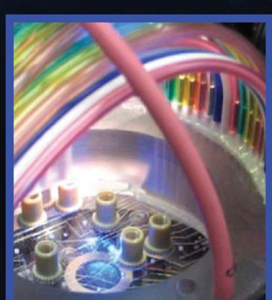
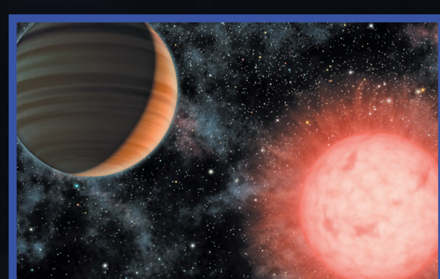
National Aeronautics and Space Administration

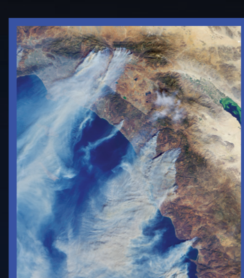
**JET PROPULSION LABORATORY**

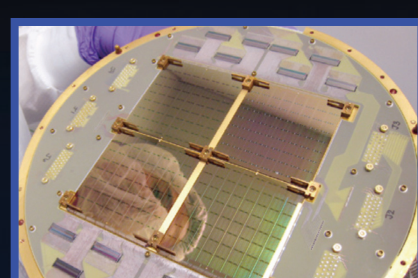
# Strategic Technology Directions

# 2009









# Preface

Strategic Technology Directions 2009 offers a distillation of technologies, their links to space missions, and science goals for NASA and the Jet Propulsion Laboratory. It derives from and updates the previous Strategic Technology Plan 2005 document.

Technologies are deemed strategic if they strive to address NASA's and JPL's grand challenges and aspirations. Examples of fundamental challenges that we and our technologies will be called upon to address are:

- *What is the concentration of carbon dioxide and other greenhouse gases that the atmosphere and oceans can absorb without crossing climatic tipping points?*
- *Are there other habitable environments and life on other bodies in the solar system and beyond?*
- *What are the structures and properties of other planetary systems?*
- *What is the nature of dark matter and dark energy, and can energy be harnessed on Earth from them?*

Many overarching technical challenges await us beyond the present horizon, if we are to respond to these and other goals:

- *How can we test, place, and operate 10m, 20m, 50m, 100m radar/sub-mm/IR/optical apertures in space?*
- *What is the technology and operations path to provide a 10-fold bandwidth increase per decade for the Deep Space Network?*
- *How do we provide a 10-fold increase in spacecraft power?*
- *How do we conduct missions to return samples to Earth from Mars and other large planets, which we must before sending people there?*

It is difficult to resist a sense of appreciation and pride of what has been achieved in the half-century since the space era began. Technologies developed to support this development, and the value of the science return, have been incalculable. It allowed us to time-stamp the beginning of the universe and appreciate that the kind of matter we are made of comprises only about 4% of it, to learn more about our solar system than all the knowledge humans had distilled since they began to ponder the sky, to understand more about Earth and the dynamics of global change from both natural causes and human activity.

Strategic technologies identified in this document also represent technology capabilities that the Jet Propulsion Laboratory believes are essential to continuing progress in pursuit of NASA's and JPL's mission, national goals, and in addressing global concerns. Advancing these technologies, that often push the theoretical limits of performance, is a major challenge, not least because such advances require sustaining an environment of imagination, creativity, and a culture of innovation for decades of dedicated effort at a time when support is provided on much-shorter time scales and sometimes not at all. The balance of what is invested on near-term projects vs. long-term development creates a healthy tension and taxes the wisdom institutions can muster. Yet without such advances, what can be achieved in the future is limited.

In reviewing this document, one is also impressed by the spectrum of knowledge and specialists' technical skills that support these advances. An organization, however, also relies on individuals whose talents bridge across science, technology, engineering, and management boundaries, joining these to create the complex systems of the next-generation missions and the resulting scientific understanding.

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# Contents

# About This Document

The *JPL Strategic Technology Directions 2009* document identifies technology areas essential for JPL's continuing contribution to NASA's future success and that should be developed with JPL leadership. The identification of these technology areas facilitates the communication of JPL's priorities and needs, prioritizes the acquisition and development of new technology by focusing resources, and provides a context for the development of alliances and partnerships. The technology directions documented here will be shared with the JPL technology research community and NASA Headquarters, and made available to JPL partners or potential partners. *JPL Strategic Technology Directions 2009* will also guide JPL technology work funded by NASA and non-NASA sponsors, as well as guide internal science research and technology-development investments.

While this document identifies strategically important areas of technology development, there are many other technologies that remain important to JPL's ability to successfully contribute to NASA's space exploration missions, including mature technologies that are commercially available and technologies whose leadership is firmly established elsewhere. JPL's approach is to partner with leading technology organizations and to actively participate with them to provide timely and mature technology capabilities to planned missions. In all such cases, it is important that JPL retain the expertise to provide adequate interfaces to the corresponding technology developers.

## Updating the 2005 Strategic Technology Plan

In 2005, JPL published the Strategic Technology Plan as a complement to JPL's 2004 Implementation Plan. The 2005 Strategic Technology Plan identified a set of thirteen technologies that strategically trace to JPL's exploration and science goals. Each of these thirteen technologies satisfies three fundamental requirements:

- The technology is of critical importance to JPL's ability to successfully contribute to NASA's exploration goals and answering NASA's science questions. In other words, it must provide an enabling or significantly enhanced capability without which future missions would not be possible or would fall short of mission exploration goals and science objectives.
- It is an area in which JPL makes a unique or distinguishing contribution that is not available externally.
- It requires some overt action on the part of JPL or NASA management to foster its development to enable its delivery at a suitable maturity level and its eventual infusion into flight missions, instruments, and operational ground systems.

For each strategic technology, the 2005 Plan identified quantitative goals and recommended timelines to accomplish the stated goals. Beginning with key science questions and exploration goals for each JPL Directorate, a linkage was established between the technologies needed to answer these questions and to achieve the goals. The traceability between the Strategic Technologies and the Directorate science questions and exploration goals critically informed the 2005 Plan.

The 2005 Plan also recommended that the list of strategic technologies be reassessed from time to time. The *JPL Strategic Technology Directions 2009* document is the first update of the 2005 Plan. The JPL Technology Working Group (TWG) led an assessment of the 2005 Plan's strategic technologies and conducted a review of the Directorate key science questions and exploration goals. Since the scope of the review and assessment activity was to develop and maintain a technology strategy, the TWG concluded early in its review and assessment activity that preparing a plan—that would include performance milestones, budget, and schedule for each of the strategic technologies—was outside the scope of this effort. It was thus decided that the 2009 document would be called a "directions" report and that the planning elements supporting technology development would be maintained elsewhere.

What follows discusses the updated list of Strategic Technologies—now ten in number. The update of the JPL Directorate key science questions and exploration goals is included as Appendix A. Being an update, the approach and methods for arriving at the 2009 strategic technologies derive from the *2005 Strategic Technology Plan.*

# Large-Aperture Systems

1

**Large-aperture systems enable astrophysical and Earth-observing optical, infrared, as well as active and passive radio-frequency, observations.**

Advances in large-aperture systems make it possible to increase our knowledge of the universe and our planet. Larger-aperture systems enable JPL to accomplish two important goals: (1) to further our understanding of the origins and evolution of the universe and the laws that govern it, and (2) to make critical measurements that improve our understanding of our home planet and help us protect our environment. Prior NASA missions, such as the Hubble Space Telescope and the Shuttle Radar Topography Mission (SRTM), advanced these goals, collecting many spectacular images and a wealth of scientific data that change how we view the world we live in. Current missions, such as the James Webb Space Telescope (JWST) and the Soil Moisture Active/Passive (SMAP) instrument, promise additional insight in the coming years.

The next generation of observatories will benefit from additional advances in large-aperture-systems technology. These observatories will collect signals from across the electromagnetic spectrum to help answer key scientific questions: Is there life on other planets? What are the origin and formative processes of the universe? What are the fundamental dynamical environmental processes of Earth? Visible observatories currently being considered for development will require optical apertures of > 8 m, while maintaining a wavefront error < 10 nm. Infrared observatories will investigate the infrared portion of the spectrum with a sub-10-K cryogenic telescope of similar diameter. Follow-ons to the Microwave Limb Sounder (MLS) will provide more precise measurement of the vertical profiles of atmospheric gases, temperature, pressure, and cloud properties, thereby improving our understanding of Earth's atmosphere and global change from rising temperatures and other anthropogenic as well as natural causes. Additional Earth science missions will use radio frequency and lidar measurements to help predict earthquakes, measure global-change impact, and monitor groundwater. Large-aperture systems will also be called upon to provide information relying on a very large portion of not only the electromagnetic but also the gravitational spectrum, as required by the distributed (formation-flying) apertures supporting the Laser Interferometer Space Antenna (LISA) joint ESA–NASA mission.

Developments in large-aperture systems will also enable future smaller missions to increase their scientific return by driving down the mass and volume needed for apertures of a given size.

To enable such future missions, several key large-aperture-system technologies must be developed:

- **Lightweight apertures** — to transmit and/or collect the electromagnetic signal for measurement while maintaining a launchable mass and volume.
- **Lightweight, precision-controlled structures** — to deploy and control the aperture elements.
- **Integrated, low-temperature thermal control** — to establish and stabilize the aperture's baseline temperature.
- **Advanced metrology** — to measure the deformation of the precision structure and aperture elements.
- **Wavefront sensing and control** — to measure the quality of the science data and correct the shape of the aperture elements and/or metering structure.
- **Precision-pointing systems** — to acquire, point, and stabilize the line-of-sight of large apertures on desired targets while maintaining demanding pointing accuracies.

Collectively, as part of an integrated system, these technologies facilitate the development of large-aperture systems with two key architectural capabilities: deployment, and adaptive metrology and control. They allow missions that are packaged in a compact volume, that can deploy to precise positions, and that can actively maintain their figure.

### 1.1. Lightweight Apertures

Large-aperture systems are fundamentally enabled by progress in reducing the weight of apertures that transmit, receive, and/or reflect electromagnetic signals for measurement. Key figures of merit are mass and volume. Advances are needed in three critical areas: lightweight optics, lightweight reflectors, and lightweight synthetic-aperture radars (SAR).

Lightweight optics have progressed from Hubble mirror areal densities of 180 kg/m$^2$ to the more recent Spitzer and JWST designs that have achieved areal densities of 28 and 20 kg/m$^2$, respectively. Technology goals are to produce a diffraction-limited visible optic in a 2 m segment size with areal densities less than 10 kg/m$^2$. Such a specification presents significant challenges because of acoustic loading during launch and gravity sag when testing on Earth. Key enabling features may include actuated mirrors, fiber-reinforced materials with a zero coefficient of thermal expansion (CTE), and damping.

Lightweight reflectors for operation in the submillimeter region have reduced surface-figure requirements and benefit from technology developments similar to those for lightweight optics. Monolithic apertures up to 8 m in size will be required to support a follow-on mission to MLS. These apertures need similar areal densities (5 to 10 kg/m$^2$) but require increased thermal stability because mission concepts dictate that they be exposed to direct sunlight. Key enabling technologies may include active materials and zero-CTE–fiber-reinforced materials.

*Microwave reflector under test in 25-foot solar simulator at JPL.*

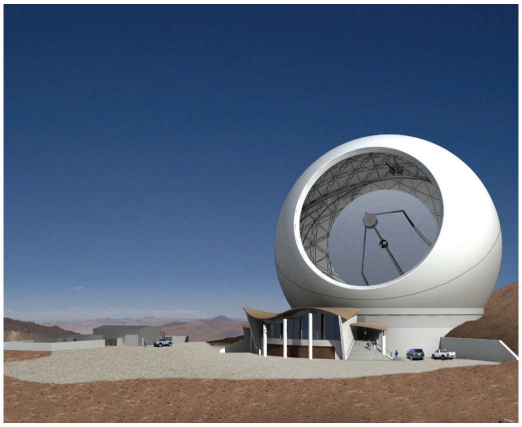
Lightweight synthetic-aperture radar systems package the transmit/receive electronics into lightweight panels. Developments are required to replace these panels with membrane antennas for L-band and millimeter-wave active arrays. Technology developments focus on the construction of large-format printed circuits (5 to 10 m class) and the integration of lightweight electronics with membrane materials.

### 1.2. Lightweight, Precision-Controlled Structures

Strong, lightweight, dimensionally precise, dynamically stable deployable structures that position lightweight apertures are a fundamental enabling capability for future space exploration. Lightweight precision-controlled structures involve multiple subtechnologies, including lightweight, deployable mounting structures and boom-/strut-supported membrane antennas for radar. These technologies will enable increased aperture sizes across the electromagnetic spectrum: in the visible to infrared, submillimeter, or microwave regions involving apertures too large to be stowed unfolded in a launch shroud. Dimensional stability is an overriding structural design driver for these large deployable apertures; their stability is driven by constraints derived from system mass and stiffness, and thermal and dynamical loads. As aperture size increases, and system mass density is correspondingly decreased, performance testing of these apertures in a 1 g environment requires both highly specialized facilities and special testing methodologies that are coupled to integrated modeling and simulation technologies.

