to Capability Development?
* Technology Maturity Level?
* Metrics for measuring Technical Maturity Advancement?
* Connection Points to Other Roadmaps?

Develop First Draft of Roadmaps
* Capability Priorities
* Integration with Other Roadmaps
* SRM Interaction

Review SRM Draft Products 4/15/05

Final Workshop
* Strategic Roadmap Alignment
* Capability Roadmap Integration

NRC Summary Review

Final Product Delivery 6/05
• Science Instrument and Sensor capability needs can be traced directly back to the following top-level strategic documentation (detailed list is shown in backup charts):
  • The Vision for Space Exploration
  • The New Age of Exploration: NASA Strategic Objectives for 2005 and Beyond
  • A Journey to Inspire, Innovate, and Discover: President’s Commission Report
  • Our Changing Planet: The US Climate Change Science Program for Fiscal Years 2004 and 2005
  • Design Reference Missions
  • NASA Enterprise Strategies
  • National Research Council Reports

• A Science Traceability Database was developed to establish, track, and communicate linkages between compelling science questions, design reference missions, science instrument measurement needs, and critical instrument and sensor capabilities/technologies gaps.
  • NASA design reference missions, existing enterprise roadmaps, science measurement priorities, and science and engineering community input was collected, reviewed and documented.
  • Interim Earth, Planetary Science, Sun-Solar System and Astrophysics spreadsheets were presented to several Strategic Roadmap Teams for review.
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</thead>
<tbody>
<tr>
<td>8</td>
<td>16</td>
<td>Is there observational evidence supporting the hypothesis that the early universe underwent a period of rapid inflation?</td>
<td>Einstein Inflation Probe</td>
<td>2012-2020</td>
<td>Polarization structure of the cosmic microwave background</td>
<td>Map the polarization structure of the cosmic microwave background</td>
<td>Cosmic Microwave Background</td>
<td>Yes</td>
<td>15,16</td>
<td>12.1</td>
<td>Very large microwave arrays, 100 mK cryo-cooler, wide-band receiver</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>What are Dynamics of Sun's Magnetic Transition Region between Photosphere and Upper Chromosphere?</td>
<td>Magnetic Transition Region Probe (MTRAP)</td>
<td>2020</td>
<td>Velocity and Vector Magnetic Fields in Chromosphere/Corona</td>
<td>Doppler Imager/ Magnetograph</td>
<td>Sun</td>
<td>Yes</td>
<td>11</td>
<td>12.2</td>
<td>Large, lightweight UV reflective optics; Up to 16K x 16K CCDs with high QE at 150 nm and low power</td>
<td>S/C at GEO</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>How similar and different are fundamental auroral acceleration processes at Jupiter and the Earth?</td>
<td>Jupiter Polar Orbiter (JPO)</td>
<td>2009</td>
<td>Auroral imagery</td>
<td>Vis/UV auroral imager</td>
<td>Jupiter</td>
<td>Yes</td>
<td>11</td>
<td>12.3</td>
<td>TDI image synthesis &amp; relative motion compensation; synchronized shutter for imager radiation shielding</td>
<td>Polar orbit around Jupiter</td>
</tr>
<tr>
<td>9</td>
<td>2, 3</td>
<td>How can weather forecast duration and reliability be improved?</td>
<td>Global Tropospheric Winds</td>
<td>2013</td>
<td>Atmospheric wind profile</td>
<td>Coherent Doppler wind lidar</td>
<td>Earth's atmosphere</td>
<td>Yes</td>
<td>5</td>
<td>12.4</td>
<td>2 J/pulse laser with 12 Hz PRF and 3 year life; 0.75 m lightweight diffraction-limited optics; high precision optical alignment;</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>How Does the Magnetotail Control Energy Flow in the Magnetosphere, and What Processes Control Magnetotail Structure and Dynamics?</td>
<td>Magnetospheric Constellation (MC)</td>
<td>2021</td>
<td>Fields &amp; Particles</td>
<td>In Situ Instruments</td>
<td>Earth's Magnetosphere</td>
<td>Yes</td>
<td>11</td>
<td>12.5</td>
<td>Nanosatellites and miniaturized radiation-tolerant low mass/power instruments</td>
<td>50-100 Nanosats in Nested Orbits</td>
</tr>
<tr>
<td>2</td>
<td>7, 8</td>
<td>Characterize the geology and geophysics of the shallow Martian crust at one site, particularly as it relates to interpreting present habitability.</td>
<td>Mars Deep Drill</td>
<td>2018</td>
<td>Investigate the thermal characteristics of the Martian subsurface</td>
<td>Drill (10 m to 50 m)</td>
<td>Mars</td>
<td>Yes</td>
<td>7, 8</td>
<td>12.6</td>
<td></td>
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</table>

*DRM = Developmental Research Mission, CBS = Critical Technology Baseline Study.
Mission Drivers

- Lunar Recon. Orbiter
- Constellation-X
- Astrobiology Field Lab
- Uranus Orbiter with Probes
- Large-Aperture UV/Optical Observatory
- Neptune Orbiter
- TPF-C
- Jupiter Polar Orbiter w/ Probes
- Mars Sample Return
- GEO/MEO InSAR
- LISA
- SAFIR
- Planet Imager

Timeframe:
- 2010
- 2020
- 2030
Science Instruments and Sensors
Near Term Capability Roadmap

12.1 Microwave Instruments and Sensors
12.2 Multi-Spectral Imaging/Spectroscopy (Vis-IR-Far IR)
12.3 Multi-Spectral Sensing (UV-Gamma)
12.4 Laser / LIDAR Remote Sensing
12.5 Direct Sensing of Particles, Fields and Waves
12.6 In Situ Instrumentation

2005  2010  2015

Major Decision  Major Event / Accomplishment / Milestone  Enhancing/ Evolutionary  Ready to Use (TRL 6)  *=No DRM Reference
<table>
<thead>
<tr>
<th>Capability Roadmap</th>
<th>Flow</th>
<th>Connection Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. High-energy power and propulsion</td>
<td></td>
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<tr>
<td>2. In-space transportation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Advanced telescopes and observatories</td>
<td></td>
<td>Dr. Ron Polidan is a member of both CRM teams. Optics, Interferometry, Structures, and Active Cryogenic Systems.</td>
</tr>
<tr>
<td>4. Communication &amp; Navigation</td>
<td></td>
<td>Future optical and RF communication systems and sensor web navigation</td>
</tr>
<tr>
<td>5. Robotic access to planetary surfaces</td>
<td></td>
<td>Robotic access for remote sensing orbital reconnaissance, surface analysis, and sample return.</td>
</tr>
<tr>
<td>6. Human planetary landing systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Human health and support systems</td>
<td></td>
<td>Radiation detection and environmental monitoring technologies</td>
</tr>
<tr>
<td>8. Human exploration systems and mobility</td>
<td></td>
<td>Access to exploration targets, InSitu analysis, sample return, mobile sensor platforms, environmental sensing</td>
</tr>
<tr>
<td>9. Autonomous systems and robotics</td>
<td></td>
<td>Robotic Systems for surface exploration</td>
</tr>
<tr>
<td>10. Transformational spaceport/range technologies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. <em>In situ</em> resource utilization</td>
<td></td>
<td>Dr. Rich Dissly is an ex officio member of the ISRU team. Resource assessment and processing relationship</td>
</tr>
<tr>
<td>13. Advanced modeling, simulation, analysis</td>
<td></td>
<td>Systems architecture studies, applications for science discovery and analysis, and instrument design tradespaces.</td>
</tr>
<tr>
<td>14. Systems engineering cost/risk analysis</td>
<td></td>
<td>Requirements development, technical solution, process management, risk management</td>
</tr>
<tr>
<td>15. Nanotechnology</td>
<td></td>
<td>Dr. Carl Stahle is an ex officio member of the Nanotechnology team. Sensing and devices, mechanisms, electronics, modeling</td>
</tr>
</tbody>
</table>

**Connection Points: Capability Roadmaps**

- **No Relationship**
- **Critical Relationship (dependent (D), synergistic (S))**
- **Moderate Relationship (enhancing (EH), Limited Synergy (LS))**
<table>
<thead>
<tr>
<th>Strategic Roadmap</th>
<th>Connection Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Lunar: Robotic and Human Exploration</td>
<td>Minimal Design Reference Missions</td>
</tr>
<tr>
<td>2. Mars: Robotic and Human Exploration</td>
<td>Presented at Meeting #1 and MEPAG follow up. MEPAG reference missions provide strategic guidance.</td>
</tr>
<tr>
<td>3. Solar System Exploration</td>
<td>Design Reference Missions are defined and strategic guidance documentation has been reviewed.</td>
</tr>
<tr>
<td>4. Search for Earth-Like Planets</td>
<td>Presented at Meeting #1. Design Reference Missions are defined and strategic guidance documentation has been reviewed. (POC: Eric Smith)</td>
</tr>
<tr>
<td>6. International Space Station</td>
<td>No Relationship</td>
</tr>
<tr>
<td>7. Space Shuttle</td>
<td>No Relationship</td>
</tr>
<tr>
<td>8. Universe Exploration</td>
<td>Presented at Meeting #1. Design Reference Missions are defined and strategic guidance documentation has been reviewed. (POC: Kathy Flanagan)</td>
</tr>
<tr>
<td>9. Earth Science and Applications from Space</td>
<td>Design Reference Missions are defined and strategic guidance documentation has been reviewed. (POC: Azita Valinia)</td>
</tr>
<tr>
<td>10. Sun-Solar System Connection</td>
<td>Presented at Meeting #1. Design Reference Missions are defined and strategic guidance documentation has been reviewed.</td>
</tr>
<tr>
<td>11. Aeronautical Technologies</td>
<td>No Relationship</td>
</tr>
<tr>
<td>12. Education</td>
<td>No Relationship</td>
</tr>
<tr>
<td>13. Nuclear Systems</td>
<td>No Relationship</td>
</tr>
</tbody>
</table>

- **No Relationship**
- **Critical Relationship**
- **Moderate Relationship**
# Science Instruments and Sensors

## Capability Roadmap Team

### 12.1 Microwave Instruments and Sensors

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
<th>Primary Expertise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soren Madsen</td>
<td>NASA JPL (Co-Lead)</td>
<td>Radar</td>
</tr>
<tr>
<td>Chris Ruf</td>
<td>Univ. Michigan (Co-Lead)</td>
<td>Atmosphere &amp; Ocean Radiometry</td>
</tr>
<tr>
<td>Dave Glackin</td>
<td>Aerospace</td>
<td>Earth Remote Sensing Satellites</td>
</tr>
<tr>
<td>Suzanne Staggs</td>
<td>Princeton</td>
<td>Cosmic Microwave Background</td>
</tr>
<tr>
<td>Azita Valinia</td>
<td>NASA Goddard</td>
<td>Earth Science Technology</td>
</tr>
<tr>
<td>Juan Rivera</td>
<td>NASA Goddard</td>
<td>Instruments Design/Engineering</td>
</tr>
<tr>
<td>Shyam Bajpai</td>
<td>NOAA SIS</td>
<td>Operational Weather Satellites</td>
</tr>
</tbody>
</table>
12.1 Microwave Instruments and Sensors

Capability Description
• Active (Radar & GPS) and Passive (Radiometer) microwave remote sensing instruments operating in the electromagnetic spectrum at wavelengths from 10 km to 100 µm (at frequencies from 30 kHz to 3 THz, respectively)

Reference Documentation
• Astronomy & Astrophysics
  – Astronomy and Astrophysics in the New Millennium, 2001, NRC Report, Astronomy and Astrophysics Survey Committee
  – Connecting Quarks with the Cosmos, 11 Science Questions for the New Century, NRC Report
  – Beyond Einstein: From the Big Bang to Black Holes, 2003, Structure and Evolution of the Universe Roadmap Team

• Earth Science
  – Strategic Plan for US Climate Change Science Program, 2003
  – Earth Science Research Plan: 6 Jan 2005 Draft

• Planetary Science

• Sun-Solar System
  – Sun-Earth Connection Roadmap: 2003 - 2028
  – The Sun to the Earth - And Beyond: A Decadal Research Strategy in Solar and Space Physics
  – Earth-Sun System: Potential Roadmap and Mission Development Activities (Draft) 12/03
12.1 Microwave Instruments and Sensors

Capability Benefits

Astronomy and Astrophysics:
• What powered the big bang?
• How and when did galaxies first form?
• What are the properties of the earliest stars?

Planetary Science:
• How long did it take Jupiter to form, and how was the formation of the Uranus and Neptune different from that of Jupiter and Saturn?
• Confirm the presence of interior oceans on Europa, measure ice thickness, elucidate formation of surface features

Earth System Science:
• How does the cryosphere respond to and affect global environmental change?
• How do atmospheric trace constituents respond to and affect global environmental change?
• How are global precipitation, evaporation, and the cycling of water changing?
• How can weather forecast duration & reliability be improved?

Earth System Science, (continued)
• How are variations in local weather, precipitation and water resources related to global climate variation?
• How is the Earth's surface being transformed by naturally-occurring tectonic and climatic processes?
• How is the global ocean circulation varying on interannual, decadal, and longer time scales?
• What are the effect of clouds and surface hydrologic processes on Earth's climate?