### 1.3. Integrated Low-Temperature Thermal Control

Large-aperture systems require thermal control to maintain dimensional stability. Thermal control technology is enabling future astronomy/astrophysics missions, including cosmic microwave background measurement, galactic and stellar evolution observations, and extrasolar planet detection. The most extreme requirements are driven by optical structures where visible wavelengths dictate the structural deformation allowed and hence dictate vibration and thermal environment control. Longer wavelengths, from the infrared to the submillimeter and millimeter regions of the electromagnetic spectrum, also require thermal control to meet error budgets at large aperture sizes. Very cold apertures are needed for ultrasensitive observations at these wavelengths, with demanding requirements on uniformity of temperature across the aperture. For membrane systems in the microwave region, a controlled environment is advantageous. Integrated low-temperature thermal control encompasses multiple technologies, including millikelvin coolers, cryocooled apertures, integrated cooler and detector systems, and large deployed sunshades.



Rendering of Cornell Caltech Atacama Telescope.

## 1.4. Advanced Metrology

Metrology refers to the highly accurate measurement of the metering structure. The next generation of astrophysics missions requires precise control of active optics on flexible structures. Advances in metrology subsystems architectures, components, and data processing will be necessary, with particular emphasis on developing multiple laser-beam launchers for ultra-high-precision dimensional measurements in spatial interferometry, as well as on very-high-precision dimensional measurements for future deployable radar phased-array antennas.

Advanced metrology is needed using two different approaches: point-to-point and imaging. Point-to-point metrology requires the development of high-precision metrology gauges and optical fiducials, integrated lightweight beam launchers, ultrastable lasers, and frequency shifters for metrology gauges. Imaging-based metrology requires the development of full-aperture metrology gauges and embedded grating technology. Both approaches benefit from radiation-hardened fiber-optic systems and components for routing metrology laser signals.

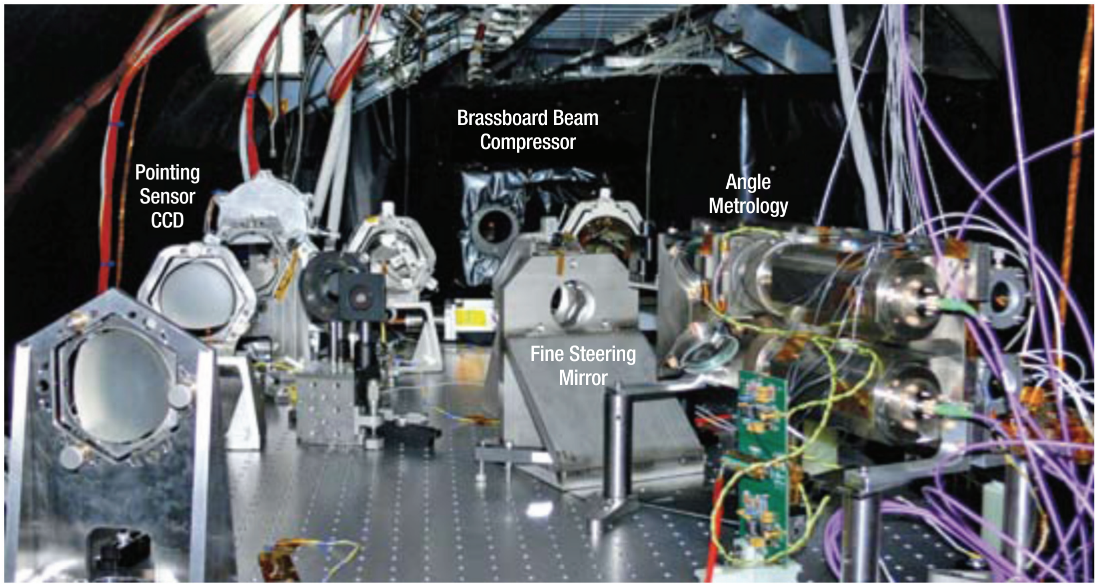
## 1.5. Wavefront Sensing and Control

Wavefront sensing and control is an essential component of active and adaptive optics. In the case of *adaptive optics*, which typically refers to systems targeting the correction of the deleterious effects of atmospheric turbulence, the fundamental advantages of larger apertures are: (1) more collecting power for greater sensitivity, and (2) higher spatial resolution. The latter advantage is compromised by atmospheric turbulence when observing the ground from space, or space from the ground, with meter-class apertures. Adaptive optics systems are designed to update readings of turbulence-induced wavefront distortions and to correct at the high temporal frequencies (up to ~ 3 kHz) encountered in atmospheric turbulence. On the other hand, *active optics* are also designed to correct various types of system deformations, such as structural and fabrication imperfections; or systematic responses to thermal loads on the primary mirror, support-structure characteristics and response, etc. Active optics systems are a major element in the lightweight, precision-controlled structures theme described above (see Sec. 1.2.) Active optics systems update at much slower rates and can use different correction elements.

Wavefront sensing and control refers to both the hardware and software technologies that power active and adaptive optical systems. As its name suggests, wavefront sensing provides a means of measuring and comparing the measured wavefront in an optical system with the ideal wavefront. Wavefront sensing can also be employed to fingerprint an optical system, i.e., retrieving the system's nominal optical prescription as well as indicating the origins of the observed aberrations. Wavefront control is the means by which inputs obtained from wavefront sensing are transformed into changes in deformable or otherwise reconfigurable elements within an optical system, bringing the measured wavefront into closer conformance with the ideal. High-speed adaptive optical systems utilize rapidly deformable mirrors in the optical system that are much smaller than the telescope primary mirror, yet are able to correct wavefront aberrations across the entire aperture area. Technology advancements needed for wavefront sensing and control include fast deformable mirrors with high spatial-frequency capability, high-sensitivity wavefront-aberration sensors, efficient algorithms for computation of phase-front and alignment corrections, and high-precision actuators.

## 1.6. Precision Pointing

Precision pointing is an integral part of the next generation of large-aperture observatories, including telescopes, interferometers, coronagraphs, and Earth-observing systems. Increasingly stringent pointing accuracy and stability levels are required for future missions to image distant worlds, measure distance between dim stars, enable long science exposures to image Earth-like planets around nearby solar systems, or to investigate from space small-scale features of our planet with instruments characterized by a narrow field of view (FOV) or pencil beams. Precision pointing requires rejection of disturbances across a wide spectrum of frequencies. Low-frequency disturbances are generally introduced by sources external to the spacecraft, such as solar pressure or atmospheric drag. High-frequency disturbances are introduced by internal sources such as reaction wheels, thrusters, or payload-cooling systems. Different disturbance sources excite different spacecraft structural modes, and pointing stability is achieved through stabilization of these vibration modes to meet performance requirements. Large-aperture, lightweight, flexible structures are particularly challenging due to control-structure interactions, requiring a control-oriented design framework. Segmented apertures bring additional challenges associated with con-




*The Guide-2 telescope (G2T) testbed, shown here in the vacuum chamber, has demonstrated star-tracking capability at an unprecedented 30 μas level.*

trolling multiple segments using a large number of actuators and sensors. Large-aperture pointing systems typically require a hierarchical control approach where the problem is decomposed into multiple coordinated control loops, defined by separating time scales and spatial degrees of freedom. Examples include alignment and calibration strategies, low-frequency active control (such as the spacecraft attitude control system), mid-frequency passive vibration isolators (such as reaction-wheel isolators, spacecraft isolators, solar array dampers), and high-frequency stabilization (such as fast-steering mirrors and hexapods). Pointing design can also be driven by special requirements such as object tracking and coordinated mirror scanning. Achieving precision pointing performance in large-aperture, lightweight, flexible structures requires advancements in such areas as hierarchical pointing systems, fine-pointing sensors and actuators, optimal fusion of multiple sensor types (fine-guidance sensors, inertial reference units, star trackers, Shack-Hartmann wavefront sensors, edge-sensors, phase-retrieval cameras, temperature sensors, etc.), knowledge-transfer systems, minimization of control-structure interactions, and structural design for maximum control authority. Multidisciplinary modeling efforts and experimental validation are essential elements in developing an advanced pointing system design. Modeling efforts involve developing high-fidelity integrated models of optical, structural, and thermal effects, actuators and sensors (including nonlinearities and hysteresis), and environmental disturbances (see Sec. 10 on Lifecycle Integrated Modeling and Simulation). Experimental validation of subarcsecond pointing performance requires an investment in high-fidelity ground-based testbeds.

## Summary

*Large-aperture systems improve collection across the electromagnetic spectrum. By combining lightweight apertures with precision deployable structures, larger, more capable apertures can be launched. When combined with low-temperature thermal control, advanced metrology, precision pointing, and wavefront sensing and control, such large-aperture systems can maintain diffraction-limited performance. Large-aperture systems enable the design and operation of future missions that improve our understanding of our planet and our universe, and other missions of national interests.*

# Detectors and Instrument Systems

2

**Detectors and instrument systems enable scientific investigations into the origin, state, and fate of the universe; habitability and the emergence of life; and the evolution of Earth's structure, climate, and biosphere. They also enable accurate control of complex engineering systems.**

*The Microdevices Laboratory (MDL) provides end-to-end capabilities for design, fabrication, and characterization of advanced components, sensors, and microdevices.*

Instruments are used in all space missions. Large missions typically carry a broad suite of instruments for a range of investigations, while small missions may be designed around individual instruments or smaller suites of focused instruments. In both cases, highly capable instruments are a key element of the successful development and operation of high-performance NASA and other missions. These systems enable scientific investigations into the origin, state, and fate of the universe; habitability and the emergence of life; and the evolution of Earth's structure, climate, and biosphere. They also enable accurate control of complex engineering systems, including spacecraft during entry, descent, and landing and spaceborne optical systems as they make precise astronomical observations.

Detector and instrument systems development is primarily aimed at the highest-performance, least-resource-demanding detectors and instruments possible to enable the scientific and engineering measurements needed to accomplish NASA's science goals. This is an ongoing effort, with major overarching challenges to reduce power, volume, mass, noise, and complexity while increasing sensitivity and data-rate capabilities. Future development goals are to advance onboard electronics, processing, and autonomy to reduce data-rate requirements and improve instrument capability and mission throughput.

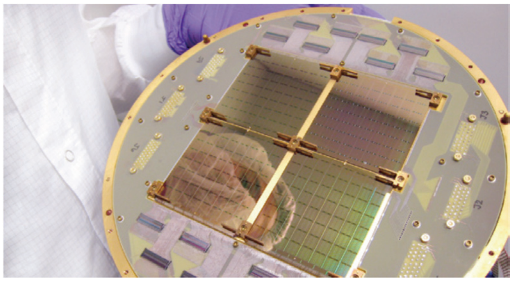
Areas of strategic focus include:

- **Detectors and focal plane systems** — that push performance to physical limits while maintaining sensitivity and allowing precision spaceborne calibration.
- **Active remote sensing** — that probes environments using radio-frequency radars, GPS signals, and laser-based ranging, absorption, and spectroscopic systems.
- **Passive remote sensing** — that incorporates the relevant optics, detectors, and heterodyne techniques, to provide cameras, spectrometers, radiometers, and polarimeters across most of the electromagnetic spectrum; as well as submillimeter imaging arrays, hyperspectral imaging systems, and atomic quantum sensors.
- **In-situ sensing** — that probes the state and evolution of solar system bodies by investigating physical properties, morphology, chemistry, mineralogy, and isotopic ratios, as well as by searching for organic molecules and for evidence of previous or present biological activity.
- **Active cooling systems for detectors and instruments** — that provide measurements with an adequate signal-to-noise ratio and that are integrated with the detection system rather than standing separate.

Progress in these areas, which encompass an especially broad set of technologies, requires specialized facilities such as the JPL Microdevices Laboratory for fundamental device research, as well as for the development of novel, flight-proven detectors and instruments that enhance NASA's mission and are not available elsewhere.

## 2.1 Detectors and Focal Plane Array Systems

Detectors and focal plane array (FPA) systems are central to scientific measurements across a wide range of the electromagnetic spectrum and generally require optimization

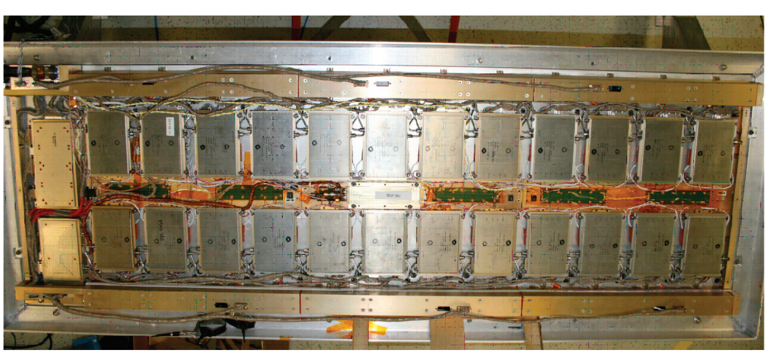


*A tile of 145-GHz TES dual-polarization bolometers for the BICEP-II instrument for a telescope at the South Pole. The complete focal plane array will have 4 tiles x 64 pixels x 2 polarizations.*

for the expected signal frequency wavelength and levels. The signals of interest can be exceedingly weak, barely above noise levels, and these detectors and focal plane arrays must be designed and engineered to reduce noise to theoretical physical limits, maintain sensitivity across the requisite detection bandwidth, and allow precision calibration in the space environment. Driven by NASA science and optical telecommunication goals, the detectors and focal planes developed by JPL operate over bands and at sensitivity levels not available in commercial systems, thus requiring in-house development. Detectors can be characterized as either superconducting or semiconducting. Superconducting detectors include superconductor-insulator-superconductor (SIS) detectors, hot-electron bolometers, microwave kinetic inductance detectors (MKID), and transition-edge sensors (TES). Semiconducting detectors include photoconducting; complementary metal-oxide semiconductor; and infrared arrays using quantum wells, wires, and dots and including superlattice and heterojunction structures. Some of these semiconducting detectors are also used as particle detectors and in developing significantly more efficient solar cells. A key development in focal plane arrays includes very large focal planes, extending to the gigapixel level, incorporating multiple detector technologies.