Assumptions

Roadmapping Philosophy
– Highlight capabilities that enable the maximum number of science applications
– Capability roadmaps are developed at Level 3 (subsystems) to highlight cross-cutting between Level 2 (instrument type) areas

What isn’t covered
– Non-microwave electromagnetic science instruments
– Non science microwave (e.g. Entry, Descent & Landing navigation)
– In situ microwave science instruments & sensors
12.1 Microwave Instruments and Sensors

**History/Current Missions**

**Astronomy & Astrophysics:** WMAP, Herschel (aka FIRST), Planck, SOFIA (airborne)

**Planetary Science:** Pioneer, Apollo–17, Magellan, Cassini, MARSIS

**Earth System Science:** MSU, AMSU, MLS, MLS-2; SeaSat, DMSP, WindSat; SIR-A,B,C; SRTM; NScat, QuikScat; GeoSat, TOPEX, Jason; ESMR, TRMM

**Mission/Strategic Drivers**

**Astronomy & Astrophysics:** Einstein Inflation Probe, SAFIR

**Planetary Science:** Jupiter Polar Orbiter/Probes, Neptune Orbiter/Probes, Prometheus (JIMO a.o.)

**Earth System Science:** Ice Thickness, Global Tropospheric Aerosols, Global Soil Moisture, Ocean Surface Winds, GEO Global Precip, mmWave GEO Radar, Land deformation InSAR, Ocean Circulation and Eddies, Cloud System Structure, Land deformation repeat pass InSAR
## 12.1 Capability Need/Gap Assessment

<table>
<thead>
<tr>
<th>Sub Capability</th>
<th>Figures of Merit</th>
<th>Current Technology</th>
<th>Needed Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interferometric SAR</td>
<td>Temporal and Spatial Resolution, swath width</td>
<td>Moderate High efficiency L-band T/R modules, Moderate ~30m² antennas</td>
<td>Large (400–700m²), deployable antennas, High efficiency rad-hard T/R modules, Digital Beam Formation (DFB) Rad-hard processor</td>
</tr>
<tr>
<td>Millimeter Wave RAR, SAR, and Interferometry</td>
<td>Electronic Beam Steering, Phase stability, Transmitted power, Receiver noise figure.</td>
<td>Non-deployable antenna; mechanical beam steering, Discrete power amplifier (EIK)</td>
<td>Large deployable antenna, Electronic Beam Formation, High freq. T/R modules</td>
</tr>
<tr>
<td>Millimeter wave Polarimeter Arrays, Spectrometers &amp; Sounders</td>
<td>Noise limit, frequency resolution, bandwidth, number of pixels, degree of system integration; DC power requirement</td>
<td>non-Quantum limit cryo receiver; moderate power consumption; 10s of pixels; individual ass’y; moderate bandwidth digital autocorrelator</td>
<td>Quantum limit cryo receiver, 1000s pixels; highly integrated; wideband digital autocorrelator, Rad-hard processor, high efficiency Cryocooler</td>
</tr>
<tr>
<td>Passive Synthetic Aperture Microwave Imagers</td>
<td>Spatial resolution, swath width, number of frequency/polarization channels, DC power, noise limit</td>
<td>TRL 6 synthetic aperture aircraft demos; TRL 4 MMIC correlating receivers, TRL 4 ASIC correlators</td>
<td>Low power MMIC receiver, massively parallel digital correlator, Rad-hard processor</td>
</tr>
</tbody>
</table>
12.1 Microwave Instruments and Sensors (Active)  
Near Term Capability Roadmap

Driving Missions

Science Measurement

Microwave Electronically Scanned Arrays
- Precision Deployable Lightweight Structures
- Phased Array Radiators and Electronics
- Wavefront Sensing and Correction

Millimeterwave Electronically Scanned Arrays
- Large Deployable Reflectors
- ESA feed arrays
- Front end electronics (T/R-modules, MMIC etc.)

Power Amplifiers, high efficiency & power
Radiation Hardened Electronics

(2010) L-Band LEO InSAR
(2014) L-Band MEO InSAR
(2014) Land Surface Topography
(2015) LEO Wetland and River Monitor
(2017) Prometheus (e.g. JIMO)*
(2019) Ocean Structure and Circulation
(2020) LEO Cloud System Structure

Land Deformation
InSAR Land Topomapper
River stage Height & Discharge Rate; Water Storage in Wetlands
Planetary Topomapper (Ka-InSAR)
Ocean Circulation & Eddies
Cloud Cover & Layers; Cloud Microphysics; Precipitation

400m² Aperture, 30KW, 5-8 kg/m²
100m boom 1km²
K-band InSAR Altimeter

50m² Aperture, 5KW, 5-10 kg/m²
Metrology Comp.
Distributed or Sngl TX?

W-Band T/R
1W, 20% eff

Ku-, Ka-, and W-Band

W-Band T/R
10W, 45% eff

Ku-Band T/R
2-5W, 30% eff

Ka-Band T/R
5-10KW

FPGA-Based, 1 MRad

2005 2010 2015

Major Decision ▲ Major Event / Accomplishment / Milestone
Enhancing/ Evolutionary ▲ Ready to Use (TRL 6)
*=No DRM Reference
12.1 Microwave Instruments and Sensors (Active)

Far Term Capability Roadmap

Driving Missions

Science Measurement

Microwave Electronically Scanned Arrays
- Precision Deployable Lightweight Structures
- Phased Array Radiators and Electronics
- Wavefront Sensing and Correction

Millimeterwave Electronically Scanned Arrays
- Large Deployable Reflectors
- ESA feed arrays
- Front end electronics (T/R-modules, MMIC etc.)

Power Amplifiers, high efficiency & power
Radiation Hardened Electronics

(2021) GEO InSAR Constellation
Land Deformation Solid Earth

(2021) GEO Doppler Rain Profiler
Rainfall and Wind in Hurricanes (Ka-Band Radar)

(2030) GEO Seismology From Space*
Real Time Imaging of Seismic Wave Propagation

>700m², 2–3 kg/m²
Integrated, Distributed Electronics

Inflatable or Deployable?

10-30m
30-100m

MmWave Single-Chip L-Band T/R, 5W, 60% eff
GaN Ka-Band MMICs (PA, LNA)

Ka-Band ESA Feed Array

Ka-Band T/R High Power +Efficiency

>1MRad, ASIC

>1M Rad

2020
2025
2030

Major Decision
Major Event / Accomplishment / Milestone
Enhancing / Evolutionary
Ready to Use (TRL 6)
* = No DRM Reference
12.1 Microwave Instruments and Sensors (Passive)
Near Term Capability Roadmap

- Passive Antennas
  - Arrays
  - Deployable large apertures
- Integrated Receivers
  - MMIC Receivers
  - THz Receivers
- Digital Correlators & Spectrometers
  - Massively Parallel Correlators
  - Wide band/High Res Spectrometers
- Radiation-Hardened Processors
- Cryocoolers

**Passive Antennas**
- TRL5 for EIP
- TRL4 for GSM
- TRL5 for JPO
- TRL5 for EIP

**Integrated Receivers**
- TRL5 for GSM
- TRL5 for GTA
- TRL5 for JPO
- TRL5 for JPO

**Digital Correlators & Spectrometers**
- Tera-IPS
- TRL5 for JPO
- TRL5 for JPO
- TRL5 for JPO

**Cryocoolers**
- TRL5 for EIP

**2005 - 2010 - 2015**
- Major Decision
- Major Event / Accomplishment / Milestone
- Enhancing/Evolutionary
- Ready to Use (TRL 6)
- *=No DRM Reference

- (2014) Jupiter Polar Orbiter with Probes
- (2012) Einstein Inflation Probe
- (2014) Sea Ice Thickness*
- (2016) Global Aerosols
- (2017) Global Soil Moisture
- Origin of Universe (microwave)
- Cryo Global Change
- Atmos. Global Change
- Global Water Cycle Δ

- 2-10K; High Efficiency
- 1-2 GHz Coverage; 100s kHz Resolution
- 5-10K; High Efficiency

- 25m Deployable
- 1000 Polarmeters
- 30-110 GHz; ~Quantum Limit
- 2 THz Cryo Receivers
12.1 Microwave Instruments and Sensors (Passive)
Far Term Capability Roadmap

Science

Driving Missions

Passive Antennas
- Arrays
- Deployable large apertures
Integrated Receivers
- MMIC Receivers
- THz Receivers
Digital Correlators & Spectrometers
- Massively Parallel Correlators
- Wide band/High Res Spectrometers
Radiation-Hardened Processors
Cryocoolers

(2018) Ocean Surface Winds
(2018) SAFIR
(2018) Neptune Orbiter w/Probes
(2022) Mars Electrification Imager
(2027) GEO Global Precipitation; Hurricane Rain & Wind

Improve Weather Forecast
Origin of Universe (far IR)
Neptune Origin Imager & Composition
Map triboelectric charging of dust storms for Human/Lander safety & Martian methane chemistry
Global Water Cycle D; Extreme Weather Forecasting

Active/Passive?
Bolo/Hetero?
<1 μm Surface
10 kg/m²
Cooled <10K
25-520 μm;
2hv (quantum limit)
10a Tera-IPS
Q~10⁶ Spectral Resolution
4-10 K; Very High Efficiency

10/100 GHz Low Loss Thinned Array
10/100 GHz Ultra-Low Power
10s Tera-IPS with Ultra-Low Power
100s Tera-IPS

4x4 Pixel
600x, Deployable Sparse Array
60/183 GHz Ultra-Low Power

2015
2020
2025

Major Decision
Major Event / Accomplishment / Milestone
Enhancing/Evolutionary
Ready to Use (TRL 6)
*=No DRM Reference
## 12.1 Capability Maturity Assessment

<table>
<thead>
<tr>
<th>Sub Capability</th>
<th>Integrated Technologies</th>
<th>State-of-the-Art</th>
<th>Req Perf @TRL 6</th>
<th>Mission Driver</th>
<th>Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Microwave Interferometric SAR</strong></td>
<td>Lightweight L-band ESA</td>
<td>Rigid panels, 10-15 kg/m² Plus deployment structure</td>
<td>Lightweight manifold, Interconnects, signal distribution, integrated T/R modules. 2-3kg/m²</td>
<td>InSAR LEO/ MEO/ GEOSync</td>
<td>2007/ 2010/ 2017</td>
</tr>
<tr>
<td></td>
<td>Low cost, efficient L-band T/R modules</td>
<td>10-30W, 40% eff, 4-5 chip MCM, $1K/module, Tx/Rx only</td>
<td>Single chip T/R (GaAs, SiGe, or CMOS), Rad Hard, Aperture Integrated, 60% eff, $100/mod</td>
<td>InSAR (see above)</td>
<td>2010/ 2017</td>
</tr>
<tr>
<td></td>
<td>Efficient MMIC T/R Modules</td>
<td>Exist up to X-band 10W, 30% efficiency</td>
<td>10W @ Ku-band, 40% eff, Phase stable</td>
<td>Ocean Structure Cloud Structure</td>
<td>2015</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5W @ Ka-band, 30% eff, Phase stable</td>
<td>LEO Wetland… Cloud; Topo</td>
<td>2010/11/15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1W @ W-band, 20% eff, 4dB NF</td>
<td>Cloud System Structure</td>
<td>2015</td>
</tr>
<tr>
<td></td>
<td>MMW Electronically Scanned Array (ESA)</td>
<td>Exist up to X-band, 5-10KW ESA, 10-15kg/m²</td>
<td>Ku-band ESA, 5KW</td>
<td>Cloud Structure</td>
<td>2015</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ka-band ESA, 1KW</td>
<td>LEO Wetland</td>
<td>2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W-band ESA, 500W</td>
<td>Cloud Structure</td>
<td>2015</td>
</tr>
</tbody>
</table>
## 12.1 Capability Maturity Assessment

<table>
<thead>
<tr>
<th>Sub Capability</th>
<th>Integrated Technologies</th>
<th>State -of-the-Art</th>
<th>Req Perf @TRL 6</th>
<th>Mission Driver</th>
<th>Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Millimeter wave Polarimeter Arrays, Spectrometer s &amp; Sounders</strong></td>
<td>THz Receiver s</td>
<td>currently ~100 element array @ 110 GHz; 2 THz but not cryo</td>
<td>~1000 element @ 110 GHz</td>
<td>Einstein Inflation Probe</td>
<td>2009</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Individual elements @ 2 THz (cryo but not quantum limit)</td>
<td>Global Trop Aerosols</td>
</tr>
<tr>
<td></td>
<td>Wide band / High res spectrometers</td>
<td></td>
<td></td>
<td>3 THz, cryo, quantum limit</td>
<td>SAFIR</td>
</tr>
<tr>
<td><strong>Passive Synthetic Aperture Microwave Imager s</strong></td>
<td>MMIC Receiver s</td>
<td>500 mW @ &lt; 60 GHz</td>
<td>500 mW @ &lt; 37 GHz</td>
<td>Sea Ice Thickness</td>
<td>2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>250 mW @ &lt; 37 GHz</td>
<td>Ocean Sfc Winds</td>
<td>2015</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100 mW @ &lt; 90 GHz</td>
<td>Neptune Orbiter</td>
<td>2015</td>
</tr>
<tr>
<td></td>
<td>Massively Parallel correlator s</td>
<td></td>
<td>1 TIPS @ TRL 6</td>
<td>S. I. T.</td>
<td>2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 Tera instruction per second (TIPS)</td>
<td>10 TIPS</td>
<td>O. S. W.</td>
<td>2015</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10 TIPS Hi Rad Environment</td>
<td>N. O.</td>
<td>2015</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100 TIPS</td>
<td>G. G. P.</td>
<td>2018</td>
</tr>
</tbody>
</table>
Other Key Technologies

Technology elements were prioritized by the degree of cross-cutting applicability to multiple DRMs. Following are elements critical (i.e. enabling) to certain DRMs but not sufficiently cross-cutting to be assigned a high priority.