General detector development challenges include reducing pixel-to-pixel nonuniformity, noise, and power requirements, as well as improving response uniformity, radiation hardness, spectral range, tunability, and quantum efficiency. Detector systems are required and are being developed to operate at higher temperatures with higher signal and polarization sensitivity, as well as having greater array sizes. Additionally, development is under way in multiband field-programmable arrays, avalanche gain devices for particle and photon counting, low-noise electronics, and random-access readouts, buttable arrays for tiling to form large focal plane arrays, three-dimensional packaging structures, and improved detector fabrication processes. Improved detector materials development is also a critical priority.

*UAVSAR active phased array — a reconfigurable L-band SAR designed to acquire airborne repeat track SAR data for differential interferometric measurements.*



Focal-plane system challenges include developing efficient ways to create very large arrays, providing appropriate array thermal control, potentially accommodating focal surface curvature (as in the Kepler mission, which launched on 6 March 2009 and achieved first light on 9 April 2009), and developing very low-noise, low-complexity readout electronics. A major new area of opportunity is large-format sensitive detector arrays for wavelengths beyond 40 μm. Longer wavelengths represent a new frontier, and large (kilopixel) arrays with good sensitivity are required for next-generation flight systems.

## 2.2 Active Remote Sensing

Instruments for active remote sensing are strategically grouped into radar systems, both full and synthetic aperture (SAR); global positioning systems (GPS); light detection and ranging (lidar); and laser spectroscopy, including absorption spectroscopy, laser-induced–breakdown spectroscopy (LIBS), and Raman spectroscopy.

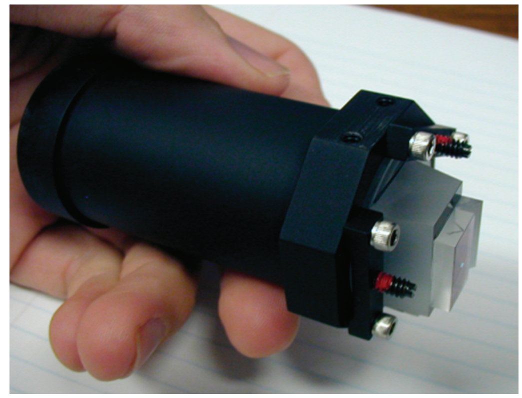
To satisfy NASA's goals in Earth and planetary science, radar systems must have a high degree of functionality. Requirements include the ability to employ multipolarization transmit and receive signals, multiband operation, adaptable resolution, scanning for increased swath, and very high measurement accuracy. JPL has extensive experience in developing and integrating radar technologies to meet scientific measurement requirements. For example, the NASA Spaceborne Imaging Radar/Synthetic Aperture Radar was the first and only SAR that was fully polarimetric at C-band and L-band, with independent horizontal and vertical channels for independent steerability, as well as phase-scanning in elevation and limited phase scanning in azimuth. Current interferometric systems that can measure Earth surface deformation for geophysical research are another example. Specific technologies needed to meet current and emerging scientific measurement requirements include low-mass antenna systems integrated with electronics, wavefront control technology, and large deployable mesh antenna systems (see Sec. 1), as well as the development of multifrequency feeds. Advances in real-time onboard data processing and the ability to handle very large data sets are also required. Other essential technologies include high-efficiency, high-power radio-frequency transmitters; phase-stable electronics for interferometry applications; and miniaturization of both transmit and receive (T/R) electronics at specific frequencies, from VHF to W-band. Altimeters at Ku- or Ka-band, with centimeter accuracy and approximate spatial resolution of 250 m, along with Ka-band landing radars with 10 cm/s velocity accuracy and approximate 1% slant-ranging accuracy, are under development. Similarly, scatterometers for ocean vector wind measurements require a similar set of technologies to meet Earth science measurement requirements.

State-of-the-art GPS receivers flying on the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), and other missions, measure precise radio-frequency signals from GPS satellites to characterize Earth's atmosphere and ionosphere by tracking the signals during occultation geometries. Such geometries occur thousands of times per day for the six-satellite COSMIC mission and provide vertical profiles of the atmosphere and ionosphere with global coverage. COSMIC has demonstrated the ability to measure temperatures in the upper troposphere/lower stratosphere to about 0.05 °C. Precision orbit determination (POD) allows the geolocation of the COSMIC satellites to less than 1 cm (radial dimension) in post-processing; GPS receivers indirectly use POD on ocean altimetry missions required to measure ocean topography, such as the Jason and Ocean Surface Topography missions. Additionally, surface-reflected GPS signals can be observed by spaceborne receivers and may prove to be a viable alternative or complement to traditional radar altimetry for ocean topography.

Modernization of the current GPS system and the emergence of new global navigation satellite systems (GNSS), such as Russia's GLONASS (Global'naya Navigatsionnaya Sputnikovaya Sistema, or Global Navigation Satellite System) and Europe's Galileo, for example, represent new opportunities that will increase the density of radio occultation measurements and, given new frequencies, complement current GPS capabilities to characterize the atmosphere and ionosphere. The ability to reprogram or reconfigure GNSS receivers after launch is one technology challenge, especially for signals that may not be currently well defined (or known). A second major technology challenge is onboard processing of radio occultation data to penetrate more deeply into the Earth's atmosphere, down to the surface, for nearly every occultation event.

Altimeters and backscatter instruments are commonly used in laser ranging systems, and a three-dimensional 128 × 128–pixel laser imaging system is in development for planetary entry, descent, and landing applications. Backscatter lidars are currently used in Earth orbit with future low-Earth-orbit (LEO) applications providing measurements of greenhouse gases. Reliable, compact, efficient, space-qualified laser sources are a pressing need, as are low-noise, high-sensitivity, and high-speed detector arrays coupled with lower-noise read-out integrated circuits. Integrating these components and subsystems into flight-realizable instrument systems presents a major challenge and is the ultimate goal.

Laser absorption spectroscopy systems, such as the 4 kg, 40 W tunable laser spectrometer on Mars Science Laboratory (MSL), and laser-induced–breakdown spectroscopy (LIBS) systems are in common scientific use. LIBS systems, which are commercially available and are being developed for space applications, have demonstrated meter-range standoff measurements. LIBS systems for quantitative analysis in high-atmospheric-pressure regimes such as Venus and Titan require additional development. An improved ability to tailor wavelengths without requiring large investments would significantly simplify absorption spectrometer development.



*Complete optical assembly of a miniature, fast (f/1.8), high-uniformity Dyson imaging spectrometer being developed for ocean science and planetary mineralogy applications.*

Similarly, 1-meter standoff point measurements have been demonstrated with sensitive ultraviolet–visible–near-infrared Raman spectrometers, which are also available commercially and are being developed for space applications. Extensive standard mineralogy and organic compound reference libraries are available, and a combined LIBS/Raman instrument with simultaneous LIBS and Raman measurements has been demonstrated as well. Sample fluorescence suppression in rover-capable Raman instruments and the miniaturization of imaging Raman systems are being developed to enhance science returns.

## 2.3 Passive Remote Sensing

Passive remote sensing systems, which incorporate the relevant optics, detectors, and heterodyne techniques, include cameras, spectrometers, radiometers, and polarimeters across most of the electromagnetic spectrum, submillimeter imaging arrays, hyperspectral imaging systems, and atomic quantum sensors.

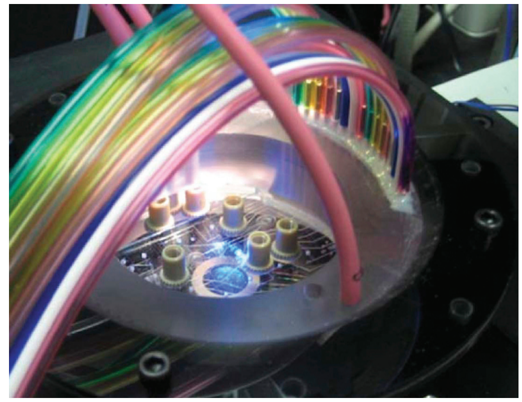
Spectrometers for radiometry employing SIS technology (see Sec. 2.1) are being used on-orbit; e.g., the Herschel heterodyne instrument for the far-infrared that operates to 1300 GHz. Additional spectrometers operate from the millimeter-wave to the far-infrared with noise temperatures necessary to meet astrophysical measurement requirements. These systems are typically cryogenically cooled. Room-temperature heterodyne receivers have been demonstrated from 100 GHz to 2500 GHz. Technology advances in this area will extend usable ambient mixer frequency ranges and provide advanced subharmonic mixers, near- and mid-infrared (NIR and MIR) heterodyne receivers and widely tunable, narrow-linewidth monolithic diode-laser local oscillators that operate at room temperature. Currently under development are far-infrared spectrometers based on transition-edge sensors (see Sec. 2.1) that are sensitive enough for background-limited operation on cold space telescopes.

Also under development are solar occultation Fourier transform infrared (FTIR) spectrometers that will seek trace gases in planetary atmospheres. These spectrometers use onboard Fourier transform calculation to reduce data downlink volume, and have been demonstrated. Flight application, however, requires improvements in their onboard data-processing capabilities.

High-sensitivity submillimeter imaging arrays operating to 360 GHz have been demonstrated or are in use in flight instruments, and radiometer arrays using compact, low-cost receiver modules up to 190 GHz have been demonstrated. Future developments will include improved antenna coupling methods for the far-infrared as well as arrays of ultrasensitive detectors for background-limited spectroscopy. Also under development are increased array formats to thousands of detectors that provide high system sensitivity in multiple observing bands to take advantage of the large gains possible with cryogenic telescopes; these developments include significant multiplexing improvements and high-yield fabrication processes to realize fundamental sensitivity limits.

Hyperspectral-imaging and imaging-spectrometer systems are a key instrument technology, with current systems, such as the Moon Mineralogy Mapper (M3), providing high-quality scientific data on-orbit. These systems are moderately fast optically (f/2.5 to f/3.5), and have 600 spatial pixels cross track with 260 spectral pixels per spatial pixel in 10 nm steps in the 430–3000 nm spectral range. Onboard processing is limited to simple summing and compression. In development at this writing are optically faster, high-uniformity systems approaching f/1 for outer planet missions that enable spectroscopy in the image domain while spanning wide spectral ranges from the UV to the thermal infrared. Development goals include low-noise broadband detector arrays with large detector elements (~ 36 μm pixel pitch) and dispersive systems for both high and moderate spectral resolution that are either purposely polarization-insensitive or polarimetric. Accompanying increased data demands are onboard computing systems that can process and identify spectral signatures and compress information for transmission.

Atomic quantum sensors include a ground-based gravity sensor that uses interfering atomic wave functions and has demonstrated the most precise known terrestrial gravity gradient measurements. Similarly, JPL has developed the world's most accurate atomic clocks that are approximately 1 liter in volume and 1 kg in mass, with a frequency stability of $10^{-15}$. Challenges include increasing accuracy while reducing mass, power requirements, and complexity. This will require ultrastable, frequency-agile, narrow-linewidth lasers as well as improvements in the optical system. Improving clock stability to $10^{-21}$, for example, would allow single-arm measurement of gravitational waves, significantly simplifying missions such as the Laser Interferometer Space Antenna (LISA).



*In-situ lab-on-a-chip analysis system being developed for future planetary missions.*

## 2.4 In-Situ Sensing

JPL has conducted spaceborne investigations of all the planets in our solar system out to Neptune and is now focused on landed missions to conduct detailed surface and subsurface studies that cannot be accomplished remotely from space. These studies require instruments that can operate in-situ to help us understand the state and evolution of solar system bodies by investigating physical properties, morphology, chemistry, mineralogy, and isotopic ratios, as well as by searching for organic molecules and for evidence of previous or present biological activity. In-situ sensing is inseparable from the problem of sample access (e.g., drilling, grinding, crushing) and processing (e.g., concentration and extraction) that are covered in Sec. 4. In-situ sensing areas include analytical instruments for life detection; particle, isotopic, and molecular sensors; imaging systems; physical sensors; and spectrometers.

Analytical instruments for life detection are exemplified by the in-situ Viking life experiments and the Mars Phoenix mission instruments (microscopy, electrochemistry, and conductivity analyzer; thermal and evolved-gas analyzer). X-ray diffraction and gas chromatography–mass spectrometry instruments are under development for MSL and other missions. Such instruments will dramatically extend "lab-on-a-chip" technology with microfluidics, subcritical extraction, and electrophoresis. Significant further development is needed in crushing, grinding, and drilling in both rock and ice, as well as laser ablation and sample feeding technologies. Advances in microfluidic technologies (including valving, actuation, and control) would represent enabling progress for in-situ space applications, as well as yield important unattended in-situ sensing and analysis capabilities on Earth.

Particle, isotopic, and molecular sensors (including gas chromatographs and mass spectrometers) are in wide scientific use and are being developed for the International Space Station and miniaturized for planetary science applications. Different types of molecular sensors using functionalized binding probes and quantum dots have been developed. Primary challenges in this area are in mass, size, and power reduction, while maintaining measurement precision and increasing measurement specificity.

Imaging systems include mature color and monochromatic microscope and camera systems that are flown routinely as part of general scientific payloads. Primary challenges in this area include mass, volume, and power reduction, as well as increasing resolution and speed, broadening sensor bandwidth, and onboard processing for extracting image information. Polarization sensitivity is also an important issue.

Physical sensors, including metrology systems as well as sensors for temperature, pressure, heat flow, seismometry, etc., are well established and commonly flown. Physical-property probes for seismometry, heat flow, dust properties, etc., require improved packaging, noise immunity, and operational protocols. Fledgling technologies such as optical sensing methods for meteorology are also promising. Miniaturization and the incorporation of new technologies such as carbon nanotubes are important as well. Improvements in microfluidics fabrication, operational protocols, and microsensors are needed to support multiple samples resulting from rover or drill missions. Finally, robustness for extreme environments needs improvement.