- Global Soil Moisture Mission
  - Precision deployable/inflatable structures (other than reflectors)
  - Control of Spinning apertures (balancing)

- Solar Radio Bursts & Termination Shock
  - Large Data Storage

- Next Generation Geodetic Networks/Observatory
  - Next Generation GPS/GNSS receivers

Capability Dependencies

- Cross-cutting between Microwave and other groups’ DRMs
  - Rad-hard processors
  - Cryo-coolers

- Cross-cutting between Microwave DRMs
  - MMIC RF Technology
  - Large scale ASIC digital signal processing
  - Rad-hard processors

- Cross-cutting between major science themes
  - Earth Science missions serve as capability test beds for other missions
    - Nimbus NEMS&SCAMS => TIROS MSU => DMSP SSM/T
    - SeaSat SAR => Magellan SAR
    - Jason MMICs => JUNO Water/Ammonia Radiometer
    - MLS receivers & spectrometers => Jupiter & Neptune Orbiters

• Microwave Science instruments have historically led to breakthrough science, enabled operational measurement capabilities and provided technology for critical exploration initiatives.
### Science Instruments and Sensors Capability Roadmap Team

**12.2 Multi-Spectral Imaging/Spectroscopy (Vis-IR-FIR)**

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
<th>Primary Expertise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Craig McCreight</td>
<td>NASA Ames (co-lead)</td>
<td>IR detectors for astronomy</td>
</tr>
<tr>
<td>Ron Polidan</td>
<td>Northrop Grumman (co-lead)</td>
<td>UV-visual-IR sensors, instrum systems</td>
</tr>
<tr>
<td>Bruce Spiering</td>
<td>NASA Stennis</td>
<td>Vis-IR remote sensing instrum’n / oceans</td>
</tr>
<tr>
<td>Steve Ackerman</td>
<td>U. Wisconsin</td>
<td>Meterology, cloud science, aerosols</td>
</tr>
<tr>
<td>Rich Dissly</td>
<td>Ball Aerospace</td>
<td>In situ, &amp; atmospheric applications</td>
</tr>
<tr>
<td>Tim Krabach</td>
<td>NASA-JPL</td>
<td>LWIR to FIR detectors</td>
</tr>
</tbody>
</table>
12.2 Multispectral Imaging/Spectroscopy (vis-IR-FIR)

Capability Description

• Instrument-level, & component, needs for advanced imaging & spectroscopy in the visible and infrared regions, extending from 0.4 - 1000+ µm. Consideration includes key support technologies, e.g., cryogenics for IR.

Reference Documentation (partial)

• Astronomy & Astrophysics
  – Astronomy and Astrophysics in the New Millennium, 2004, NRC Astronomy and Astrophysics Survey Committee (Note that this is a National Academy study rather than a specific NASA roadmap)
  – Beyond Einstein: From the Big Bang to Black Holes, 2003, Structure and Evolution of the Universe Roadmap Team

• Earth Science
  – Strategic Plan for US Climate Change Science Program, 2003
  – Earth Science Research Plan: 6 Jan 2005 Draft

• Planetary Science

• Sun-Solar System
  – Sun-Earth Connection Roadmap: 2003 - 2028
  – The Sun to the Earth - And Beyond: A Decadal Research Strategy in Solar and Space Physics
12.2 Multi-Spectral Imaging/Spectroscopy (Vis-IR-FIR)

**Capability Benefits**

**Earth Science:**
- How do trace atmospheric constituents affect global climate change?
- How is climate change affected by trends in solar irradiation?
- How can weather forecasting be improved and made more reliable?

**Planetary Science:**
- What processes marked the initial stages of planet & satellite formation?
- Which processes produce & maintain habitable zones within the solar system?
- How long did it take for Jupiter to form, & how did its formation differ from that of the other gas giant planets?

**Sun-Solar Studies:**
- What are the dynamics of the sun’s transition region?
- What are the similarities between auroral acceleration processes of different planets?

**(Universe & Earth-like planet search):**
- Is there evidence of life in other planetary systems?
- How are planetary systems formed, & what are their properties?
- Did the early universe undergo a process of rapid expansion?

**Sub-Team Assumptions**

- Vis-IR near-field sensing, or measurements within planetary atmospheres, covered by *in situ*
- Important overlaps with telescope technology team (long-baseline systems) in developing advanced interferometers
- Agency will support necessary infrastructure (fabrication, testing, expertise)
12.2 Multi-Spectral Imaging/Spectroscopy (Vis-IR-FIR)

**History/Current Missions**

**Earth Science:** LandSat, Ikonos, Quickbird 2, MODIS (Terra, Aqua), AIRS (Aqua)

**Planetary:** THEMIS, VIMS (Cassini), HiRISE & CRISM (Mars Recon Orbiter), TES (Mars Global Surveyor)

**Sun-Solar:** LASCO, MDI-SDI (SOHO), SOT (Solar-B), SECCHI/STEREO

**Astronomy:** IRAC, IRS, MIPS (Spitzer), ACS (HST), NIRCam, NIRSpec, MIRI (JWST)

**Mission/Strategic Drivers**

**Earth Science:** Black Carbon, Total Column Ozone, GEO Coastal Carbon, L2 Earth Atmosphere Solar Interferometer, LEO Cloud Particle Structure, GEO Lightning Imager

**Planetary Science:** Jupiter Polar Orbiter/Probes, Europa Geophysical Explorer, Neptune Orbiter/Probes

**Sun-Solar:** MTRAP, Jupiter Polar Orbiter/Probes

**Universe+Earth-like Planets:** TPF-C, TPF-I, Einstein Inflation Probe, JDEM, Lg Ap. UVO Observ, SAFIR, Life Finder, Planet Imager/Mapper
## 12.2 Capability Need/Gap Assessment

<table>
<thead>
<tr>
<th>Sub Capability</th>
<th>Figures of Merit</th>
<th>Current Technology</th>
<th>Needed Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible Detector Arrays</td>
<td>Pixel Count, Uniformity, Quantum Efficiency, Noise, Crosstalk</td>
<td>≤1 k x 2 k format, Radiation degradation, Transition (CCD &lt;-&gt; CMOS), Few, changeable foundaries</td>
<td>&gt;2 k x 2 k format; mosaics, Radiation tolerance, Stable fabrication, infrastructure</td>
</tr>
<tr>
<td>IR Detector Arrays</td>
<td>Pixel Count, Noise, Power Dissipation, Temperature, Frame Time, and ability to sync to scene</td>
<td>~1E4 pxls for some applications, ~1E6 pxls for astrophysics, limited mosaics, Low-T’s required, Irregular effects</td>
<td>Large formats for all applications, mosaics, Higher T arrays proven, Wider spectral response, Linear, fast response, High-throughput fab &amp; testing</td>
</tr>
<tr>
<td>Far-IR Detector Arrays</td>
<td>Pixel Count, Uniformity, Quantum Efficiency, Noise, Crosstalk</td>
<td>Parallel investigations of best detection approaches, Early development of readout /mux approaches, Limited system demonstrations</td>
<td>Mature 1E4 pxl background-limited arrays, Demonstration of polarization, &amp; 0.1-0.3 K cryogenics, High-T FIR broadband detectors, Stable fab &amp; testing</td>
</tr>
<tr>
<td>≥6 K Cryocoolers for Space</td>
<td>Cooling Power, Ultimate temperature, Thermodynamic Efficiency, Lifetime, Vibration</td>
<td>Limited flight experience, Sig. reluctance to adopt in projects, Life tests in lab-preliminary but encouraging</td>
<td>Flight experience, No reluctance to adopt in projects, Long-life proven in lab (unattended)</td>
</tr>
<tr>
<td>Sub-kelvin coolers</td>
<td>Cooling Power, Ultimate temperature, Thermodynamic Efficiency, Lifetime</td>
<td>Few systems developed &amp; qual’d for flight, Alternate systems under investigation</td>
<td>Mature, high-efficiency systems for zero-g, Proven when staged to adv., 6 K coolers</td>
</tr>
<tr>
<td>Instrument Optics</td>
<td>Transmissivity, Spectral resolution, Element diameter and uniformity, Survives thermal cycling</td>
<td>Moderate size filters, Moderate capability dispersive instruments, Emerging active masks</td>
<td>Large, high-τ filters, Large, powerful dispersive instruments, Proven masks, &amp; other techniques</td>
</tr>
</tbody>
</table>
12.2 Multi-Spectral Imaging/Spectroscopy (Vis-IR-FIR)

Far Term Capability Road

Driving Missions

Science Measurement

Detector Arrays and Readouts

- Vis Arrays
- Vis & SWIR FPAs
- 3-30 μm Spect’r I
- High-Speed Mpxl FPA

Cryo Coolers

- ≥6 K
- ≤2 K

Instrument Optics, Filters

- Light Optics
- Light, Low- Scatter Optics
- High Thruput Stable Optics
- Wide Angle FOV, Narrow Band Filters at H-alpha
- Stable, High- Contrast FPA

(2020) Lg Ap. UV Optl Observ’y
(2024) LEO Cloud Particle Structure
(2025) Life Finder
(2027) GEO Lightning Imager
(2035) Planet Imager

Dist’n of Elements, Lg Scale Structure
Know Climate Effects of Cloud, Surface Processes
Xsolar Planet: Find Cond’n’s for Life
Improved Weather Forecast Duration, Reliability, Models
Image xsolar planet; Detect atmosphere, continents, ice.

Solar: Dynamics of Mag Trans’n Region
Hi Sens Vis & SWIR FPAs
3-30 μm Spect’r FPA
High-Speed Mpxl FPA
Stable, High- Contrast FPA

High Effic’y Active Coolers
Ultra-Stable Optics

2020  2025  2030

Major Decision  Major Event / Accomplishment / Milestone  Enhancing/ Evolutionary  Ready to Use (TRL 6)  *No DRM Reference
### 12.2 Capability Maturity Assessment

<table>
<thead>
<tr>
<th>Sub Capability</th>
<th>Integrated Technologies</th>
<th>State-of-the-Art</th>
<th>Required Performance (@TRL 6)</th>
<th>Mission Driver</th>
<th>Need Date (@TRL 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible Photometer / Camera</td>
<td>Visible focal plane, readout electronics, imaging optics</td>
<td>2 k x 4 k pixel CCD. Two-chip FPA. Conventional drive electronics. ~5 e⁻ noise</td>
<td>~5E8 BLIP CCD pxls at 140 K. ASIC. 4 e⁻ noise</td>
<td>JDEM</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>High contrast FPA w/ coronograph</td>
<td>TPF-C</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~1E8 pxl vis array mosaic, photon counting</td>
<td>Lg UVO Obs</td>
<td>2016</td>
</tr>
<tr>
<td>IR Photometer / Sounder / Camera</td>
<td>IR focal plane, adv readout, adv optics, cryocooler</td>
<td>2 k x 2 k pixel near-IR array. Lab cryocooler.</td>
<td>~2E8 BLIP NIR pxs at 140 K (4 e⁻ noise) +ASIC</td>
<td>JDEM</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~1E6 room temp array, 0.02 K NEΔT</td>
<td>Neptune Pol Orbiter</td>
<td>2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td>320 x 240 µbolo array (THEMIS). 0.04 K NEΔT</td>
<td>3-17 µm BLIP arrays</td>
<td>Total Col O₃</td>
<td>2014</td>
</tr>
<tr>
<td>Far IR Imaging Instrument</td>
<td>FIR bolometer array with readout, 6 K cooler, sub-K cooler</td>
<td>~400 element arrays; ~1E-18 W/√Hz. Unproven muxing. Lab cryocoolers</td>
<td>1E3 pxl BLIP array with polarization sensitivity</td>
<td>Einstein Infl Probe</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1E4 pxl BLIP array; NEP 1E-18 W/√Hz</td>
<td>SAFIR</td>
<td>2014</td>
</tr>
<tr>
<td>Adv Vis and IR Spectrometers</td>
<td>Focal planes, readouts, dispersive optics &amp; mech’sms</td>
<td>Small-scale instruments f space, &lt;Mpxl arrays. Ground-based interferometers.</td>
<td>IR Imaging FTS configuration. ~1E6 pxls</td>
<td>Neptune Pol Orbiter</td>
<td>2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8 m boom, 0.1 µm path stab’y</td>
<td>L2 Interf’r</td>
<td>2015</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1E3 pxl BLIP array; NEP 1E-20 W/√Hz</td>
<td>SAFIR</td>
<td>2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hi-thruput filter at 10 µm; high contrast FPA High-stability demo</td>
<td>TPF-I</td>
<td>2016</td>
</tr>
</tbody>
</table>
12.2 Multi-Spectral Imaging/Spectroscopy (Vis-IR-FIR)

Other Key Technologies
- Intra-instrument calibration sources
- Imaging optics
- Data processing & compression systems (real-time feature extraction, etc.)
- Mechanisms

Connection Points to Other Roadmaps
- *In situ*
- UV-gamma sensing
- Microwave (sub-mm astrophysics)
- Telescopes
- Nanotechnology
- Infrastructure (fabrication, test, expertise)

- **Sustained development of larger-format, higher-sensitivity focal plane arrays is key to meeting future instrument needs, across the spectrum.**
- **Important component (e.g., optics) and support (e.g., cryogenics) technologies are also critical, & they need to be proven at the instrument-system level.**
Science Instruments and Sensors
Capability Roadmap Team

12.3 Multi-spectral Sensing, UV – Gamma

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
<th>Primary Expertise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-Lead Brian Ramsey</td>
<td>NASA MSFC</td>
<td>X-Gamma Instrumentation</td>
</tr>
<tr>
<td>Co-Lead David Chenette</td>
<td>Lockheed Martin</td>
<td>Space Radiation Measurements</td>
</tr>
<tr>
<td>Ron Polidan</td>
<td>Northrop Grumman</td>
<td>UV Instrument Systems</td>
</tr>
<tr>
<td>Juan Rivera</td>
<td>NASA GSFC</td>
<td>Instruments Design/Engineering</td>
</tr>
<tr>
<td>Azita Valinia</td>
<td>NASA GSFC</td>
<td>Earth Science Technology</td>
</tr>
</tbody>
</table>
12.3 Multi-spectral Sensing, UV – Gamma

**Capability Description**

- This contains all the capability requirements to enable remote sensing and scientific investigations (Imaging, Spectrometry, Polarimetry, Timing, and Interferometry) for the UV to gamma ray wavelength range (\(< 0.4 \) m).

**Reference Documentation**

- **Astronomy & Astrophysics**
  - Astronomy and Astrophysics in the New Millennium, 2004, NRC Astronomy and Astrophysics Survey Committee (Note that this is a National Academy study rather than a specific NASA roadmap).
  - Beyond Einstein: From the Big Bang to Black Holes, 2003, Structure and Evolution of the Universe Roadmap Team.

- **Earth Science**

- **Planetary Science**

- **Sun-Solar System**
  - The Sun to the Earth - And Beyond: A Decadal Research Strategy in Solar and Space Physics.
12.3 Multi-spectral Sensing, UV – Gamma

**Capability Benefits**

**Universe & Earth-like planet search:**
- Determine origin of stars, planets, life
- Determine origin of elements
- Probe early universe
- Map distribution of dark matter
- Perform black hole census
- Probe formation and evolution of black holes
- Probe space and time around black hole

**Sun-Solar Studies:**
- Measure and understand the magnetic transition region
- Determine the dynamics of the sun’s transition region
- Determine solar reconnection mechanisms
- Probe structure of region between heliosphere and local galactic environment

**Sub-Team Assumptions**

- Light-weight, high-resolution, grazing & normal incidence and diffractive optics, plus coatings, are covered by Advanced Telescopes and Observatories (CRM #4)

- Formation flying capabilities and necessary metrology are covered by CRM #4

- Cooling of large structures (including large-area detectors) and general thermal control covered elsewhere

- Adequate provisions made at the appropriate time for calibration and testing

- Advanced data handling capabilities are available when needed (high-speed telemetry, data compression, etc)
12.3 Multi-spectral Sensing, UV – Gamma

History/Current Missions

– **Sun-Solar:**
  - SOHO (1995)
  - IMAGE (2000)
  - RHESSI (2002)
  - STEREO (2006)

– **Universe & Origins:**
  - EUVE (1992)
  - HST (1990)
  - FUSE (1999)
  - Uhuru (1970)
  - Einstein (1978)
  - Chandra (1999)
  - Compton GRO (1991)
  - GLAST (2007/8)

Mission/Strategic Drivers

– **Sun-Solar:**
  - MTRAP (2020)
  - RAM (2032)
  - SCOPE (2033)

– **Universe+Earth-like Planets:**
  - Constellation-X (2014)
  - Black Hole Finder Probe (2018)
  - Large UV Observatory (2020)
  - Black Hole Imager (2025)
  - Advanced Compton Telescope (2026)
  - Gen-X (2027)
  - Stellar Imager (2034)
### 12.3 Capability Need/Gap Assessment

<table>
<thead>
<tr>
<th>Sub Capability</th>
<th>Figures of Merit</th>
<th>Current Technology</th>
<th>Needed Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV Imaging and Spectrometry</td>
<td>Large-format focal plane detectors: Microchannel plate performance</td>
<td>Limited by quantum efficiency and overall number of pixels</td>
<td>Factor of 10 increase in pixel number and factor of 2-5 increase in quantum efficiency</td>
</tr>
<tr>
<td>UV &amp; X-ray Imaging and Spectrometry</td>
<td>Large-format focal plane detectors: CCD and active pixel sensor performance</td>
<td>Megapixel CCDs with moderate power requirements, moderate readout speeds, and limited UV and X-ray response</td>
<td>Larger CCDs with two orders of magnitude less power (possible change of technology to active pixel sensors), faster readout rate, and extended UV (&lt; 200 nm) and x-ray (&gt; 6 keV) response</td>
</tr>
<tr>
<td>X-Ray Imaging and Spectrometry</td>
<td>High-energy-resolution pixelated detector performance</td>
<td>Limited energy resolution, pixel array sizes and count rate capability</td>
<td>Factor of 2 and 4 (near and far term) improvement in energy resolution, 30 and 3.10^5 (near and far term) increase in pixel number and factor of ten increase in rate capability</td>
</tr>
<tr>
<td>Cryogenic cooler performance</td>
<td>Limited lifetime (laboratory prototype) continuous (50mk) coolers Cryocoolers requiring too much power and weight.</td>
<td>Long-lifetime (7 year) systems</td>
<td>Reduced mass and power (factors of two) and increased robustness</td>
</tr>
<tr>
<td>Gamma Ray Imaging and Spectrometry</td>
<td>Readout electronics power, noise, yield and architecture</td>
<td>Systems cannot handle future channel counts and noise requirements Low custom-chip yields (10-20%) Typical current architecture leads to long interconnects.</td>
<td>Systems to handle 100 x more channels with low-noise interconnects Factor of 2-5 increase in custom chip yield (due to large number needed) Novel ways to interconnect to reduce noise and provide near seamless arrays</td>
</tr>
</tbody>
</table>
**12.3 Multi-Spectral Sensing (UV-Gamma)**

**Near Term Capability Road**

**Science Measurement**

- **Driving Missions**
  - Con X (2014)
  - BHFP (2018)
  - MTRAP (2020)
  - LUVO (2020)

**Science Measurement**

- **UV MCP**
  - 10 Megapixel, 20 % QE 150nm

- **UV CCD/APS**
  - Megapixel, UV response
  - 1 Hz frame rate, 10 W / megapixel
  - 30 Hz rate

- **X-ray CCD/APS**
  - 36 pixel array, 3 eV
  - 100 c/s pixel
  - 10^3 pixel array, 2 eV
  - 2000 c/s pixel

- **High-Energy Resolution**
  - Pixelated Detectors
  - 50mK prototype ADR
  - 300 μW/W cryocooler, 40kg
  - 50 mK, 7 year life
  - 500 μW/W, 25kg

- **Cryogenic Coolers**
  - 10^4 pixels (GLAST)
  - 100 μW/ channel (Caltech)
  - 10-20% yield

- **Mega-to-Giga Channel Analog Electronics**
  - 5x10^7 channels
  - ~ few μWatt / channel
  - 50% ASIC yield

**Timeline**

- 2005: Major Decision
- 2010: Enhancing/Evolutionary
- 2015: Ready to Use (TRL 6)
- *=No DRM Reference

**Reference**

12.3 Multi-Spectral Sensing (UV-Gamma)
Far Term Capability Road
## 12.3 Capability Maturity Assessment

<table>
<thead>
<tr>
<th>Sub Capability</th>
<th>Integrated Technology</th>
<th>Figures of Merit</th>
<th>State of the Art</th>
<th>Required Performance (@ TRL 6)</th>
<th>Mission Driver</th>
<th>Need Date (@TRL 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV Imaging and Spectrometry</td>
<td>Large Format Focal Plane Detectors : Microchannel Plates</td>
<td>Overall size</td>
<td>10^7 pixels</td>
<td>10^6</td>
<td>LUVO</td>
<td>2016</td>
</tr>
<tr>
<td></td>
<td>Quantum efficiency</td>
<td>10-15%</td>
<td>50%</td>
<td>LUVO</td>
<td>2016</td>
<td></td>
</tr>
<tr>
<td>UV &amp; X-Ray Imaging and Spectrometry</td>
<td>Large Format Focal Plane Detectors : CCDs and Active Pixel Sensors</td>
<td>Total pixels</td>
<td>Megapixel</td>
<td>&gt; 10^8 (UV)</td>
<td>MTRAP</td>
<td>2016</td>
</tr>
<tr>
<td></td>
<td>Pixels / chip</td>
<td>Megapixel</td>
<td>6k x 6k, buttable (UV)</td>
<td>MTRAP</td>
<td>2016</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power Resolution</td>
<td>10 W / Megapixel</td>
<td>4k x 4k, 4-side buttable (X-ray)</td>
<td>BHI</td>
<td>2021</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Readout speed</td>
<td>120 eV @ 6 keV</td>
<td>0.1 W / Megapixel</td>
<td>BHI</td>
<td>2021</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Response</td>
<td>1 Hz</td>
<td>&lt; 120 eV</td>
<td>BHI</td>
<td>2021</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt; 150 nm, below ∼ 6 keV</td>
<td>30 Hz</td>
<td>Extended UV response</td>
<td>Con-X</td>
<td>2010</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>X-ray response above 6 keV</td>
<td>MTRAP</td>
<td>2016</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Gen X</td>
<td>2023</td>
<td></td>
</tr>
<tr>
<td>X-Ray Imaging and Spectrometry</td>
<td>High-Energy-Resolution Pixelated Detectors</td>
<td>Energy resolution</td>
<td>6 eV , 6 keV ASTRO-E</td>
<td>2 eV (Con-X),</td>
<td>Con-X</td>
<td>2010</td>
</tr>
<tr>
<td></td>
<td>Number of pixels</td>
<td>2.7 eV in lab</td>
<td>1eV (Gen-X)</td>
<td>Gen-X</td>
<td>2023</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Count rate capability</td>
<td>36 pixels array (ASTRO-E)</td>
<td>10^2 pixel</td>
<td>Gen-X</td>
<td>2023</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10^7 pixel</td>
<td>Gen-X</td>
<td>2023</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt; 10^3 c/s-pixel</td>
<td>Con-X</td>
<td>2010</td>
<td></td>
</tr>
<tr>
<td>Cryogenic Coolers</td>
<td>Temperature Load</td>
<td>50 mK</td>
<td>50 mK</td>
<td>Con-X</td>
<td>2010</td>
<td></td>
</tr>
<tr>
<td>Operation</td>
<td>5 μW</td>
<td>5 μW</td>
<td>Gen-X</td>
<td>2023</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lifetime Efficiency</td>
<td>Continuous ADR</td>
<td>~ 50 μW</td>
<td>Continuous or duty cycle &gt; 95%</td>
<td>Con-X</td>
<td>2010</td>
<td></td>
</tr>
<tr>
<td></td>
<td>lab prototype</td>
<td>7 year</td>
<td>5 year</td>
<td>Con-X</td>
<td>2010</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 μW/W (cryocooler)</td>
<td>500 μW/W</td>
<td>500 μW/W</td>
<td>Con-X</td>
<td>2010</td>
<td></td>
</tr>
<tr>
<td>Gamma-Ray Imaging and Spectrometry</td>
<td>Mega-to-Giga Channel Analog Electronics</td>
<td>Number of channels</td>
<td>10^6 (GLAST)</td>
<td>5.10^6-10^8</td>
<td>BHFP</td>
<td>2014</td>
</tr>
<tr>
<td></td>
<td>Power/channel</td>
<td>100μW / channel (Caltech)</td>
<td>100μW-2μW /channel</td>
<td>BHFP</td>
<td>2014</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Noise/channel</td>
<td>200 e rms (no interconnects)</td>
<td>&lt; 300 e rms with interconnects/coupling</td>
<td>BHFP</td>
<td>2014</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yield</td>
<td>10-20%</td>
<td>50% for 10^7 ASICs</td>
<td>BHFP</td>
<td>2014</td>
<td></td>
</tr>
</tbody>
</table>
**Other Key Technologies**

- High-resolution, light-weight optics
- Formation flying
- Precision metrology
- On-board data processing, storage, and high-bandwidth telemetry
- Cooling of large area detectors and thermal control in general
- On ground (and in flight) calibration of high-resolution detector systems and associated optics

**Connection Points to Other Roadmaps**

- Telescopes and large structures
- Telecommunications
- Advanced modeling
- Infrastructure (fabrication, test, expertise)

**The key development for the UV through X-ray range is higher-performance focal plane detectors and their associated systems.**

**For gamma-ray missions, the driving technology requirement is low-power electronics and architectures supporting Mega-to-Giga channel instruments.**
### 12.4 Laser/LIDAR Remote Sensing

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
<th>Primary Expertise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maria Zuber</td>
<td>MIT (co-lead)</td>
<td>Laser ranging and altimetry</td>
</tr>
<tr>
<td>Richard Barney</td>
<td>NASA/GSFC (co-lead)</td>
<td>Laser instrument design</td>
</tr>
<tr>
<td>Richard Dissly</td>
<td>Ball Aerospace</td>
<td>In Situ and atmospheric instrumentation</td>
</tr>
</tbody>
</table>
12.4 Laser/LIDAR Remote Sensing

Capability Description

- Laser/LIDAR remote sensing includes active laser and LIDAR instrumentation used on situ, roving, aerial and orbital platforms and operating from the ultraviolet to near-infrared wavelengths.