Spectrometers include Raman spectrometers that provide nondestructive rock target selection and material identification, while absorption spectrometers, such as the tunable laser spectrometer (TLS) and the Sample Analysis at Mars (SAM) instrument suite on MSL, cavity ring-down spectroscopy, cavity-enhanced, direct-comb spectroscopy and noise-immune, cavity-enhanced, optical-heterodyne, molecular spectroscopy provide extremely sensitive analytical techniques. The miniature thermal emission spectrometer represents the state of the art in rover mast spectrometers, and reflectance imaging spectrometers at approximately 30 cm to 1 mm resolution for rover arms are being proposed. Advanced room-temperature tunable lasers with high efficiency and needed output power are being developed in support of our spectrometer efforts. Furthermore, spectrometer system design could be simplified by combining multiple nondestructive spectroscopic and imaging techniques to increase the certainty of identification and accuracy of characterization.

## 2.5 Active Cooling Systems for Detectors and Instruments

Many instruments, such as those that deal with infrared astronomy and Earth science, must be actively cooled to provide measurements with an adequate signal-to-noise ratio. Cooling may be necessary only for detectors, for example, to reduce dark current or enable superconductivity, or may extend to critical optical components to reduce thermal emissions that mask the very faint signals being observed. The most sensitive spectrometers for astrophysics, for example, require cooling entire instruments to temperatures as low as 50 to 100 mK for background reduction.

Active detector and instrument cooling systems include passive radiators, stored cryogens (dewars), cryocoolers (magnetic, mechanical, sorption/evaporative), and thermal transport and isolation techniques. Challenges are to develop cryocooler systems that can efficiently reach 50 to 100 mK for astrophysics missions, and reach < 4 K for Earth-science missions. These coolers must be highly efficient, provide continuous cooling, have adequate thermal lift, impose minimal vibration and electromagnetic interference upon instrument performance, minimize their overall impact on system complexity, and have long life in the harsh space environment.

Two intermittent-cooling 50 mK adiabatic demagnetization refrigerators and one 300 mK intermittent-cooling evaporative cooler have flown, both staged from stored cryogens at < 2 K; both are dependent on the high power-rejection capability provided by a stored cryogen. No continuous-operation subkelvin coolers have flown, nor have flight subkelvin coolers been staged from mechanical cryocoolers. Advances in both areas would enable long-duration astrophysics missions. Both require significant development in cooling system operation and integration with detector and optics systems.

# 3 Advanced Propulsion and Power

**Advanced propulsion and power enable the next generation of high delta-v deep-space missions and high-performance power sources and energy storage systems for deep-space and extreme-environment planetary surface missions.**

Robotic exploration of our solar system is only made possible by our ability to propel and deliver the spacecraft to its destination (and sometimes back to Earth), and to provide the power required to operate the instruments and systems that acquire scientific data and transmit them back to Earth. Challenging deep-space missions frequently require large spacecraft velocity changes (delta-v) from advanced propulsion systems to reach the target and maneuver to obtain data and samples, and the missions often need significant power in extreme environments. Advanced propulsion and power systems are thus critical elements in spacecraft design and often determine the overall mission capabilities and performance.

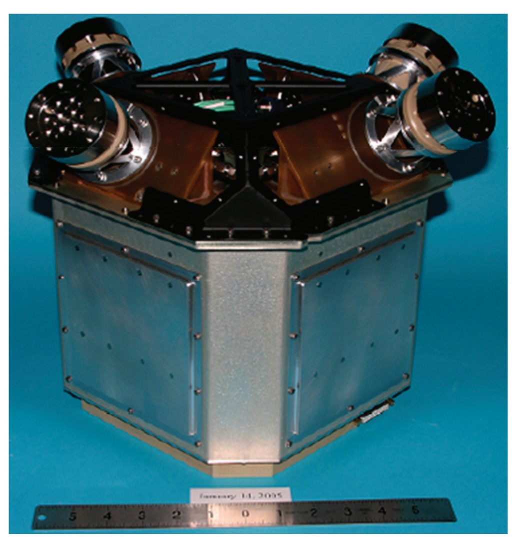
To fully realize challenging deep-space missions, technology advances in five key areas are needed.

- **Electric propulsion.** The total impulse capability of electric thrusters must be increased to reduce the number of thrusters required to complete missions, and higher-efficiency electric-propulsion systems with lower cost and risk are needed to ensure credible mission proposals.
- **Chemical propulsion.** Improvements in feed systems—such as pressurization systems, low-mass tanks, and cryogenic storage components—and advances in propulsion-system modeling are needed to increase chemical thruster capabilities for future larger-mission classes.
- **Precision propulsion.** Micro- and millinewton thruster development must be advanced to flight status to provide extended life and reliability for precision formation flying and orbit control in next-generation Earth-observation and other science missions.
- **Power systems.** Higher-efficiency and higher specific-power solar arrays and radioisotope power systems are needed to provide increased power for deep-space missions.
- **Energy storage.** Improved primary batteries, rechargeable batteries, and fuel cells with high specific energy and long-life capability are needed for the extreme environments that will be faced by future missions.

Advances in these technologies will make more challenging missions possible and reduce the system cost sufficiently to enable new Flagship, New Frontiers, Discovery, and space physics missions.

## 3.1 Advanced Electric-Propulsion Technologies

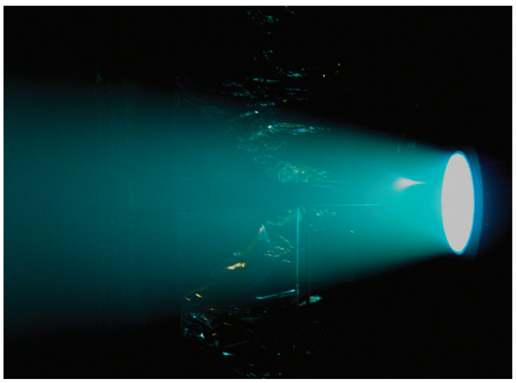
Advanced electric-propulsion technologies consist of electric-propulsion systems based on ion and Hall thrusters. These capabilities were successfully demonstrated on Deep Space 1 and the Dawn mission. Because electric-propulsion systems can deliver more mass for deep-space missions and can accommodate flexible launch dates and trajectories, they enable many future missions. Development of an electric-propulsion stage using advanced thruster technolo-



*Micronewton thruster cluster to be flown on ST-7.*

gies and accompanying components, including solar electric power sources, is critically needed for future flagship missions and will be directly applicable to other missions as the technology matures and costs decrease.

Solar electric propulsion is presently flying on Dawn, which uses 2.3 kW NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) engines. Other thruster technologies are available or emerging with higher power, thrust, and specific impulse ($I_{sp}$) capabilities. JPL is the system integrator for the NASA Glenn Research Center–developed NASA's Evolutionary Xenon Thruster (NEXT) that provides power levels up to 7.2 kW, thrust up to 0.25 N, and an $I_{sp}$ up



*Thruster plume from a 4.5 kW ion thruster.*

to 4000 s. In addition, commercial electric thrusters used for station-keeping and orbit-raising applications on communications satellites offer power up to P = 4.5 kW, thrust in the range of 0.1–0.25 N and $I_{sp}$'s in the range of 1500–3500 s. These thrusters are viable low-cost candidates for future NASA deep-space-mission prime propulsion.

## 3.2 Advanced Chemical-Propulsion Technologies

Advanced chemical-propulsion technologies include millinewton thrusters, throttleable monopropellant thrusters, ultralightweight tanks, and 100 to 200 lb–class bipropellant thrusters. Advances must be made to improve thruster performance and reduce risk and costs for attitude control system, and entry, descent, and landing (EDL) systems. Specific improvements include the development of electronic regulation of pressurization systems for propellant tanks, lower-mass tanks, pump-fed thruster development, and variable-thrust bipropellant engine modeling as well as deep-space-propulsion improvements in cryogenic propellant storage systems and components.

## 3.3 Precision Micro/Nano Propulsion

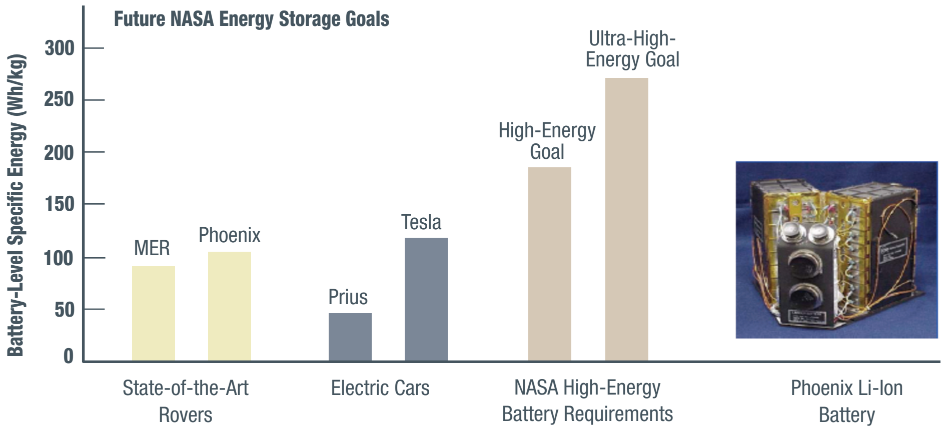
Advanced thrusters are required for precision motion control/repositioning and high $I_{sp}$ for low-mass, multiyear missions. Solar pressure and aerodynamic drag compensation and repositioning requirements dictate $I_{sp}$ and thrust level, while precision control of attitude and interspacecraft distance drive minimum impulse. These thrusters produce micronewton thrust levels for solar-wind compensation and precision-attitude control. Precision noncontaminating propulsion is needed, especially for science missions with cryogenic optics and close-proximity spacecraft operations, to keep payload optical/infrared surfaces and guidance–navigation–control sensors pristine. Additional requirements are for high-efficiency thrusters that enable 5- to 10-year mission lifetimes that include significant maneuvering requirements.

Performance targets for micro/nano propulsion include a miniature xenon thruster throttleable in the 0–3 mN range and with a 10-year life. Continued development and flight qualification of this thruster is required for future missions.

## 3.4 Power Sources for Deep-Space Missions

The power sources for deep-space missions include solar-cell array and radioisotope power systems. Solar arrays with specific power in the range of 40–80 W/kg are currently used in Earth-orbital missions and deep-space missions at distances up to about 4 AU. Future orbital and deep-space missions require advanced solar arrays with higher efficiency ( > 35%), and high specific power ( > 200 W/kg). Some deep-space and planetary-surface missions require advanced solar arrays capable of operating in extreme environments (radiation, low temperatures, high temperatures, dust). Using advanced materials and novel synthesis techniques, such high-efficiency solar cells and arrays are under development for use in future spacecraft applications. These advanced cells will increase power availability and reduce solar array size for a given power, and may also have applications for terrestrial energy production applications as well, if fabrication costs can be driven to sufficiently low levels.

Radioisotope power systems (RPS) with specific power of ~ 3 W/kg are currently used in deep-space missions beyond ~ 4 AU, or for planetary surface missions where there is limited sunlight. JPL has long used RPS for deep-space missions, including Voyager, Galileo, and Cassini, and will be using RPS for MSL, the next Mars rover. Future deep-space missions require advanced RPS with long-life capability ( > 20 years), higher conversion efficiency ( > 10%), and higher specific power ( > 6 W/kg). Some deep-space missions require the ability to operate in high-radiation environments. Advanced thermoelectric radioisotope generators are under development at JPL for future space missions. The capabilities of smaller RPS are being explored for future exploration missions. The development of small RPS enables smaller landers at extreme latitudes or regions of low solar illumination, subsurface probes, and deep-space microsatellites.




*NASA's energy storage battery goals are substantially more aggressive than state-of-the-art and commercial off-the-shelf technology.*

## 3.5 Energy Storage for Deep-Space Missions

The energy storage systems presently being used in space science missions include both primary and rechargeable batteries. Fuel cells are also being used in some human space missions.

Primary batteries with specific energy of ~ 250 Wh/kg are currently used in missions such as planetary probes, landers, rovers, and sample-return capsules where one-time usage is sufficient. Advanced primary batteries with high specific energy ( > 500 Wh/kg) and long storage-life capability ( > 15 years) are required for future missions. Some planetary surface missions require primary batteries that can operate in extreme environments (high temperatures, low temperatures, and high radiation). JPL, in partnership with industry, is presently developing high-temperature ( > 400 ºC) and high-specific-energy primary batteries (lithium–cobalt sulfide, $LiCoS_2$) for Venus surface missions and low-temperature ( < –80 ºC) primary batteries (lithium–carbon monofluoride, LiCFX) for Mars and outer-planet surface missions.

Rechargeable batteries with specific energies of ~ 100 Wh/kg are currently used in robotic and human space missions (orbiters, landers, and rovers) as electrical energy storage devices. Advanced rechargeable batteries with high specific energy ( > 200 Wh/kg) and long-life capability ( > 15 years) are required for future space missions. Some missions require operational capability in extreme environments (low temperature, high temperature, and high radiation). JPL, in partnership with other NASA centers, is presently developing high-energy-density Li ion batteries ( > 200 Wh/kg) that can operate at low temperatures (~ –60 °C) for future space missions.