Reference Documentation

- **Astronomy & Astrophysics**
  - Connecting Quarks with the Cosmos (2003)

- **Earth Science**
  - Strategic Plan for US Climate Change Science Program, 2003
  - Earth Science Enterprise Strategy, 1 Oct 2003
  - Earth Science Research Plan: 6 Jan 2005 Draft

- **Planetary Science**

- **Sun-Solar System**
  - Sun-Earth Connection Roadmap: 2003 - 2028
  - The Sun to the Earth - And Beyond: A Decadal Research Strategy in Solar and Space Physics
  - Solar and Space Physics and Its Role in Space Exploration
12.4 Laser/LIDAR Remote Sensing

Illustrative Capability Benefits

• Earth Science:
  • What do the distributions of ozone, aerosols and climate change imply about present-day climate?
  • How do tropospheric winds affect weather?
  • What do the distributions of trace gases imply for global warming?
  • What is the three-dimensional structure of the world’s vegetation?
  • What are the implications of photosynthetic efficiency for biological productivity?

Planetary Science:

• What is the surface evolution of the solid planets and how does surface geology relate to planetary thermal evolution?
• What is the history of volatile compounds, especially water, across the solar system?
• What does the solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?

Astrophysics & Search for Earthlike Planets:

• What happens at the edge of black holes?
• What is the nature of the pre-inflation universe?

Assumptions

• Receiver optics and infrastructure also addressed by Advanced Telescopes and Observatories Capability Roadmap.
• Agency will support risk reduction activities, including aircraft and ground-based prototype testing.
• Sensors must reach technical maturity 3-5 years before launch.
• Some Earth science sensors have direct planetary applications and vice versa.
• Astrophysical applications using metrology included.
• Tradeoffs:
  • Detection probability: power vs. aperture vs. detector sensitivity
  • Spatial coverage: # beams vs. scanning vs. pixelated detectors
• Not covered here: optical communication, landing range finders, in situ systems.
• Other things that matter: platform stability, alignment, precise & stable oscillators, precision optics, rad-hard, low-noise electronics
12.4 Laser/LIDAR Remote Sensing

Past/Current Missions
- Clementine LIDAR -- 1994
- LITE -- 1994
- NEAR NLR -- 1997
- MGS MOLA -- 1999
- SLA 1 & 2
- Icesat/GLAS -- 2003
- MESSENGER MLA -- launched 2004
- CALIPSO/CALIOP -- 2005 launch
- ALADIN/AEOLIS ADM -- 2007 launch
- LRO LOLA -- 2008 launch

Future Driving Missions

- Earth Science:
  - CALIPSO/CALIOP
  - Tropical Winds
  - High Resolution CO₂
  - Advanced Land Cover Change
  - Stratospheric Composition
  - Photosynthetic Efficiency

- Planetary Science:
  - Lunar Reconnaissance Orbiter
  - Europa Geophysical Orbiter
  - Mars High-resolution Spatial Mapper

- Universe+Earth-like Planets:
  - LISA
  - Big Bang Observer
### 12.4 Capability Need/Gap Assessment

<table>
<thead>
<tr>
<th>Sub Capability</th>
<th>Figures of Merit</th>
<th>Current Technology</th>
<th>Needed Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ranging Altimeters/ Backscatter LIDARS</strong></td>
<td>Time of flight Signal intensity Detector sensitivity</td>
<td>Single laser profiling systems</td>
<td>Multiple beams, scanning or pixelated detectors with long lifetime.</td>
</tr>
<tr>
<td><strong>Doppler Wind Profilers</strong></td>
<td>Doppler shift of narrow linewidth beam</td>
<td>Demonstrated from ground &amp; aircraft; Orbital sensors underdevelopment</td>
<td>Longer lifetime, increased resolution for Earth and planetary applications</td>
</tr>
<tr>
<td><strong>Surface/Atmosphere Reflectance Spectrometers</strong></td>
<td>Detect presence of chemical component and concentration through absorption, fluorescence at targeted wavelengths</td>
<td>Demonstrated from aircraft</td>
<td>Requires high-power systems with tunability and fine range gating</td>
</tr>
<tr>
<td><strong>Interferometers</strong></td>
<td>Precise measurement of distance</td>
<td>Demonstrated in lab</td>
<td>Advanced systems capable of operation in orbit and free space.</td>
</tr>
</tbody>
</table>
12.4 Laser/LIDAR Remote Sensing
Near Term Capability Road

Driving Missions
- CALIPSO/CALIOP (2005)
- Lunar Recon (2009)
- LISA (2012)
- Global Tropospheric Winds (2013)
- Hi Res CO₂ (2013)
- Advanced Land Cover Change (2017)

Science Measurements
- Aerosols and Cloud Properties
- Global Topography; Polar Illumination
- Black hole Astrophysics
- Winds with 2-D Vector
- Trace Gas Sources
- Continuous Measurements of Land Cover

- Lifetime
- Sampling Rate
- High Power 190 Watt (inst)
- High Frequency Stability Risk Reduction Demo
- Frequency Access 1 μm vs. 2 μm
- Detectors

- 10³ Shots
- 3 W Demo
- 3 W CW Tuneability over 1 GHz Stable to +/- 2 MHz
- 75 kHz

2005 2010 2015
- Major Decision
- Major Event / Accomplishment / Milestone
- Enhancing/ Evolutionary
- Ready to Use (TRL 6)
- *=No DRM Reference

Reference
- 2005
- 2010
- 2015
12.4 Laser/LIDAR Remote Sensing
Far Term Capability Road

- **(2012)** Europa Geophysical Explorer
- **(2018)** Stratospheric Composition
- **(2020)** Photosynthetic Efficiency
- **(2023)** Mars High Resolution Spatial Mapper*
- **(2025)** Big Bang Observer

**Science Measurement**
- Time Varying Tide
- Ozone, Aerosols and Cloud Particles
- Induced Fluorescence due to Plant Life
- High-resolution Local Topography & Surface Roughness
- Gravitational Waves

**Driving Missions**
- High Power
  - 500 MJ/pulse, UV
  - 75 MJ/pulse, Vis
  - 300 MJ/pulse, NIR

- High Frequency Stability
  - >1 J/pulse

- Frequency Access
  - 1 part in $10^{13}$

- Detectors
  - 10^2 pixels

**Lifetime**
- >10^9 shots

**Sampling Rate**
- 100 kHz

**2015**
- Major Decision

**2020**
- Major Event / Accomplishment / Milestone
- Enhancing / Evolutionary

**2025**
- Ready to Use (TRL 6)
- *No DRM Reference
### 12.4 Capability Maturity Assessment

<table>
<thead>
<tr>
<th>Sub Capability</th>
<th>Integrated Technologies</th>
<th>State-of-the-Art</th>
<th>Required Performance @ TRL 6</th>
<th>Mission Driver</th>
<th>Need Date (@TRL 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ranging Altimeters/ Backscatter LIDARS</strong></td>
<td>Surface coverage Range resolution Sampling rate</td>
<td>5 beams along track</td>
<td>Near-total surfical sampling 1 cm 10^2 kHz</td>
<td>Europa Geophysics Orbiter Advanced Land Cover Change Mars High resolution Mapper</td>
<td>2009</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 cm 40 Hz</td>
<td></td>
<td></td>
<td>2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 cm 40 Hz</td>
<td></td>
<td></td>
<td>2020</td>
</tr>
<tr>
<td><strong>Doppler Wind Profilers</strong></td>
<td>Laser lifetime Laser energy Laser tunability Frequency lock settling time</td>
<td>None space qualified</td>
<td>3-5 years 2 J/pulse +/- 5 GHz 10 msec</td>
<td>Global Tropospheric Winds</td>
<td>2010</td>
</tr>
<tr>
<td><strong>Surface/Atmosphere Reflectance Spectrometers</strong></td>
<td>Laser power Laser frequency access Laser frequency stability</td>
<td>None space qualified</td>
<td>3 W various; particularly IR +/- 2 MHz, continuously tunable over 1 GHz</td>
<td>High Resolution CO2 Stratospheric Composition Photosynthetic Efficiency</td>
<td>2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2016</td>
</tr>
<tr>
<td><strong>Interferometers</strong></td>
<td>Laser power Laser lifetime Laser frequency stability</td>
<td>30 mWatt &lt;1 year 1 part in 10^13 (lab)</td>
<td>300 Watt &gt;5 years 1 part in 10^13 (space) +/-5 GHz 10^8 improvement 10^-12 over 1 λ.</td>
<td>LISA Big Bang Observer</td>
<td>2009</td>
</tr>
<tr>
<td></td>
<td>Laser tunability Laser noise Laser phase measurement</td>
<td>10^-11 m (in lab) 10^-4 over +/- 50 kHz</td>
<td></td>
<td></td>
<td>2022</td>
</tr>
</tbody>
</table>
Other Key Technologies

- Radiation-hard electronics
- Imaging optics
- Mechanisms

Connection Points to Other Roadmaps

- In situ
- Telescopes & structures
- Data processing & storage
- Advanced communications
- Infrastructure (fabrication, test)
- Nanotechnology
- Formation Flying

- Key challenge is to develop reliable, efficient, space-qualified laser sources at wavelengths required by science.
- Identified tradeoffs dictate that competition must be used to choose optimal designs.
- Funding transition from low TRL (~1) to mid TRL (~4) is essential to risk and cost management.
## Science Instruments and Sensors Capability Roadmap Team

### 12.5 Direct Sensing of Particles, Fields and Waves

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
<th>Primary Expertise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Richard McEntire</td>
<td>JHU/APL</td>
<td>Particle Instrumentation</td>
</tr>
<tr>
<td>Carl Stahle</td>
<td>NASA GSFC</td>
<td>Detector Systems</td>
</tr>
<tr>
<td>Tim Krabach</td>
<td>NASA JPL</td>
<td>LWIR to FIR Detectors</td>
</tr>
<tr>
<td>Paul Mahaffy</td>
<td>NASA GSFC</td>
<td>Analytical Systems</td>
</tr>
<tr>
<td>Dave Chenette</td>
<td>Lockheed Martin</td>
<td>Space Radiation Measurement</td>
</tr>
</tbody>
</table>
12.5 Direct Sensing of Particles, Fields and Waves

Capability Description

• Direct sensing of Particles, Fields and Waves includes both in-situ and remote sensing of particles (ions, electrons, neutral atoms, from plasma energies to over 100 MeV), electric, magnetic, and gravity fields; and gravitational, electric, magnetic and plasma waves. The measurements cover the entire range of space environments from earth, solar, planetary, interplanetary, to galactic and beyond.

Reference Documentation

• Astronomy & Astrophysics
  – Beyond Einstein: From the Big Bang to Black Holes, 2003, Structure and Evolution of the Universe Roadmap Team
• Earth Science
  – Earth Science Research Plan: 6 Jan 2005 Draft
• Sun-Solar System
  – Sun-Earth Connection Roadmap: 2003 – 2028
  – The Sun to the Earth - And Beyond: A Decadal Research Strategy in Solar and Space Physics
  – Earth-Sun System: Potential Roadmap and Mission Dev. Activities (Draft) 12/03
• Planetary Science
12.5 Direct Sensing of Particles, Fields and Waves

**Capability Benefits**

**Gravitational Waves and Fields**

- What is the geometry of the Universe and the nature of dark energy?
- Is there observational evidence supporting the hypothesis that the early universe underwent a period of rapid inflation?
- How do super massive black holes at the centers of galaxies form or evolve and what happens when they merge?
- What are the motions of the Earth's interior, and how do they directly impact our environment?
- How long did it take the gas giant Jupiter to form, and how was the formation of the ice giants (Uranus and Neptune) different from that of Jupiter and its gas-giant sibling, Saturn?

**Assumptions**

Laser transmit/receive telescopes, and laser telescope pointing actuator will be covered by the Advanced Telescopes and Observatories CRM.

Laser development will be covered by Laser/LIDAR sub-team.

Development of technology for astrophysics needs to measure gravitational waves will be sufficient for measurements of the gravity field for planetary and earth science applications.
### 12.5 Direct Sensing of Particles, Fields and Waves

**Capability Benefits**

**Energetic Particles, Fields and Waves**

- What is the origin and societal impact of variability in the Sun-Earth system?
- How is the supersonic solar wind produced, and how does it evolve from the Sun's transition region to the boundary of the heliosphere?
- How and where are solar energetic particles accelerated, what is their composition, how do they propagate through the heliosphere? What is their impact on the safety of extended manned exploration of the moon, Mars and beyond?
- What is the detailed structure of the heliosphere, how does it change with time and modulate the intensity of galactic cosmic rays?
- What is the nature of the interstellar medium, and how does the heliosphere interact with it?
- How does the space environment and ionosphere and upper atmosphere of the Earth respond to varying external and internal influences? What are the coupling mechanisms? How do interactions at other planets compare? What can magnetic field measurements tell us about the internal structure of these planets?
- What are the fundamental processes that operate in space plasmas; how is energy transferred from stressed magnetic fields to heat plasmas and accelerate particles?

### Assumptions

Most future direct measurement missions will be multi-spacecraft and/or very limited in payload mass, power and cost. While many individual Particles and Fields measurement needs can be met with present technology, deliberate evolutionary miniaturization of instruments and electronics is extremely important to enhance or enable these future missions.

Miniaturization and reduction in mass and power needs are shared with the in-situ and remote-sensing teams, and for spacecraft avionics.
12.5 Direct Sensing of Particles, Fields and Waves

**Past / Current Missions**

**Terrestrial**
- GRACE
- Polar
- IMAGE
- TIMED
- Cluster

**Planetary**
- Galileo
- Cassini
- Messenger

**Heliospheric**
- Voyager
- Ulysses
- ACE

**Future Driving Missions**

**Terrestrial:** Ionosphere/Thermosphere Storm Probes (ITSP), Radiation Belt Storm Probes (RBSP), Geospace Electrodynamics Connection (GEC), Magnetospheric Constellation

**Planetary:** Jupiter Polar Orbiter/Probes (JPO), Europa Orbiter

**Heliospheric:** Solar Probe (SP), Inner Heliosphere Sentinels (IHS), Telemachus, Interstellar Probe (ISP), Heliospheric Imager and Galactic Observer (HIGO)

**Astrophysics:** Laser Interferometer Space Antenna (LISA), Big Bang Observer (BBO)
## 12.5 Capability Need/Gap Assessment

<table>
<thead>
<tr>
<th>Sub Capability</th>
<th>Figures of Merit</th>
<th>Current Technology</th>
<th>Needed Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational Waves and Fields</td>
<td>High sensitivity to low frequency (10^{-3} – 1 Hz) relative displacement of proof masses</td>
<td>Laser Interferometry</td>
<td>High power, stable, long-life lasers; Interferometer system; Disturbance compensation system (DISCOS); Telescope accuracy and pointing</td>
</tr>
<tr>
<td>Particle Detectors (plasmas, energetic electrons, ions, neutrals)</td>
<td>Energy/species/charge coverage and resolution, Solid angle coverage and resolution, Dynamic range</td>
<td>Electrostatic analyzers; Time-of-Flight (TOF) and Solid State Detector (SSD) telescopes</td>
<td>Compact sensors with better energy/angle coverage; Low threshold array detectors; UV blind gratings; Conversion surfaces; Highly integrated signal processing</td>
</tr>
<tr>
<td>Vector magnetometers</td>
<td>Sensitivity, Absolute accuracy, Radiation tolerance, Orientation knowledge, Spacecraft magnetic field contamination</td>
<td>Vector: Fluxgate; Scalar: He Precession 3 - 10 m boom</td>
<td>New fluxgate cores or alternate Miniature scalar sensors; Mrad tolerant electronics; Multi-sensor systems: 0.5 to 1 m booms</td>
</tr>
<tr>
<td>Scalar magnetometers</td>
<td>Frequency coverage (DC-40 MHz), Sensitivity</td>
<td>Mix of analog &amp; digital electronics in pass bands, each with a different receiver 50 m spin plane boom, 2.25 kg 10 m spin axis boom, 5 kg</td>
<td>Highly flexible, digital coverage of entire bandwidth; Lower power, mass, cost Lightweight electric field booms, reliable deployment for both spinning &amp; non-spinning spacecraft</td>
</tr>
<tr>
<td>Particle Detectors</td>
<td>3 axis Sensitivity</td>
<td>Relatively high power processors; Low efficiency DC converters; High power A/D; HVPS limited reliability; Large.</td>
<td>More standard components that are radiation hard, low power, and miniature.</td>
</tr>
</tbody>
</table>

## Measurement of EM waves

| DC Electric Fields | Low power, Radiation hard (>1 Mrad), High speed, High resolution, Reliable | Relatively high power processors; Low efficiency DC converters; High power A/D; HVPS limited reliability; Large. | More standard components that are radiation hard, low power, and miniature. |
12.5 Direct Sensing of Particles, Fields and Waves

Major Decision
Major Event / Accomplishment / Milestone
Enhancing/ Evolutionary
Ready to Use (TRL 6)
* = No DRM Reference
12.5 Direct Sensing of Particles, Fields and Waves

**Science Measurement**

- **Gravitational Waves/Fields**
  - Laser Interferometry
    - High Power Laser
    - 4 S/C Solar Wind turbulence
    - 10⁻¹⁶ m, 1 Hz
    - 300 W
    - 10⁻¹⁷ m/s/s
  - Spacecraft Disturbance Control
    - Gravitational Reference Sensor
    - Plasma isotopic composition
    - Very low mass power
    - ENA conversion
    - Surfaces, imaging, composition
- **Particle Detectors**
  - Energy, charge, direction
    - <10pT
- **Magnetometers**
  - Stable, accurate miniaturized electronics
    - 1 pT
    - Very light boom
- **E Fields and Waves**
  - Low mass booms
- **Low Power, Rad Hard Electronics**
  - [ASICS, µprocessors, etc.]

**Driving Missions**

- (2023) L1 Diamond
- (2024) SPI
- (2025) BBO
- (2026) Telemachus
- (2029) ISP
- (2032) HIGO

**2020 - 2030**

- 2020
- 2025
- 2030

- Major Decision
- Major Event / Accomplishment / Milestone
- Enhancing / Evolutionary
- Ready to Use (TRL 6)
- *=No DRM Reference
# 12.5 Capability Maturity Assessment

<table>
<thead>
<tr>
<th>Sub Capability</th>
<th>Integrated Technologies</th>
<th>State-of-the-Art</th>
<th>Required Performance (@TRL 6)</th>
<th>Mission Driver</th>
<th>Need Date (@TRL 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational Waves and Fields</td>
<td>High power, stable, reliable lasers; S/C DISCOS; Gravitational Reference Sensor (GRS)</td>
<td>30 mW laser, life &lt; 1 yr Interferometry 10^{-11} m, 10Hz GRS: 10^{-10} m/s/s</td>
<td>1 W laser, life ≥ 5 yr Interferometry 10^{-12} m, 10^{-3} Hz GRS: 10^{-15} m/s/s 300 W laser, life ≥ 5 yr Interferometry 10^{-16} m, 1 Hz GRS: 10^{-17} m/s/s</td>
<td>Laser Interferometer Space Antenna (LISA) Big Bang Observer (BBO)</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2021</td>
</tr>
<tr>
<td>Particle Detectors (plasmas, energetic electrons, ions, neutrals)</td>
<td>Ion implanted SSD detectors and arrays; MCP TOF systems; Signal processing; HVPS</td>
<td>SSD energy thresholds ≥ 10 keV; Limited arrays and higher power; Soft integrated electronics.</td>
<td>Ion implanted SSDs 15 µm to 5 mm thick; Large arrays; Low power, low noise, rad hard electronics; UV suppression grids; Stable charge conversion coatings</td>
<td>RBSP Solar Probe, IHS ISP HIGO</td>
<td>2008 2010 2025 2028</td>
</tr>
<tr>
<td>Vector Magnetometers</td>
<td>Vector field: fluxgate Absolute scalar: He Electronics: &gt; 16 bit A/DSs, stable oscillator</td>
<td>Fluxgate: 10 pT, 0.1 nT/week; Scalar (He): 1 pT, 1 ppm 30 krad electronics Boom (3 - 10 m)</td>
<td>Low noise core material Multi-sensor system Rad hard electronics (~ Mrad) 1 pT vector sensitivity &lt; 1 W Low resource: &lt;0.2 W, &lt;0.1kg</td>
<td>All Solar Probe, ISP Europa, RBSP ISP Mag Con</td>
<td>2010 2010 2008 2025 2017</td>
</tr>
<tr>
<td>Scalar Magnetometers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measurement of EM waves</td>
<td>A/D converter DSP (Digital Signal Processor chip) Antenna</td>
<td>8 bits, ≤ 20 Msp @ 500 mW Non-rad hard, &gt; 1 W 50 m spin at 3 kg 10 m axial at 5 kg</td>
<td>18 bits @ 80 Msp @ ≤ 100 mW Rad hard, 250 mW, 10^3 pt. FFT at 3 MHz 50 m spin, ≤ 1 kg (inc. sensor) Axial ~ 20 m, rigid, ≤ 2 kg</td>
<td>RBSP Solar Probe ISP</td>
<td>2008 2010 2025</td>
</tr>
<tr>
<td>DC Electric Fields</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower power, radiation hard electronics</td>
<td>Microprocessor DC/DC converters A/D converters HVPS</td>
<td>~ 10 Mps/W Efficiencies ~ 20 - 50% 14 bits, 10MHz, 250mW 150 - 400 gm</td>
<td>100 Mps/W, on par with cellphone technology Efficiencies ~ 85% ≥ 14 bits, 80 MHz, 50 mW Standard design, &lt; 100 gm</td>
<td>Europa Geo Explorer Solar Probe All multi-spacecraft missions</td>
<td>2008 2010 2008 on</td>
</tr>
</tbody>
</table>
### Other Key Technologies
- MEMS
- High quality mirrors
- Miniaturization of S/C avionics
- Manufacturing cost reductions for multiple S/C

### Connection Points to Other Roadmaps
- Laser Remote Sensing
- Formation Flying
- Advanced telescopes and observatories
- Visible-UV sensing
- In-Situ instruments
- Nanotechnology
- Infrastructure (fabrication, test, calibration)

---

- **Gravitational Wave measurements address fundamental cosmological physics**, and can be made from space over key frequencies \((10^{-3} - 1 \text{ Hz})\) with a sensitivity impossible to achieve on the Earth. The technology advances needed will be synergistic with other missions.

- **Particles and Fields measurements are planned at many locations in planetary magnetospheres and throughout and beyond the heliosphere.** Deliberate evolutionary advances in instrumentation and electronics are needed to enhance mission science and reduce mission cost – and are synergistic with In-Situ and many other mission areas.
### Science Instruments and Sensors

#### Capability Roadmap Team

**12.6 In-Situ Instrumentation**

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
<th>Primary Expertise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tim Krabach</td>
<td>NASA-JPL (co-lead)</td>
<td>Astrobiological systems</td>
</tr>
<tr>
<td>Rich Dissly</td>
<td>Ball Aerospace (co-lead)</td>
<td>Analytical systems</td>
</tr>
<tr>
<td>Paul Mahaffy</td>
<td>NASA-Goddard</td>
<td>Analytical systems</td>
</tr>
<tr>
<td>Richard McEntire</td>
<td>JHU-APL</td>
<td>Particles and fields</td>
</tr>
<tr>
<td>Dave Chenette</td>
<td>Lockheed Martin</td>
<td>High-energy detectors</td>
</tr>
</tbody>
</table>
12.6 In-Situ Instrumentation

**Capability Description**
- In-situ covers a wide range of measurement techniques and capabilities, with the defining characteristics that the instruments must be in close proximity with the investigation target.
- **Includes** technologies essential to NASA science missions involving:
  - Landed planetary exploration (e.g. Mars Science Laboratory)
  - Sample return (e.g. Genesis)
  - Atmospheric probes (e.g. Huygens)
- **Also includes** key technologies for NASA exploration missions:
  - Prospecting for in-situ resources on the moon and Mars

**Reference Documentation**
- **Planetary Science**
    - Astrobiology Field Laboratory SSG
    - Groundbreaking Mars Sample Return SSG
    - Mars Deep Drill Missions SSG
  - Lunar – Under development

In Situ Instrumentation

Science Instruments and Sensors

12.0

12.6

Chair: Tim Krabach, JPL
Co-Chair: Rich Dissly, BATC

Imaging/Microscopy

Mineralogical/Elemental Analysis

Chemical Detection and Identification

Isotope Analysis/Age Dating

Biological Detection and Identification

Geophysical Measurements

Sample Handling and Preparation

In Situ Instrument Engineering
12.6 In-Situ Instrumentation

Capability Benefits

Planetary Science:
- What processes marked the initial stages of planet & satellite formation?
- Where are the habitable zones for life in the solar system, and what are the planetary processes responsible for producing and sustaining habitable worlds?
- How long did it take the gas giant Jupiter to form, and how was the formation of the ice giants (Uranus and Neptune) different from that of Jupiter and its gas-giant sibling, Saturn?
- How did the impactor flux decay during the solar system’s youth, and in what way(s) did this decline influence the timing of life’s emergence on Earth?
- What is the history of volatile compounds, especially water, across the solar system?
- What is the nature of the organic material in the solar system? Its history?
- What global mechanisms affect the evolution of volatiles on planetary bodies?
- Does (or did) life exist beyond Earth?
- Why did the terrestrial planets differ so dramatically in their evolution?
- How do the processes that shape the contemporary character of planetary bodies operate and interact?
- What does the solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?