Fuel cells are particularly attractive for human space science missions such as the Space Shuttle. These fuel cells have specific power in the range of 70–100 W/kg and a life of ~ 2500 h. Advanced fuel cells with high specific power (200 W/kg), higher efficiency ( > 75%), long-life capability ( > 15,000 h), and higher specific power are needed for future human space missions. JPL is working on the development of such advanced fuel cells.

### Summary

*Advanced propulsion and power are key technologies required to perform challenging future planetary exploration missions. Significant improvements in these technologies will enable a broader range of science and exploration missions, and enhance JPL's role as a NASA center. JPL will leverage its mission success and propulsion expertise to develop an electric propulsion stage utilizing the most advanced thrusters, to improve power and energy storage systems and their ability to perform in extreme environments, to develop higher-performance chemical thrusters for attitude control systems and EDL applications, and to prepare micropropulsion systems for precision formation flying applications.*

# In-Situ Planetary Exploration Systems

4

**In-situ planetary exploration systems enable planetary and small-body surface, subsurface, and atmosphere exploration leading to sample acquisition, retrieval, and return to Earth.**

A new epoch in robotic exploration of the solar system has opened and its promise of new and unexpected findings beckons us forward. The Mars Pathfinder and Mars Exploration Rover missions enticed us with their exotic findings and observations. Yet these missions, novel and exciting as they are, mark only the beginning of this new era of detailed, in-situ exploration of Earth's planetary neighbors.

Mars has been the object of intense scientific scrutiny for more than four decades. This same interest will extend to other bodies in the solar system in the future, spurred by the scientific observations obtained from orbiting spacecraft, such as Galileo and Cassini. Such interest, already triggered by observations of Enceladus, Europa, and Titan, will only grow. And that scientific interest, sparked by remote observations, can only be satisfied by in-situ examination of the bodies themselves.

The next generation of scientific missions to Mars and other bodies in the solar system requires technology advances in five key areas.

- **Entry, descent, and landing (EDL).** To extend current capabilities to larger scales, higher speeds, greater precision, and higher unit loads for Mars entry, and to develop capabilities for higher-density atmospheres like Venus and Titan while providing greatly improved landing precision.
- **Mobility.** To extend existing capabilities to yield rovers with greater range and speed and to develop the capabilities to explore through the atmosphere and beneath oceans.
- **Sample acquisition and handling.** To improve and extend existing capabilities to obtain and dexterously manipulate subsurface and surface samples.
- **Autonomous orbiting sample retrieval and capture.** To create the capabilities necessary to return a sample from Mars to Earth.
- **Planetary protection.** To enable uncompromised and safe exploration of planetary bodies in our solar system that may harbor life.

Gathering in-situ scientific observations and data will require increasingly capable spacecraft, planetary landers, and rovers. These vehicles will be more massive than those of today. Earth's atmosphere and atmospheric drag limit the diameter of launch vehicles, which in turn limits the diameter of entry heat shields for planetary spacecraft designed to land. The continually increasing mass of planetary landers increases the per-unit-area heat load and force borne by heat shields and parachutes. The dense atmospheres and higher entry velocities at bodies like Titan and Venus exacerbate these effects and heighten the need for technology advances to provide mission-critical capabilities. Onboard propulsion requirements can be reduced by advances in aerocapture—a technique that exploits aerodynamic forces to effect the transition from a hyperbolic interplanetary trajectory to an orbit about the planetary body. Another challenge is landing spacecraft precisely at a desired location while autonomously avoiding landing hazards.

The most compelling scientific questions often require investigations of sites on the planet that are inhospitable to a safe landing. As a result, rovers that are more capable in every way are needed to go farther and more rapidly than present rovers, and do so autonomously, while requiring less power. On some bodies, these requirements may result in the use of lighter-than-air (buoyant) vehicles, penetrators, or submersibles instead of rovers. Once the rover reaches a scientifically interesting site, it must be able to obtain a specified sample and to prepare and present that sample for scientific analysis. Today's relatively limited capabilities in this regard must be improved for future missions.

The first interplanetary mission to return a sample to Earth for detailed scientific analysis would be from Mars. Such a mission is not imminent because the technology required to accomplish such a mission successfully is not yet in place. In addition to substantial technology advances needed in the areas of EDL, mobility, and sample acquisition and handling, we must develop the capabilities that enable the spacecraft system to detect a sample-bearing canister in space, to rendezvous with that canister, to transfer that sample to an Earth-return vehicle, and to return to Earth. This requires significant technology advances in autonomous orbiting sample retrieval and capture, which comprise a wide spectrum of disciplines. Human exploration of Mars in the distant future cannot be contemplated until the capability to return at least a modest-sized Martian sample to Earth has been successfully demonstrated.

Any mission that will enter and operate within the atmosphere or on the surface of the solar system's extraterrestrial bodies must protect that body from biological contamination by the visitor from Earth. Therefore, spacecraft must be designed with sterilization-related requirements in mind. To do so, improved sterilization capabilities drawn from the planetary-protection discipline are necessary to meet these requirements affordably and practically. Developing the capability to preclude back contamination from a sample-return mission is an additional technology advance essential to a sample-return mission.

Future, more demanding missions will require more capable onboard planning and data analysis, not only to permit distant missions to be productive despite lengthy round-trip light times but also to provide the ability to take advantage of unanticipated or variable events of scientific interest. The issues associated with advancing autonomy technology are critical to in-situ planetary exploration and are discussed in Sec. 9.

## 4.1 Entry, Descent, and Landing

EDL is made possible by a broad spectrum of related technologies, including the design and fabrication of a mass-efficient heat shield, the design and deployment of a supersonic parachute, the use of advanced navigation and guidance to reduce the size of the landing error ellipse, the use of sensors during planetary descent to identify and avoid hazards in the landing area, and the design and implementation of a mass-efficient propulsion system to control the spacecraft attitude and rates during all phases of the descent. Similarly, the reduction of propulsion requirements made possible through the use of aerocapture, can be essential for an in-situ exploration mission.

To date, heat shield and parachute designs for robotic missions derive from designs qualified for NASA's Viking and Apollo programs. Future missions to Titan, Europa, or Venus impose heat-transfer rates and pressures well beyond the qualification ranges of those prior missions. Technology advances in these two disciplines are essential for future cost-effective in situ exploration.

Future in-situ missions also require a significant reduction in the size of the landing error ellipse, as well as techniques to identify and avoid landing-site hazards. Present landing error ellipses on Mars have a major axis on the order of 100 km. To make the desired future scientific measurements, this landing error ellipse must be reduced to a major axis less than 10 km, and perhaps as small as a few hundred meters. (The Mars Science Laboratory has developed the capability to reduce the major-axis landing error to 20 km, but this technology has not yet been accomplished on Mars. MSL is planned for launch in 2011.) To do so will require both improvements in entry systems, the ability to determine the vehicle's precise location during descent, and to actively guide the vehicle to a predetermined landing site. During the terminal phase of the descent, we must be able to identify hazards and control the final descent to avoid those hazards.

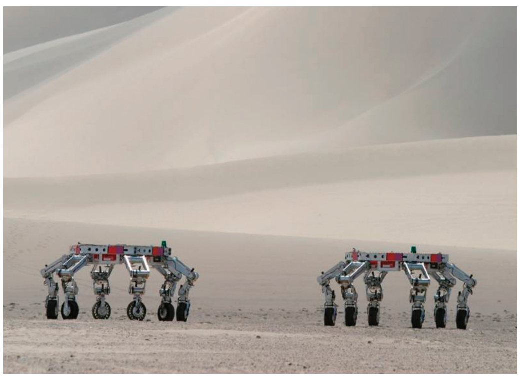
## 4.2 Mobility

When we think about mobility today in the context of in-situ exploration, the rovers on Mars come to mind. However, a future Mars sample-return mission will require a rover significantly more capable than today's rovers. The future rover must be able to traverse long distances with increased autonomy and must complete its tasks of sample selection and collection within a 365-sol period.

Mobility is not restricted to rovers. Although mission designers recognize that the energy available will be extremely limited, mission plans for missions to perform in-situ investigations of cloud-covered planets and moons like Venus and Titan call for the use of robotic balloons, called "aerobots,"

*The full-scale metallized balloon, produced by ILC Dover, could be used today for operation in the Earth-like temperatures found at 55 km altitude in Venus' atmosphere for mid-altitude exploration of the planet's surface.*

that carry instruments to analyze the atmosphere and cameras to photograph the surface while flying thousands of kilometers. To follow the step first taken by the 1985 Soviet VEGA balloon mission, Venus mission designers envision helium-filled balloons with a polymer skin (for use in the cooler upper atmosphere) or with a thin metal skin (for use in the very hot lower atmosphere) as the technological approaches of choice. The denser atmosphere at Titan may be explorable with a Montgolfier balloon, one whose lift is gained by containing and then heating the local atmosphere with the waste heat from the radioisotope power source that supplies electrical power. At present, early proof-of-concept activities have been accomplished, and for use at Venus, full-scale prototypes have been constructed and are being validated. Materials suitable for use at Titan's cryogenic temperatures have been developed and prototype designs are being evaluated. Ongoing efforts are directed toward



*Two ATHLETE rovers in front of sand dunes.*

bringing these technology advances to the necessary level of maturity for flight-mission implementation and toward addressing their integration into vehicle design.

Even less well defined are the mobility requirements and technology advancements needed to provide the requisite mobility on bodies like Enceladus, an icy satellite of Saturn thought to have a large, subsurface liquid ocean. In this case, a submersible capable of drilling to the subsurface liquid ocean is desired.

## 4.3 Sample Acquisition and Handling

Sample acquisition and handling is the sine qua non of in-situ analysis and exploration. The NASA planetary-exploration systems developed to date to obtain, manipulate, and deliver samples have been limited to scraping and scooping, placing samples into an instrument's opening using gravity, and examining abraded rock surfaces. The ability to obtain an intact core sample, to drill and extract that sample from a desired depth, to prepare that sample in different ways, and deliver it precisely are areas of capability not yet realized. For sample-return missions, the ability to place a pristine sample into a sample container must be augmented with the capability to ensure that such a sample is both unique and scientifically interesting.

Scientists have indicated their desire to obtain on Mars an intact core sample (1 cm diameter by approximately 5 cm long). This capability does not currently exist. Nor does the capability exist to prepare a soil sample with a specified or known distribution of particulate sizes. Similar requirements are expected for missions to bodies other than Mars.

Sample acquisition and handling for bodies like Enceladus, and the scientific instruments needed to analyze the samples, are presently largely undefined.

## 4.4 Autonomous Orbiting Sample Retrieval and Capture

At present, the architecture of a future Mars sample-return mission includes a sample container into which a pristine sample is placed and maintained in its as-taken condition, a Mars ascent vehicle that launches the sample container into an orbit about Mars, and an Earth-return vehicle to detect and rendezvous with the orbiting sample container and transfer the sample to the Earth-entry vehicle (while precluding back contamination), after which the vehicle will return to Earth.

To implement this architecture, technological capabilities not now available at acceptable risk must be developed and validated.

- The capability to autonomously detect a small, unpowered target in an orbit about Mars that is known only approximately.
- The capability to apportion requirements between the planetary surface ascent vehicle and the Earth-return vehicle to optimize the mission/flight system design for sample return from planets and small bodies.
- The capability to rendezvous autonomously with that small target starting from a separation distance approaching 50,000 km.
- The capability to transfer the sample container autonomously to the Earth-entry vehicle while maintaining the sample in pristine condition and precluding back contamination.

The return of the sample to Earth and its retrieval also present difficult tasks, but not as challenging as the four listed above.

Some work to develop the capability to rendezvous autonomously in space has been undertaken by the U. S. Department of Defense. The resulting experiments have illustrated the difficulty of the work remaining to make a Mars sample-return mission possible.

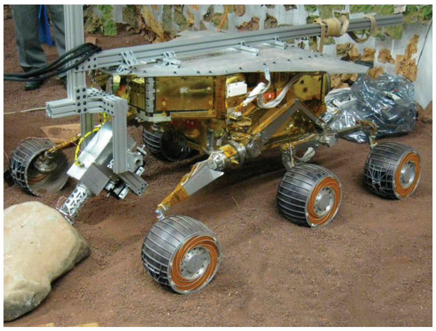
## 4.5 Planetary Protection

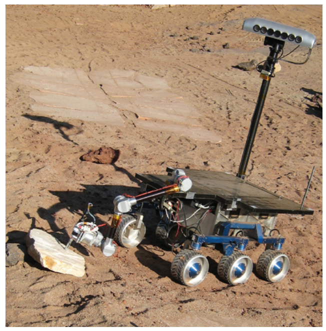
For any spacecraft that introduces itself into an extraterrestrial environment, it is imperative that it not introduce terrestrial life forms capable of thriving in that environment (forward contamination). Otherwise, the mission would

*Below right: Honeybee coring and abrasion tool testing at JPL.*

*Left: Rover coring testing for future sampling missions to Mars.*

compromise not only the extraterrestrial body but also the scientific studies we wish to conduct. Planetary protection is the collection of technological capabilities that are applied during spacecraft design, fabrication, and test to ensure its post-launch sterility level and, for sample-return missions, the return containment of the extraterrestrial sample so that it does not present a threat to Earth (backward contamination). Because sterilization is an issue at every scale of a spacecraft's design and assembly, from the molecular to the





completed spacecraft, it is an issue that must be considered from the very outset of the design phase. Planetary protection is a discipline that depends on many technological capabilities.