Sub-Team Assumptions

- Vis-IR far-field sensing, or measurements outside of planetary atmospheres, covered by Multi-spectral Imaging subteam
- In-situ measurements of interplanetary plasmas covered in Particles, Fields and Waves subteam
- In-Situ sensors for astronaut health and safety are not covered by this group
- General curatorial facilities for sample return will be covered by NASA, including quarantine facilities, independent of this assessment
-Analytical instrumentation and mission-specific environmental maintenance for returned samples are not necessarily provided; this team has not covered capability needs in this area yet
- Complete in situ instrument development must include appropriate environmental testbeds for evaluation of components, subsystems, and instruments;
Past / Current Missions

- Mars
  - Viking
  - Pathfinder
  - MER
  - Phoenix
  - MSL

- Sample Return
  - Apollo
  - Genesis
  - Stardust

- Other Planetary
  - Pioneer Venus Probes
  - Galileo Probe
  - Huygens Lander

Future Driving Missions

**Mars:** Astrobiology Field Lab, Groundbreaking Mars Sample Return, Deep Drill, Long-Lived Lander Network

**Sample Return:** Lunar South Pole-Aitken Basin SR, Comet Surface SR, Comet Cryogenic SR, Asteroid SR, Venus Surface SR, Mercury SR

**Other Planetary:** Lunar Seismic Network, Venus In-Situ Explorer, Jupiter Polar Orbiter/Probes, Neptune Orbiter/Probes, Europa Pathfinder Lander, Titan Explorer, Europa Astrobiology Lander, Uranus Orbiter/Probes, Neptune Orbiter w/ Triton Lander
### 12.6 Capability Need/Gap Assessment

<table>
<thead>
<tr>
<th>Sub Capability</th>
<th>Figures of Merit</th>
<th>Current Technology</th>
<th>Needed Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomarker Detection and Characterization</td>
<td>* Sensitivity</td>
<td>* Characterization of viable organisms that can be cultured</td>
<td>* Quantitative assessment of all organic material</td>
</tr>
<tr>
<td></td>
<td>* Selectivity</td>
<td>* Terrestrial contamination exceeds detection limits</td>
<td>* Technology to ensure isolation from terrestrial contamination</td>
</tr>
<tr>
<td></td>
<td>* Contamination ID and quantification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample Handling &amp; Preparation</td>
<td>* Operability in relevant environment</td>
<td>* Bias from particle size and density</td>
<td>* No bias or fractionation in end-to-end sample handling chain, even in multi-phase samples</td>
</tr>
<tr>
<td></td>
<td>* Degree of sample alteration</td>
<td>* Qualitative ability to preserve volatile fractions</td>
<td>* Ability to selectively subsample in primary sample acquisition</td>
</tr>
<tr>
<td></td>
<td>* Subsampling accuracy</td>
<td>* Operability over limited temperature ranges</td>
<td>* Operability from 40K to 750K</td>
</tr>
<tr>
<td>Planetary Protection</td>
<td>* Sensitivity to detection of viable organisms</td>
<td>* Characterization of viable organisms that can be cultured</td>
<td>* Characterization of any viable organisms</td>
</tr>
<tr>
<td></td>
<td>* Breadth of detection of viable organisms</td>
<td>* Detection levels well below sterilization levels</td>
<td>* Sterilization levels on par with detection levels</td>
</tr>
<tr>
<td></td>
<td>* Degree of sterilization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical Identification at Small Spatial Scales</td>
<td>* Spatial resolution</td>
<td>* Micron-level chemical and isotopic assessment in terrestrial labs</td>
<td>* Micron-level chemical and isotopic assessment in flight package</td>
</tr>
<tr>
<td></td>
<td>* Sensitivity</td>
<td>* AFM for crude surface analysis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Selectivity or mass resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miniaturization, Ruggedization, and Payload Integration</td>
<td>* Mass</td>
<td>* Payload elements developed separately, little common mass and power elements</td>
<td>* Payload elements developed together minimize mass and power resources</td>
</tr>
<tr>
<td></td>
<td>* Power</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Shock/Vibe tolerance</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Survivability in extreme environments</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Capability 12.6 In-Situ Instrumentation
Far Term Roadmap

<table>
<thead>
<tr>
<th>Driving Missions</th>
<th>Science Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2020) Comet Cryo Sample Return*</td>
<td>Biomarker detection &amp; characterization</td>
</tr>
<tr>
<td>(2022) Europa Pathfinder Lander</td>
<td>Subsurface sample, volatile preservation</td>
</tr>
<tr>
<td>(2020) Titan Explorer</td>
<td>Surface Composition mapping</td>
</tr>
<tr>
<td>(2025) Mercury Sample Return*</td>
<td>Near-surface composition &amp; organic survey</td>
</tr>
<tr>
<td>(2025) Uranus Orbiter w/ Probes</td>
<td>Near-surface composition</td>
</tr>
<tr>
<td>(2030) Europa Astrobiology Lander*</td>
<td>Atm structure &amp; composition</td>
</tr>
<tr>
<td>(2032) Triton Lander</td>
<td>Detailed organic assessment at extended depth</td>
</tr>
</tbody>
</table>

- Biomarker detection & characterization
- Sample handling & processing
- Planetary protection
- Chemical ID at small spatial scales
- Miniaturization and payload integration

**2020**
- Comet Cryo Sample Return*
- Titan Explorer
- Europa Pathfinder Lander

**2025**
- Mercury Sample Return*
- Uranus Orbiter w/ Probes
- Europa Astrobiology Lander*

**2030**
- Triton Lander

---

- Major Decision
- Major Event / Accomplishment / Milestone
- Enhancing/Evolutionary
- Ready to Use (TRL 6)
- *=No DRM Reference
<table>
<thead>
<tr>
<th>Sub Capability</th>
<th>Integrated Technologies</th>
<th>State-of-the-Art</th>
<th>Req Perf @TRL 6</th>
<th>Mission Driver</th>
<th>Need Date (@ TRL 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomarker assessment</td>
<td>Multiple assay techniques</td>
<td>Lab-based commercial systems</td>
<td>ppb sensitivity and miniaturization to flight scales</td>
<td>Mars AFL</td>
<td>2012</td>
</tr>
<tr>
<td>Sample Handling</td>
<td>Cryo mechanisms</td>
<td>MER</td>
<td>40K demo</td>
<td>Lunar Polar Explorer</td>
<td>2009</td>
</tr>
<tr>
<td></td>
<td>Subsampling</td>
<td>MER RAT</td>
<td>mm-scale sampling of sedimentary layers</td>
<td>AFL</td>
<td>2012</td>
</tr>
<tr>
<td></td>
<td>Sample phase preservation</td>
<td>MER</td>
<td>No heating of samples above -20C</td>
<td>AFL</td>
<td>2012</td>
</tr>
<tr>
<td>Planetary Protection</td>
<td>Sensitive assays</td>
<td>Subset of viable spores cultivated</td>
<td>Full range of viable life characterized</td>
<td>Mars SR</td>
<td>2009</td>
</tr>
<tr>
<td></td>
<td>Contamination control in sample handling</td>
<td>Organic contamination in lunar sample of tens of ppb</td>
<td>Sub-ppb organic contamination in returned samples</td>
<td>Mars SR</td>
<td>2009</td>
</tr>
<tr>
<td>Chem ID at small spatial scales</td>
<td>Minaturized imaging systems</td>
<td>Submicron imaging, Phoenix AFM</td>
<td>Submicron imaging combined with chemical / isotopic analysis</td>
<td>Mars AFL</td>
<td>2012</td>
</tr>
<tr>
<td></td>
<td>Miniaturized composition probes</td>
<td>Lab-based systems</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
12.6 In-Situ Instrumentation

Other Key Technologies
• Environmentally relevant testbeds
• Payload system integration
• Mechanisms in extreme environments
• Electronics in extreme environments
• Distributed processing

Connection Points to Other Roadmaps
• Atmospheric entry systems
• Landing systems
• Planetary surface and subsurface access
• Cryogenic sample handling
• Remote sensing and sounding of surface/subsurface composition
• Nanotechnology

• Robust 'mid-TRL programs needed to close gap between needed and available capabilities for lunar and non-Mars destinations (for example, a MIDP-like program for New Frontiers)

• In situ performance should be validated in relevant testbeds prior to competitive selection (for example, instrument breadboard sensitivity and precision proven in realistic Mars testbed)

• In situ instrument development will be key enabling technology for exploration missions to the Moon, Mars, and beyond; specific driving missions may change, but driving science likely will not.
Science Instruments and Sensors Capability Roadmap
Co-Chair Summary

NASA Co-Chair: Rich Barney, NASA
External Co-Chair: Maria Zuber, MIT

March 16, 2005
12.1 Microwave Instruments and Sensors
- Large deployable antennas
- Integrated high efficiency T/R modules
- Radiation hard electronics
- Quantum limited cryogenic receivers
- High frequency, low power MMIC receivers
- Large scale digital spectrometers and correlators (rad-hard FPGAs and ASICs)
- Low power, long life cryocoolers

12.2 Multi-Spectral Imaging / Spectroscopy (vis-IR-FIR)
- Low power, long life Coolers
- Detectors & Readout Electronics (large format, better sensitivity)
- Optics (dispersive/imaging; instrument level including filters, coolers, polarimeters)

12.3 Multi-Spectral Sensing (UV-Gamma)
- Large format CCDs / active pixel sensors
- High-energy-resolution single-photon detectors
- Low power, long life cryogenic coolers to achieve less than 0.1K
- Mega-to-Giga channel analog electronics
- Optics (Normal / grazing incidence, higher-energy optics, gratings)

12.4 Lasers / LIDAR
- High energy lasers (for atmospheric sensing, formation flying, etc.)
- Quality control of laser systems (all components)
- Frequency stability & selection
- Spatial coverage: multibeam, scanning, pixelated detectors
- High-sensitivity detectors

12.5 Direct Sensing of Fields Particles, and Waves
- High power lasers
- Spacecraft disturbance compensation systems
- Detectors and detector arrays, light weight rigid booms
- Compact, rad hard, high integration electronics and sensors

12.6 In Situ Instrumentation
- Sample Handling in Multiple Relevant Environment as a function of Mission specific target
- Sample Acquisition on the surface of Mars
- Miniaturization for instruments and integrated payloads (Nano) electronics; better integrated across the board.
• Major challenges in development required technologies/capabilities:
  – Science Payloads may operate in severe environments:
    _ Jovian radiation belts
    _ Venus surface environment (460°C, 90 bars)
    _ Outer planet surfaces and atmospheres (sub 100K)
  – Flight demonstration to retire risks that require an orbital flight will continue to
    be a pacing item for the introduction of new technologies required to reduce
    capability gaps.
  – Infrastructure investments are required to develop performance testing
    capabilities for long term technology development.

• Science Payloads are (usually) extremely resource constrained.
  – Limited mass, volume, power and data rate
  – Impacts applicability of cryogenically cooled sensors
  – High fidelity instrument systems models are required to perform early risk
    assessments and technical resource trade studies.

• Linkage of orbital and ground-based observations (sensor webs) represents a
  significant future opportunity for Earth and solar system studies.
• Prioritization of capabilities/technologies needed to achieve the Vision for Space Exploration must be traceable to science measurement needs.

• A sustained, low TRL, science instrument component technology development program is needed to close identified capability gaps.

• An organized, prioritized technology plan that is well coordinated with and supported by the science community served is key to acquiring technology funding.

• Proposal teams to share their experiences and “wish lists” of technologies that would have made their science more achievable and competitive.

• Commercial/Academia partnerships with NASA are essential to implementing technology solutions required to narrow or close critical capability gaps.
The Science Instruments and Sensors Capability Roadmap team has investigated current NASA exploration and science measurement strategies, design reference missions, and science instrument/sensor technology roadmaps to identify critical science measurement capability gaps and assess future technology development needs...a work in progress.

• Excellent interaction with the public Science and Engineering communities at open meetings and workshops
  • Limited discussions with Strategic Roadmap Teams has been very productive

• Several key sub-capabilities have been identified that cut across instrument and sensors capabilities. NASA technology investment in these sub-capabilities will enable several exploration missions.

• Need for maturation plan / program for enabling advanced instrument insertion into flight.

• Integration with the Strategic Roadmap Teams is key to developing science instrument and sensor roadmaps that are responsive to strategic mission needs.

• Competed, peer-reviewed development programs are best approach for NASA.
Forward Work

– Make changes to roadmaps based on verbal feedback from NRC review.

– Receive the draft Strategic Roadmaps by April 15th.
  _ Continue productive interchange with SRM teams.

– Make changes to CRM Title roadmaps to ensure consistency with Strategic Roadmaps requirements.

– Develop rough order of magnitude cost estimates for the CRM Title Capability Roadmap (awaits input on current investment from NASA).

– Prepare for 2nd NRC Review which will address 4 additional questions:
  _ Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?
  _ Do the capability roadmaps articulate a clear sense of priorities among various elements?
  _ Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?
  _ Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?