- **Sterilization, cleaning, and aseptic processing.** To ensure that a robotic planetary spacecraft is sterile to the levels required by international agreement, techniques are developed to sterilize equipment and maintain their biological cleanliness at every level during the fabrication, assembly, and test processes, from piece part to whole spacecraft. To ensure that the spacecraft's permissible bioburden level is addressed in a manner commensurate with the spacecraft's mission, analysis techniques are developed to permit accurate risk assessment. The degree to which these techniques is applied is determined by the science requirements, and by cost and schedule considerations for each individual mission.
- **Recontamination prevention.** Design and implementation of biobarriers to maintain a sterile environment and prevent the recontamination of sterile parts and assemblies as they are stored or incorporated into larger assemblies is a planetary protection capability needed throughout the project's fabrication and ATLO phases, through to deployment at the mission target.
- **Sample handling and processing.** For samples returned to Earth, planetary protection provides two critical capabilities: the ability to return a sample while preventing back contamination of Earth by an extraterrestrial source, and the ability to prevent contamination of the sample while manipulating it from its extraterrestrial source to the terrestrial biocontainment facility in which it will be analyzed.
- **Cost and risk-reduction management.** To provide the ability to estimate both the costs of different approaches to spacecraft sterilization and the efficacy of those approaches to biobioburden management of different designs, planetary protection seeks to provide the analytical tools that will allow spacecraft managers to incorporate the most cost-effective approach to effective planetary protection for their mission design and architecture.

### Summary

*In-situ planetary exploration would be enabled by a set of as-yet unrealized capabilities that are key to future planetary exploration, whether at the outer planets, Mars, or Venus. Validating these capabilities and making them available to planetary missions will be both technically difficult and time consuming, and will require a thoughtful, long-term, sustained, and focused effort.*

# Survivable Systems for Extreme Environments

5

**Survivable electronic and mechanical systems enable reliable operations under extreme radiation, temperature, pressure, and particulate conditions.**

The environments for solar system in-situ exploration missions cover extremes of temperature, pressure, and radiation that far exceed the operational limits of currently space-rated electronics, electronic packaging, thermal control, sensors, actuators, power sources, and batteries. At one extreme, Venus lander missions need to survive at 460 °C (730 K) temperatures and 90-bar pressures, and must pass through corrosive sulfuric acid clouds during descent (the current state of the art limits the duration of Venus surface exploration to only 1 to 2 hours). At the other extreme, Titan, Europa, asteroids, comets, and Mars missions require operations under extremely cold temperatures in the range of –180 to –120 °C (~ 90-150 K). For missions to comets or close to the Sun, high-velocity impacts are a real concern, with impact velocities reaching greater than 500 km/s at 4 solar radii (perihelion for a solar-probe mission). Missions to Europa must survive megarad radiation levels behind typical shielding thicknesses combined with very low temperatures in the vicinity of –160 °C (~ 110 K). In fact, all space missions recommended in *New Frontiers in the Solar System: An Integrated Exploration Strategy*, the National Research Council's decadal survey on solar system exploration, require operations in extreme environments at very high and very low temperatures, high and low pressures, corrosive atmospheres, or high radiation.

Spacecraft survival in these environments requires not only that mission designers test and model the effects but also that they develop systems solutions, including fault tolerance, thermal management, systems integration, and

*Critical environments for planetary missions.*

| Mission | Environment: Radiation Mrads/mils Aluminum | Cold °C | Hot °C | Thermal Cycling °C | Duration (Long Life) | Solid Particles | Surface Pressure bar |
|---|---|---|---|---|---|---|---|
| Europa (Orbiter) Europa (Lander) | 2~3/100 | –160 | — | — | >9 Years | Ring Particles | — |
| Titan (TSSM) | 0.03/100 | –180 | — | — | 14 Years | Ring Debris Enceladus Plume | 1.5 |
| Venus (VISTA) | 0.02/100 | — | 487 | — | Surface–1 Day 2-year Mission | — | 92 |
| Moon (M3) | 0.01/100 | –230 | 130 | –230 to +130 | 20 Years | Dust | — |
| Mars (MSL) | 0.01/100 | –128 | — | –128 to +20 | 2+ Years | Dust | — |
| Earth (GEO-1 Year) | 0.03/100 | –150 | — | — | 20 Years | Orbital Debris | — |
| Deep Space (DAWN) | 0.01/100 | — | — | — | 10 Years | — | — |

functional redundancy. Investments in technologies for developing these systems and for operations and survivability in extreme environments will enable the successful development of future NASA missions, will strengthen capabilities in systems design for survivability in extreme environments, and open the way to new, superior, and more reliable future mission architectures.

## 5.1 Survival in High-Radiation Environments

Improvements in technology for spacecraft survival in high-radiation environments to enable the viability of Europa, Titan, lunar, and mid-Earth-orbit missions are needed. Missions to Europa (both lander and orbiter) present a challenge of surviving megarad radiation levels behind typical shielding thicknesses. Significant efforts to meet high-radiation challenges will need to include test, analysis, and mitigation of single-event effects for complex processors and other integrated circuits at high device operating speeds. Total dose testing at high- and low-dose rates must be performed to high radiation levels to validate test methods for long-life missions. Tests and analysis of device performance in combined environments, total dose, displacement damage dose, and heavy ion must be performed to validate radiation-effects models. Methodology used in the development of device performance data and worst-case analysis must be developed to support reliable modeling and a probabilistic approach to system survival.

## 5.2 Survival in Particulate and Hypervelocity Impact Environments

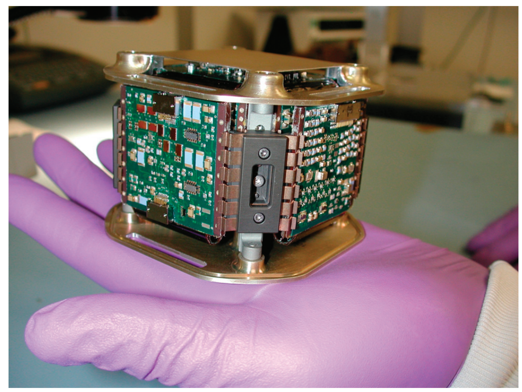
An important consideration when building survivable systems is the reliability, extended functionality, and operation of systems in particulate environments; for example, lunar surface missions must operate in the highly abrasive lunar dust, and all missions must penetrate orbital-debris fields. Potential impacts by meteoroids or Earth space debris at velocities in the range of 20–40 km/s short term and > 500 km/s long term (solar probe) are also an issue. JPL has developed a roadmap for impact environments—including debris, comets, and meteoroids—that includes modeling, testing, and shielding, as well as some of the leading models for dust environments.

## 5.3 Electronics and Mechanical Systems for Extreme Temperatures and Pressures Over Wide Temperature Ranges

Previous strategies in this area generally involved isolation of the spacecraft from the environment; however, isolation approaches can add substantially to weight, mass, and power. Environmentally tolerant technologies may provide better solutions, particularly in subsystems such as sensors, drilling mechanisms, sample acquisition, and energy storage.

In order to get the maximum science return, it is critical that JPL develop electronic and mechanical subsystems designed to survive temperature extremes. The challenges, outlined below, may be categorized into the following areas: cold-temperature operations, high-temperature and high-pressure operations, and operations at wide temperature ranges.

**Low-temperature operation.** Several targeted missions and mission classes require the ability to function in extreme cold. These include missions to the Moon, Europa (lander only), deep-space missions (astrophysics and planet finding), and any mission requiring sample acquisition as well as actuators or transmitters outside any interplanetary spacecraft.



*A distributed motor controller for brushless actuators for operation from –130 to +85 °C for more than 2000 cycles.*

Many of the currently available electronics will not perform at extreme cold. Additionally, many metals undergo brittle phase transitions with abrupt changes in properties, which are not well understood, in the extreme cold environments. Other performance issues at cold temperatures include the following: the effects of combined low temperature and radiation; the reliability issues of field-effect transistors due to hot carriers; freeze-out of advanced complementary metal-oxide semiconductors at very cold temperatures; severe single-event effects at cold temperatures for silicon-germanium semiconductors; and battery operations at low temperatures.

**High-temperature and high-pressure operation.** To achieve successful missions, previous Venus landers employed high-temperature pressure vessels with thermally protected electronics, which had a maximum surface lifetime of 127 minutes. Extending the operating range of electronic systems to the temperatures (485 °C, ~ 760 K) and pressures (90 bar) of the Venus ground ambient would significantly increase the science return of future missions. Toward that end, current work endeavors to develop an innovative sensor preamplifier capable of working in the Venus ground ambient and designed using commercial components (thermionic vacuum devices; wide-bandgap, solid-state devices; thick-film resistors; high-temperature ceramic capacitors; and monometallic interfaces). To identify commercial components and electronic packaging materials capable of operation within the specified environment, a series of active devices, passive components, and packaging materials was screened for operability at 500 °C (~ 775 K), targeting a tenfold increase in mission lifetime. The technology developed could also be used for Jupiter deep probes, which reach pressures of up to 100 bar at temperatures of 450 °C (~ 725 K).

Survivability and operation of electronic systems in extreme environments are critical to the success of future NASA missions. Mission requirements for planets such as Venus cover the extremes of the temperature spectrum, greatly exceeding the rated limits of operation and survival of current commercially available military and space-rated electronics, electronic packaging, and sensors. In addition, the desire to incorporate distributed electronics into future missions necessitates that disciplines for making such systems are investigated as soon as possible.

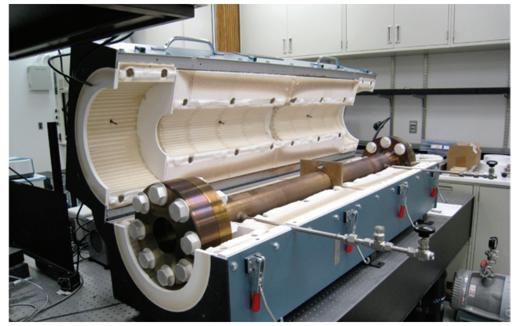
**Operations at wide temperature ranges.** Both lunar and Mars missions involve extreme temperature cycling. In the case of Mars, temperatures may vary from –130 to +20 °C (143–293 K), with a cycle approximately every 25 hours. For an extended mission, this translates into thousands of cycles. Lunar extremes are even greater (–230 to +130 °C, ~ 40–400 K) but with a cycle every month. Such extreme cases involve not only extreme temperatures but also fatigue issues not generally encountered in commercial, military, or space applications.

## 5.4 Reliability of Systems for Extended Lifetimes

Survivable systems need to have extensive reliability for extended lifetimes. Electronics are generally not designed to be functional for more than 10 years, unless specially fabricated for long life. Long-life systems ultimately need a 20-year (or greater) lifetime and are critical for extended lunar-stay missions, deep- and interstellar-space missions, and some Earth-orbiting missions.

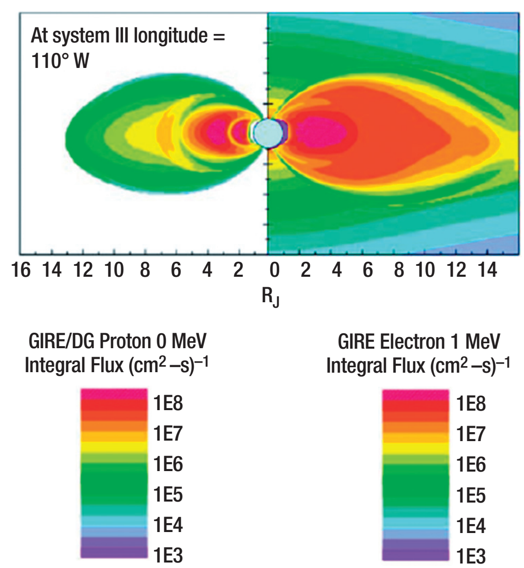
## 5.5 Space-Radiation Modeling

Modeling radiation environments is another important aspect of extreme environments technology. Extensive models have been developed for both the Jovian and Saturnian environments. Measurements of the high-energy, omnidirectional electron environment were used to develop a new model of Jupiter's trapped electron radiation in the Jovian equatorial plane; this omnidirectional equatorial model was combined with components of the original Divine model of Jovian electron radiation to yield estimates of the out-of-plane radiation environment, referred to as the Galileo Interim Radiation Electron (GIRE) model. The GIRE model was then used to calculate the Europa mission dose for an average and a 1-sigma worst-case situation. While work remains to be done, the GIRE model represents a significant step forward in the study of the Jovian radiation environment, and provides a valuable tool for estimating and designing for that environment for future space missions.



*The Venus Environmental Chamber (VEC) enables testing of laser-based instruments in the high-pressure, high-temperature Venus surface environment for future lander missions.*

Saturnian radiation belts have not received as much attention as the Jovian radiation belts because they are not nearly as intense; the famous Saturnian particle rings tend to deplete the belts near where their peak would occur. As a result, there has not been a systematic development of engineering models of the Saturnian radiation environment for mission design, with the exception of the Divine (1990) study that used published data from several charged-particle experiments from several flybys of Saturn to generate numerical models for the electron and proton radiation belts; however, Divine never formally developed a computer program that could be used for general mission analyses.




*Contour plots of Jupiter's radiation belts based on the JPL Galileo Interim Radiation Electron model. The left panel illustrates the Jovian 10-MeV proton integral fluxes, while the right panel illustrates the 1-MeV electron integral fluxes.*

JPL has attempted to fill that void by developing the Saturn Radiation Model (SATRAD), which is a software version of the Divine model that can be used as a design tool for missions to Saturn. Extension and refinement of these models will be critical to future missions to Europa and Titan as well as extended Jovian missions.

## Summary

*Whether it is temperature, pressure, radiation, or dust, nearly all of the planned planetary and deep-space missions must contend with an extreme environment component. NASA cannot afford prior decades' strategies of extensive overdesign. Improving understanding of extreme environments is of critical strategic importance. The ability to design for specific radiation levels allows flying the correct components without excessive shielding. Understanding the behavior of electronics and materials at extreme cold and with large temperature swings allows designers to prepare for reliable extended missions. The items identified in this section provide the kernel of critical extreme environments technologies for successful future planetary and deep-space missions.*

# Deep-Space Navigation

6

**Deep-space navigation enables missions to precisely target distant solar system bodies, as well as particular sites on those bodies. This navigation not only takes place in real time for control and operation of the spacecraft, but also in many cases includes later higher-fidelity reconstruction of the trajectory for subsequent trajectory corrections, as well as scientific and operational purposes.**

Existing technologies—Doppler, range, delta-differential one-way range (Delta-DOR), onboard optical—have been used in varying degrees since the late 1950s to navigate spacecraft—with ever-increasing precision and accuracy. Increasingly, higher-fidelity models of the solar system and its dynamics as well as the dynamics of the spacecraft trajectory have become necessary. Much higher computing demands both in terms of speed and precision have been necessary to achieve these results. Methods of designing ever-more complex trajectories with an associated increased understanding of possible spacecraft dynamics have been developed that, in turn, can drive requirements on spacecraft design. JPL's expertise in deep-space mission design and navigation has enabled many successful planetary missions, such as multiple missions to Mars using orbiters and landers, complex missions at both Jupiter and Saturn with probes and long-term orbiters, and missions to comets and asteroids along with sample-return segments. Missions that use the complicated gravitational interaction of the Sun and Earth to accomplish specific mission objectives and constraints (Genesis, Spitzer Space Telescope) have also been accomplished.

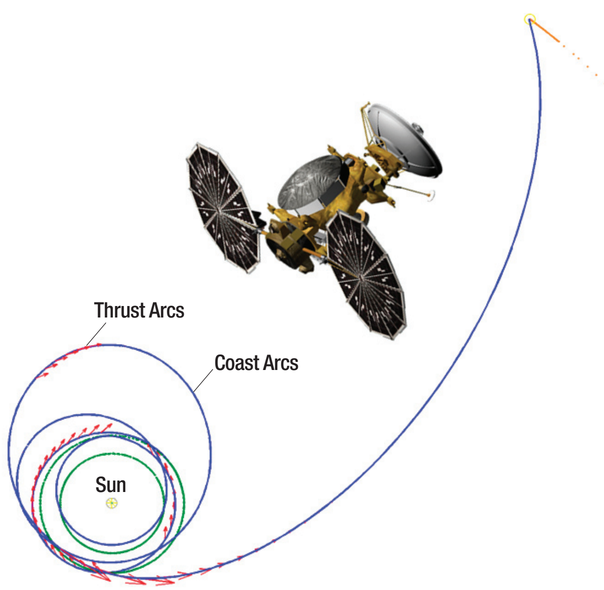
Future missions will need to build on these successful developments to meet tightening performance requirements and growing demands for autonomous response of spacecraft to new environments (atmospheric winds, comet outgassing jets, high radiation, etc.) Missions consisting of multiple spacecraft will require coordinated navigation. Missions in the New Frontiers and Discovery sets will require development of low-thrust and low-energy mission design and navigation capabilities, and more extensive search capabilities for multiple flyby trajectories, enabling efficient and economical exploration. This is particularly important for sample-return missions and proposed Outer Planet Flagship Missions. Methods must be developed to efficiently explore complex satellite tour designs, innovative science orbits, and efficient capture of these orbits. This also applies to missions using any type of low-thrust propulsion—including solar electric, nuclear electric, solar sail, and plasma sail—for any mission segment. Future small-body sample-return missions and interior-characterization missions require further reductions of uncertainties in navigation delivery to small bodies by an order of magnitude. Finally, missions that need very high accuracy relative to the target (planet, satellite, asteroid, or comet) to achieve science goals, reduce mission costs for ground resources, and release ground resources for other applications will require the continued development and extension of the multimission, autonomous, onboard navigation system (AutoNav) to be a complete AutoGNC (autonomous guidance, navigation, and control) system. The technology challenges for deep-space navigation include the following areas, discussed below:

- Mission design and navigation methods;
- Precision tracking, guidance, navigation and control; and
- Onboard autonomous guidance, navigation and control.

## 6.1 Mission Design and Navigation Methods

Deep-space mission design encompasses the methods and techniques used to find the existence of, develop the specific details of, and outline the operational considerations and constraints for a specific concept necessary to accomplish a set of scientific objectives. This is usually done initially within the context of an "envelope" of potential designs generally meeting the overall desires. Navigation methods include both the analysis of real-time data received during actual mission operation and a simulation in the design phases as part of the overall mission design. For both mission design and navigation, a large set of software tools and analysis techniques is necessary at a variety of precision and fidelity levels for different stages of design from early pre–Phase A concept studies through flight operations. This set includes tools and techniques for propagating and optimizing trajectories; reducing observational quantities using mathematical filtering algorithms; and simulating spacecraft guidance, attitude control, and maneuvering capabilities.

Extension of current methods for finding and navigating complex trajectories involving multiple flybys, low-thrust trajectories, and trajectories involving lengthy three-body arcs is necessary to meet the requirements of many future mission scenarios. In some cases, all three of those aspects may be involved in a single mission. Algorithms are required that provide rapid and highly accurate orbital thrust profiles for maintaining orbit about a small body. In addition, advances are needed to decrease the time required to compute small-body landing trajectories in a highly complex gravity and topography field from several months to a few hours or less. Most, if not all, missions to small bodies will arrive at their destination with no detailed knowledge of the gravitational and topographical characteristics of that body. The algorithms, both onboard and on the ground, to analyze and appropriately control the spacecraft in this unknown environment must be adaptable and flexible enough to ensure spacecraft safety and accomplish the mission objectives.

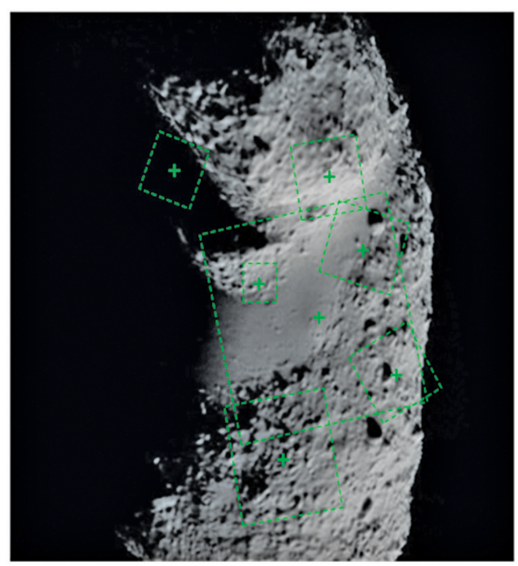



*Interplanetary trajectory design leverages electric propulsion to reduce project risk.*

## 6.2 Precision Tracking and Guidance

Currently, precision tracking and guidance are primarily required for delivery of landers to the surface of a body, e.g., the Mars Exploration Rovers (MERs) and Phoenix at Mars, or to minimize the propellant necessary to insert an orbiter into the desired orbit, e.g., the Mars Reconnaissance Orbiter (MRO) at Mars and Cassini at Saturn. Maintaining an orbit both in a knowledge and control sense also requires high precision (e.g., MRO, Cassini). Missions utilizing flybys of gravitating bodies during the mission to accomplish their objectives also require high-precision tracking and guidance, since even very small delivery errors at the intermediate body or bodies are greatly magnified and must be corrected right after the flyby with potentially costly midcourse maneuvers.

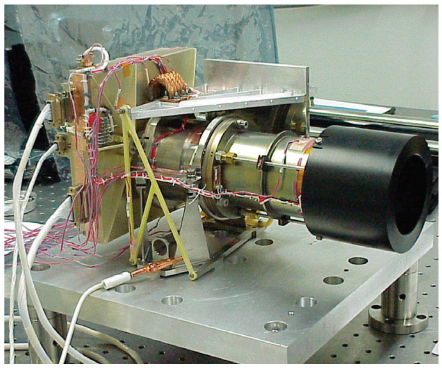
Future missions will require the characterization of small-body internal/subsurface physical characteristics required to model the complex gravity field of a nonspherical body as well as the characterization of spatial and temporal variations of surface composition. This also requires navigational tracking measurements, currently performed using the vehicle's X-band communications systems, and involves measurements of two-way Doppler shifts, two-way ranging, and interferometric measurements of angular offsets from stellar radio sources (Delta-DOR). Future migration to Ka-band, spacecraft-to-spacecraft tracking, and optical communications will offer new challenges as well as opportunities for tracking measurement accuracy improvements. The goal is to achieve navigation accuracy to 1 m in the vicinity of a small body. This will allow very close orbiting, hovering, "touch-and-go" sampling of the surface, and safe landing on the surface. Future spacecraft development with advanced capabilities during atmospheric flight will allow landing on the surface of a planetary body with an atmosphere to within tens of meters rather than tens of kilometers. Hazard avoidance will also be possible. This will be enabled with active control and guidance during the atmospheric portion of the flight and require the development of analysis tools to design such trajectories.



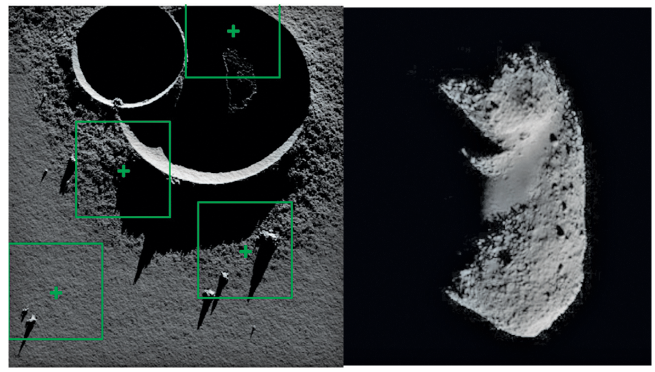
*Far right: example of AutoGNC system capable of touch-and-go operations.*

## 6.3 Onboard Autonomous Navigation

Onboard autonomous guidance navigation and control requirements have been met in the past by the Deep Space 1, Stardust, and Deep Impact missions, which, collectively, have captured all of NASA's close-up images of comets.



*MRO optical navigation camera validation.*



*Far right: Altair lunar landing and "touch and go" on comet Wirtanen, AutoGNC simulations.*

For those missions, a system called AutoNav performed an autonomous navigation function, utilizing images of the target body (a comet), computing the spacecraft position, and correcting the camera-body pointing to keep the comet nucleus in view. In the case of Deep Space 1 and Deep Impact, AutoNav corrected the spacecraft trajectory as well; and for Deep Impact, this was used to guide the impactor spacecraft to a collision with the nucleus. The challenges for future missions are to provide systems capable of orbital rendezvous, sample capture, and, eventually, sample return. This will require autonomous systems that interact with observation systems, onboard planning, and highly accurate onboard reference maps, and will include an extensive array of surface feature-recognition capabilities to provide accurate terrain-relative navigation. Autonomous system error-detection and self-maintenance are integrated with autonomous navigation, guidance, and attitude control functions into pre-developed mission flight software, providing a high degree of robustness, intelligence, adaptability, "self-awareness," and fault recovery (AutoGNC).

## Summary

*Deep-space navigation technologies have enabled every deep-space mission ever flown. As these technologies have advanced, ever-more complex missions have been successfully accomplished. The advancement of these technologies will allow missions that were barely conceivable only a few years ago to be accomplished efficiently and effectively, resulting in scientific insights and understanding far beyond what is currently in hand.*

# Precision Formation Flying

7

**Precision formation flying enables a new class of mission architectures with the potential of unprecedented science performance by the precise control of collaborative distributed spacecraft systems.**

Many future astrophysical science missions, such as extrasolar terrestrial planet interferometer missions, X-ray interferometer missions, and optical/ultraviolet deep-space imagers call for instrument apertures or baselines beyond the scope of even deployable structures. The only practical approach for providing the measurement capability required by the science community's goals is precision formation flying (PFF) of distributed instruments. In effect, PFF synthesizes a virtual structure, enabling apertures and baselines orders of magnitude greater than the largest monolithic spacecraft instrument dimension.

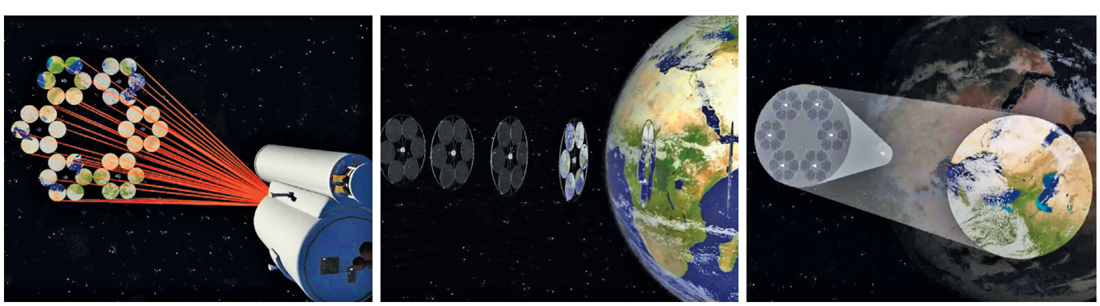
Future Earth-science missions, such as terrestrial probe and observation missions, would also benefit from PFF technologies. These missions would use PFF to simultaneously sample a volume of near-Earth space or create single-pass interferometric synthetic-aperture radars.

Non-NASA applications of PFF include synthesized communication satellites for high-gain service to specific geographical regions, e.g., a particular theater of operations, high-resolution ground-moving target indicator (ground-MTI) synthetic-aperture radars, and arrays of apertures for high-resolution surveillance of and from geosynchronous orbit (GEO).