– Complete Capability Roadmaps by June, 2005.
Backup
Reference Documentation (Docushare Library)

- The Vision for Space Exploration
- A Journey to Inspire, Innovate, and Discover: President’s Commission Report
- Our Changing Planet: The US Climate Change Science Program for Fiscal Years 2004 and 2005
- Design Reference Missions
  - APIO DRMs
    - Solar System Exploration - 2000 to 2035 (Draft 3): DRM_SSE
    - Universe Design Reference Missions (12/13/04)
    - Architecture Study #2, Human Exploration of Mars, Artificial-Gravity Nuclear Electric Propulsion Option (7/15/03)
    - Reference Mission Version 3.0 Addendum to the Human Exploration of Mars (6/01/98)
    - Mars 98 Reference Mission: Reference Mission of the NASA Mars Exploration Study Team (7/7/97)
    - Lunar Surface Reference Missions: A Description of Human and Robotic Surface Activities (07/01/03)
    - The Mars Surface Reference Mission: A Description of Human and Robotic Surface Activities (12/01)
  - Other DRMs
    - Advanced Mission Studies: Mars Exploration Program Analysis Group
      - Astrobiology Field Laboratory-2013 (Biosignature Detection)
      - Ground Breaking Mars Sample Return
      - Mars Deep Drill: Explore Active Hydrothermal Habitats
      - Mars Deep Drill: Search for Evidence of Past Life
Reference Documentation
(Docushare Library)

• Enterprise Strategies
  – Earth Science Application Plan
  – Earth Science Research Plan (Draft)
  – Sun-Earth Connection Roadmap (2003-2028)
  – Physics of the Universe: A Strategic Plan for Federal Research
  – Solar System Exploration Roadmap
  – Structure and Evolution of the Universe Roadmap

• National Research Council Reports
  – Astronomy and Astrophysics in the New Millennium   Astronomy and Astrophysics Survey Committee, Board on Physics and Astronomy, Space Studies Board
  – Implementing Climate and Global Change Research: A Review of the Final U.S. Climate Change Science Program Strategic Plan   Committee to Review the U.S. Climate Change Science Program Strategic Plan
  – Solar and Space Physics and Its Role in Space Exploration   Committee on Assessment of the Role of Solar and Space Physics in NASA's Space Exploration Initiative, NRC
  – The Sun to the Earth -- and Beyond: A Decadal Research Strategy in Solar and Space Physics   Solar and Space Physics Survey Committee
  – The Sun to the Earth -- and Beyond: Panel Reports   Solar and Space Physics Survey Committee, Committee on Solar and Space Physics
  – Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century,   Committee on the Physics of the Universe, NRC
# Exploration/Science Traceability

<table>
<thead>
<tr>
<th><em>References:</em></th>
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<tr>
<td>4: Earth Science Applications Plan, 2004</td>
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<tr>
<td>7: Mars Deep Drill Search for Evidence of Past Life, Sylvia Miller, John Essmiller, David Beaty, JPL, January 16, 2004</td>
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<tr>
<td>8: Mars Deep Drill Explore Active Hydrothermal Habitats, Sylvia Miller, John Essmiller, David Beaty, JPL, January 16, 2004</td>
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<td>10: Groundbreaking Mars Sample Return, Richard Mattingly, JPL, March 8, 2004</td>
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<td>11: Sun-Earth Connection Roadmap: 2003 - 2028</td>
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<td>12: The Sun to the Earth - And Beyond: A Decadal Research Strategy in Solar and Space Physics</td>
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<td>14: Astronomy and Astrophysics in the New Millennium, 2004, NRC Astronomy and Astrophysics Survey Committee</td>
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<tr>
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<tr>
<td>16: Beyond Einstein: From the Big Bang to Black Holes, 2003, Structure and Evolution of the Universe Roadmap Team</td>
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<tr>
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<td>18: Benford, D. “SAFIR: Single Aperture Far Infrared Observatory”</td>
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<tr>
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# Missions Referenced in Roadmaps

*sorted by mission name*

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<th><strong>Launch</strong></th>
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<td>GEO Global Precip</td>
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<td>GEO In SAR Constellation</td>
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<td>GEO Lightning Imager</td>
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<td>Geospace Electrodynamics Connection (GEC)</td>
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<td><em>GEO Seismology from Space</em></td>
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**Legend:**
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<th>Design Reference Mission</th>
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<td>Global Soil Moisture</td>
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<td>Global Tropospheric Winds</td>
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<td>Global Tropospheric Aerosols</td>
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<td>Hi Res CO2</td>
<td>12.4</td>
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<td>Interstellar Prob</td>
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<td>Joint Dark Energy Mission</td>
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<td>Jupiter Polar Orbiter</td>
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<td>12.5</td>
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<td>L1 Diamond</td>
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<td>L2 - Earth Atmosphere Solar Interferometer</td>
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<td><em>Land Surface Topography</em></td>
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<td>LEO Cloud System Structure</td>
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<td>Leo Wetland &amp; River Monitor</td>
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<tr>
<td>Life Finder</td>
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<td>Magnetic Constellation</td>
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<td><strong>Mars Electrification Imager</strong>*</td>
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<td>Reconnection and Microscale</td>
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<td>Venus In-Situ-Experiment (Explorer)</td>
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Acronyms

- ACE - Advanced Composition Explorer
- ACS - Advanced Camera for Surveys
- ACT - Advanced Compton Telescope
- ADR - Adiabatic Demagnetization Refrigerator
- AFL - Astrobiology Field Laboratory
- AIRS - Atmospheric Infrared Sounder
- Aladdin/AEOLUS ADM - ESA Aladdin (Satellite) AEOLUS Atmospheric Dynamics Mission (Doppler Wind Lidar)
- AMSU - Advanced Microwave Sounding Unit
- APL - John Hopkins University Applied Physics Laboratory
- ARC - Ames Research Center
- ASIC - application-specific integrated circuit
- ASTEP - Astrobiology Science and Technology for Exploring Planets
- ASTID - Astrobiology Science and Technology Instrument Development
- ATO - Advanced Telescopes and Observatories
- BATC - Ball Aerospace and Technologies Corporation
- BBO - Big Bang Observer
- BHFP - Black Hole Finder Probe
- BHI - Black Hole Imager
- BLIP - background limited infrared photo-detector
- Bolos - Bolometer Arrays
- BW - bandwidth
- Calipso/CALIOP - Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations/
- Cloud Aerosol Lidar with Orthogonal Polarization.
- CCDS - Charge Coupled Devices
- Cluster - it is a Mission to study small-scale structures of the magnetosphere and its environment in three dimensions. Cluster is constituted of four identical spacecraft that will flight in a tetrahedral configuration.
- CMB - Cosmic Microwave Background
- CMOS - complementary metal-oxide semi-conductor
- Con-X - Constellation-X
- CRISM - Compact Reconnaissance Spectrometer for Mars
Acronyms

- CRM- Capability Roadmap
- CSSR- Comet Surface Sample Return
- DBF- Digital Beam Formation
- DC- direct current
- DMSP- Defense Meteorological Satellite Program
- DRMs- Design Reference Missions
- DSP- Digital Signal Processor chip
- EG- Europa Geophysics
- EIP- Einstein Inflation Probe
- ESA- electronically scanned arrays
- ESMR-Nimbus-5 Electrically Scanning Microwave Radiometer
- ESTO- Earth Science Technology Office
- Far IR- Far Infrared
- FIR- Far Infrared
- FOV- Field- of-View
- FPGA- Field-Programmable Gate Array
- GaAs- Gallium Arsenide
- GEC- Geospace Electrodynamics Connection
- Gen X-Generation X
- GEO- Geosynchronous Orbit
- GEO Coastal C- GEO Coastal Carbon
- GEOSAT- Geodetic Satellite Mission
- GGP- GEO Global Precipitation
- GLAST- Gamma Ray Large Area Space Telescope
- GPS- Global Positioning System
- GPS/GNSS- Global Positioning System/Global Navigation Satellite System
- GRACE- Gravity Recovery and Climate Experiment
- GSFC- Goddard Space Flight Center
- GSM- Global Soil Moisture
- GTA- Global Tropospheric Aerosols
- HCIPE- High Capability Instruments
Acronyms

- HIGO- Heliospheric Imager and Galactic Observer
- HIRISE- High Resolution Imaging Science Experiment
- HRes CO2- High Resolution CO2
- HST- Hubble Space Telescope
- HVPS- High Voltage Power Supply
- ICESAT/GLAS- Ice, Cloud and land Elevation Satellite/Geoscience Laser Altimeter System
- IHS- Inner Heliosphere Sentinels
- IMAGE- Imager for Magnetopause to Auroral Global Exploration
- InSAR (MEO)- Interferometric Synthetic Aperture Radar
- IPS- Integrated power systems
- IR- Infrared
- IRAC- Infrared Array Camera (Spitzer)
- IRS- Infrared Spectrograph (Spitzer)
- ISP- Interstellar Probe
- ITSP- Ionosphere/Thermosphere Storm Probes
- JIMO- Prometheus Jupiter Icy Moons Orbiter
- JPL- Jet Propulsion Laboratory
- JPO- Jupiter Polar Orbiter
- JPOP- Jupiter Polar Orbiter Probes
- JWST- James Webb Space Telescope
- LASCO- Large Angle and Spectrometric Coronagraph Experiment
- LEO- Low Earth Orbit
- Leo LFSM- LEO Low Frequency Soil Moisture
- LF- Life Finder
- LFF InSAR- L-band Formation Flying InSAR
- LHP- Loop Heat Pipe
- LIDAR- Light Detection and Ranging
- LISA- Laser Interferometer Space Antenna
- LITE- Lidar in Space Technology Experiment
- LM- Lockheed Martin
- LOLA- Lunar Reconnaissance Laser Altimeter
Acronyms

- LRO- Lunar Reconnaissance Orbiter
- Lunar SPA-SR- Lunar South Pole-Aitken Basin Sample Return
- LUVO- Large Aperture Ultraviolet Optical Observatory
- LWIR- Long Wave Infrared
- L2 Interfr- L2 Interferometer
- MARSIS- Mars Advanced Radar for Subsurface and Ionosphere Sounding
- MC- Magnetospheric Constellation
- MCM- multi-chip module
- MCP- Micro-channel Plate
- MDI/SOI- Michelson Doppler Imager/Solar Oscillations Investigation
- MEMS- Micro-Electro-Mechanical Systems
- MEO- Mid Earth Orbit
- MER- Mars Exploration Rover
- MER RAT- Mars Exploration Rover Rock Abrasion Tool
- MHRSM- Mars High Resolution Spatial Mapper
- MIPS- Multiband Imaging Photometer for SIRTF
- MIRI- Mid Infrared Instrument
- MIT- Massachusetts Institute of Technology
- MLA- Mercury Laser Altimeter
- MLS- Microwave Limb Sounder
- MMIC- Monolithic Microwave Integrated Circuit
- MMS- Magnetospheric Multiscale
- mmWave- millimeter wave
- MMW- millimeter wave
- MODIS- Moderate Resolution Imaging Spectro-radiometer
- MGS MOLA – Mars Global Surveyor Mars Orbiter Laser Altimeter
- MIDP- Mars Instrument Development Program
- MRO- Mars Reconnaissance Orbiter
- MSFC- Marshall Space Flight Center
- MSL- Mars Surface Laboratory
- MSU- Microwave Sounding Unit
Acronyms

- MTRAP- Magnetic Transition Region Probe
- Nano- Nanotechnology
- NEAR NLR- Near Laser Rangefinder
- NGST- Northrop Grumman Space Technology
- NIRCam- Near Infrared Camera
- NIRSpec- Near Infrared Spectrometer
- NO- Neptune Orbiter
- NOAA- National Oceanic and Atmospheric Administration
- NRC- National Research Council
- NRO- National Reconnaissance Office
- NSCAT-NASA Scatterometer
- OSS- Office of Space Science
- OSW- Ocean Surface Winds
- Phoenix AFM- Phoenix Atomic Force Microscope
- PI- Planet Imager
- PIDDIP- Planetary Instrument Development and Definition Program
- PM- Planet Mapper
- QE- Quantum Efficiency
- QGG- Quantum Gravity Gradiometer
- QuickScat- NASA Quick Scatterometer
- RAM- Reconnection and Microscale
- RBSP- Radiation Belt Storm Probes
- SAFIR- Single Aperture Far Infrared Observatory
- SAR- Synthetic Aperture Radar
- SC- Stratospheric Composition
- SC/ Spacecraft
- SCOPE- Solar Connections Observatory for Planetary Environments
- SeaSat-JPL-designed Earth-orbital mission, launched in 1978, to flight-test five instruments
- SECCHI/STEREO- Sun Earth Connection Coronal and Heliospheric Investigation/Solar Terrestrial Relations Observatory
- SEU- Structure and Evolution of the Universe
Acronyms

- SI- Stellar Imager
- SiGe- Silicon Germanium
- SIR-A, B, C- Spaceborne Imaging Radars- A, B, C
- SIT- Sea Ice Thickness
- SLA 1 and 2- Shuttle Laser Altimeters 1 and 2
- SMD- Science Mission Directorate
- SOFIA- Stratospheric Observatory for Infrared Astronomy
- SOHO- Solar and Heliosphere Observatory
- SOT- Solar-B Solar Optical Telescope
- SP- Solar Probe
- SPI- Solar Probe Imager
- SRTM- Shuttle Radar Topography Mission
- SSD- Solid State Detector
- SSED- Solar System Exploration Division
- SSES- Solar System Exploration Subcommittee
- SWIR FPA- Short Wave Infrared Focal Plane Assembly
- TDI- Time Delay and Integration
- TES- Thermal Emission Spectrometer (Mars Global Surveyor)
- THEMIS- The History of Events and Macroscale Interactions During Substorms
- TIMED- Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics
- TIPS- tera instruction per second
- TOF- Time-of-Flight
- TOPEX- TOPEX/Poseidon- Joint US-French orbital mission
- TPF-C- Terrestrial Planet Finder-Coronagraph
- TPF-I- Terrestrial Planet Finder- Interferometer
- T/R- transmitter/receiver
- TRL- Technology Readiness Level
- TRMM- Tropical Rainfall Measuring Mission
- UM- University of Michigan
- UV- Ultraviolet
Acronyms

- UW- University of Wisconsin
- VIMS- Visual and Infrared Mapping Spectrometer (Cassini)
- Vis- Visible
- VISE- Venus In Situ Explorer
- WindSat- Ocean Surface Wind Measurements from Space
- WMAP- Wilkinson Microwave Anisotropy Probe