Recently, the concept of fractionated spacecraft (FSC) has been introduced. An FSC system calls for functions of a hitherto monolithic spacecraft to be distributed over a cluster of separate spacecraft or modules. Each cluster element performs a subset of the monolithic functions, such as computation or power. FSC offers flexibility, risk diversification, and physical distribution of spacecraft modules to minimize system interactions that lead to system fragility. Flexibility is increased by the ability to add, replace, or reconfigure modules and thereby continually update an FSC's architecture throughout its development and operational life. Further, FSC systems can be incrementally deployed and degrade gracefully. PFF achieves the benefits of FSC, cluster sensing, guidance and control architectures and algorithms, and actuation that must be distributed across modules and coordinated through communication.

Each type of PFF mission creates unique technology needs. For astrophysical interferometry, interspacecraft range and bearing knowledge requirements are on the nanometer and subarcsecond levels, respectively. Improved wide field-of-view (FOV) sensors and high-fidelity simulation tools are essential to operate such missions and to validate system performance prior to launch. Precision, centimeter-level drag-free control, repeat-track control, and formation control all require micropropulsion systems. Current astrophysical science missions, such as stellar imagers and X-ray interferometers, rely on formations of twenty-plus spacecraft. This will require high-bandwidth, low-latency, and robust interspacecraft communication systems and distributed command and sensing architectures to coordinate these complex precise formations. Even smaller missions of

*Precision formation aperture for Earth observation from GEO. From left to right: On-orbit manufacturing formation, forming precision aperture with laser metrology, and observing with virtual structure.*



only two or three spacecraft must develop distributed command systems to avoid large, expensive mission operation teams. Finally, advanced formation guidance, estimation, and control architectures and algorithms are necessary for robust, fuel-optimal formation operation of any formation; for example, to perform reconfigurations for science retargeting and to ensure collision avoidance.

The following specific areas for development are discussed below in terms of their importance and status.

- Distributed-spacecraft architectures
- Wireless data transfer
- Formation sensing and control

## 7.1 Distributed-Spacecraft Architectures

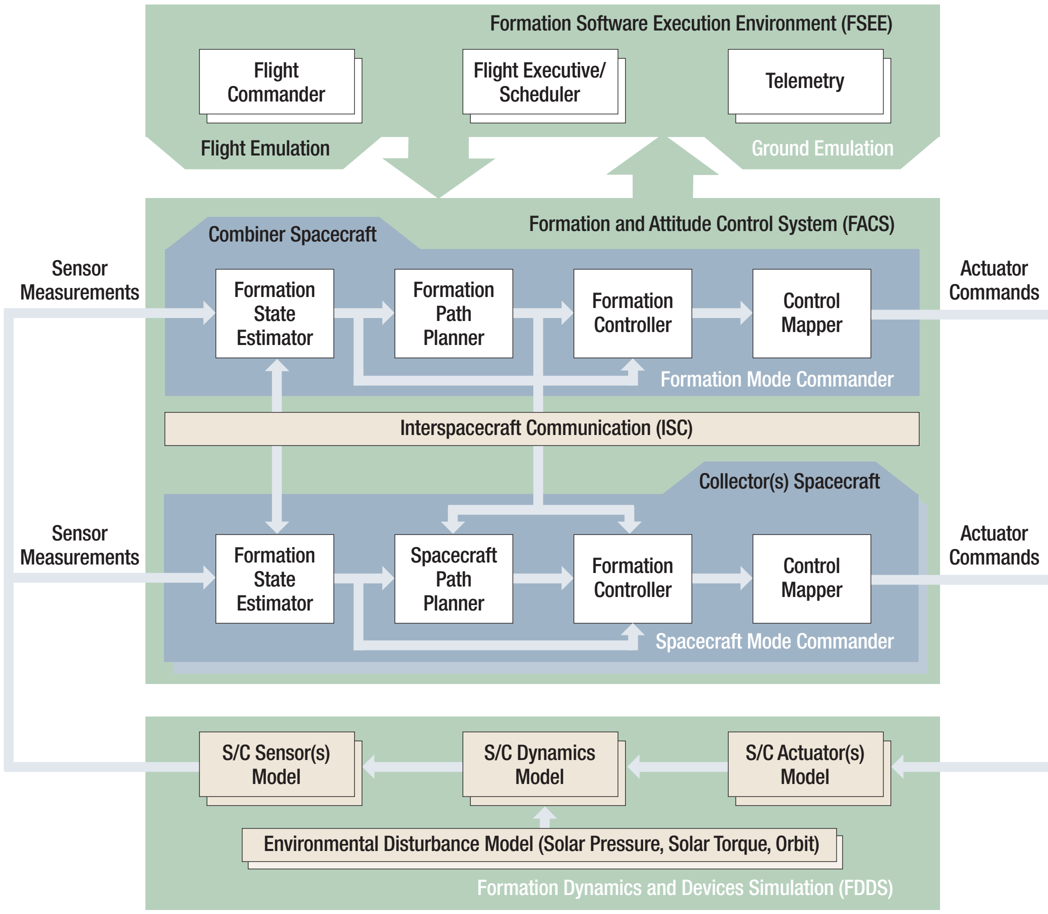
Distributed-spacecraft architectures are fundamentally different from single-spacecraft architectures. They require the combination of distributed sensor measurements, path-planning, and control capabilities, subject to communication capacity, to guarantee formation performance. Distributed architectures can enhance collision avoidance, allow for allocation and balancing of fuel consumption, and allow for graceful degradation in the case of system failure. New, scalable, and robust classes of distributed multispacecraft system architectures must be developed that integrate formation sensing, communication, and control. To function as a formation, the spacecraft must be coupled through automatic control. Such control requires two elements: interspacecraft range and bearing information to determine the present formation configuration, and optimal desired trajectories that achieve science goals. These two elements are, respectively, formation estimation and formation guidance. All three capabilities—guidance, estimation, and control—must function in a distributed manner since precision performance requirements coupled with computational, scalability, and robustness constraints typically prevent any one spacecraft in a formation from having full formation knowledge in a timely manner. Distributed architectures determine how a formation is coordinated and, hence, the possible stability and performance characteristics achievable for given communication and sensing systems. As such, distributed architectures must be able to support a wide range of communication and sensing topologies and capabilities and further, must be able to adapt to changing topologies. Future performance targets include the development of architectures of up to 30 spacecraft with subcentimeter performance over a 10-year mission life, with consistent graceful degradation while meeting sensor/communication requirements.

## 7.2 Wireless Data Transfer

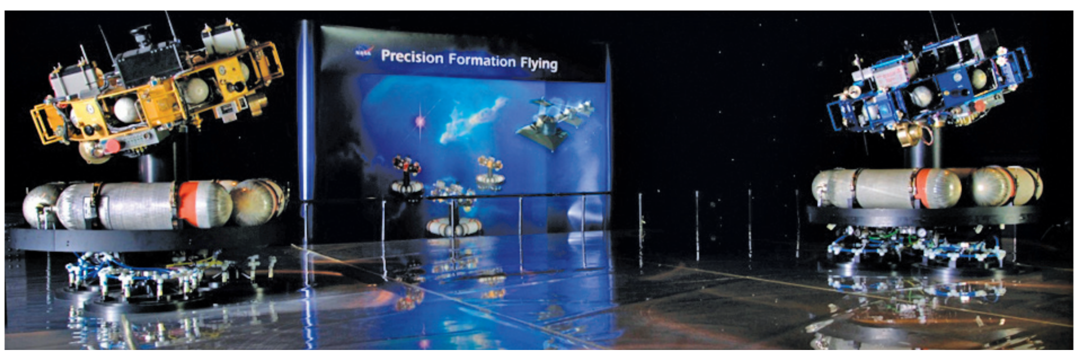
High-throughput, low-latency, multipoint (cross-linking) communications with adaptable routing and robustness to fading is necessary to support formation-flying missions. Throughput and latency directly impact interspacecraft control and knowledge performance as well as payload operational efficiency. Real-time control quality of service must be maintained over large dynamic ranges, some latency, and varying number of spacecraft and formation geometries. Payloads will require tens to thousands of megabit-per-second data rates for target recognition/science-in-the-loop applications. Coordinating multiple spacecraft requires distributing locally available information (e.g., a local interspacecraft sensor measurement) throughout a formation. Health and high-level coordination information must also be disseminated, such as a spacecraft's readiness to perform a certain maneuver. For these reasons, and unlike any single-spacecraft application, formations require closing control loops over a distributed wireless data bus. For example, a sensor on one spacecraft may be used to control an actuator on another. Hence, the overall precision performance of the formation can be limited by the ability of interspacecraft communications. While technologies such as cellular towers are fine for terrestrial voice applications, formations require highly reliable systems that are free of single-point-failures and have high bandwidth and guaranteed low latency. For the precision levels envisaged, dropped packets can cause a synthesized instrument to stop functioning, severely reducing observational efficiency. Finally, the range over which formations operate means that the communication system must be capable of simultaneously talking to a spacecraft hundreds of kilometers away without deafening a spacecraft tens of meters away, a problem area referred to as cross-linking. Short-term performance targets for wireless data transfer for PFF include operating 30 spacecraft at 100 Mbps data rates, with seamless network integration.

## 7.3 Formation Sensing and Control

Formations require interspacecraft knowledge to synthesize virtual structures for large instruments. Direct relative optical and radio frequency sensing of interspacecraft range and bearing is essential, especially for deep-space and GEO missions that cannot fully utilize global positioning system (GPS) capabilities. For astrophysical and exoplanet interferometry, the range and bearing knowledge between spacecraft must be sensed to the nanometer level for science and to the micrometer-to-millimeter level for precision formation control. Space-qualified, high-precision metrology systems with a large dynamic range and the ability to simultaneously track multiple neighboring spacecraft are required. Further, variable lighting conditions and several orders-of-magnitude dynamic ranges must be accommodated, while maintaining reasonable mass/power/volume and ease of integration. Finally, beyond GPS, knowledge based on Deep Space Network information is not sufficient for formation member spacecraft to find one another. So, the first step after deployment is to initialize the formation: spacecraft must establish communication and search for each other with onboard formation sensors. The capability of sensors, particularly their FOV, drives situational awareness within a formation and can enable attendant collision-avoidance capability. Sensors must provide relative knowledge from submeter/degree-to-micrometer/arcsecond level of range/bearing performance to support robust science observations




*Architecture for a PFF control of spacecraft.*




*High PFF simulation testbeds.*

over operating distances of meters to tens of kilometers. For large formations, sensors must function with multiple spacecraft in FOV and minimal coupling to flight systems.

For control, advanced formation guidance and estimation and control algorithms are necessary for robust, fuel-optimal formation operation, including reconfiguration and collision avoidance. The algorithms and methodologies are the low-level counterpart to the high-level distributed architectures. To validate PFF architectures and algorithms, JPL is developing a high-fidelity real-time simulation environment for formation-flying missions; the environment is called the formation algorithms and simulation testbed (FAST) and is a generalization of a typical single-spacecraft real-time testbed to precision formations. It allows high-fidelity development, testing, and characterization of formation control algorithms, flight software, and mission concepts.

## Summary

*Many future Earth and deep-space missions that achieve a host of measurement capabilities, both in the NASA and non-NASA communities, will be enabled by precision formation flying. Essential precision collaborative flight of distributed spacecraft systems requires PFF-critical technology developments ranging from architectures to methodologies, to hardware and software.*

# Deep-Space Communications

8

**Deep-space communications enable high-bandwidth networked planetary communication rates in support of high science data volumes and cost-effective, high-capability ground stations.**

Communications are among the most critical functions in space exploration. The communications system provides the link to the spacecraft from Earth and brings scientific data from spacecraft to Earth. It also tracks the spacecraft and provides it with information required to perform its job. Without communications, a successful mission would be impossible. The demands on deep-space communications systems are ever increasing. NASA estimates that the deep-space communications capability will need to grow by a factor of 10 during each of the coming decades. In addition, deep-space communications is one of a set of enabling technologies that allow the development of new mission concepts.

The principal challenge of deep-space communications is the enormous distances that our spacecraft travel: up to tens of billions of miles from Earth. Communications performance is inversely proportional to the square of this distance. Doubling the distance between the spacecraft and Earth requires a factor of four increase in performance to maintain the same communications level with the spacecraft. This must be accomplished while observing mass and power limitations imposed by spacecraft systems. Current and future space missions also demand that increasing information be transmitted. For example, Mars return data rates (the number of bits per second) have increased by a factor of 10 over the last decade and are likely to continue increasing at this rate into the future.

Another important challenge is posed by the extreme reliability that space missions require. After launch, spacecraft problems can only be diagnosed, repaired, or mitigated through the communications system. Since planetary missions often last more than a decade, communications reliability must also be maintained throughout the very long system lifetimes.

In addition to mission communications, direct science observations are possible using existing communication links. Radio science uses perturbations in the link to deduce either spacecraft motion, e.g., motion induced by unknown gravity fields, or properties of the medium through which the signal has passed, e.g., densities of planetary atmospheres. Additional uses of the radio link include interferometry for an even finer measure of spacecraft motion and radar to measure or even image bodies in space.

The Earth end of the communications system for deep-space missions is the Deep Space Network (DSN), comprising antenna complexes at three locations around the world. These facilities, approximately 120 degrees apart on Earth, provide continuous coverage for deep-space missions. Each complex includes one 70 m diameter antenna and a number of 34 m antennas. These antennas may be used individually or in combination (antenna arraying) to meet each space mission's communications requirements.

A large portion of deep-space communications research addresses communications system engineering, radios, antennas, transmitters, signal detectors, modulation techniques, coding theory, data compression, and simulation. Deep-space communications research includes optical communications as well as related expertise in optical instruments, optics systems design, optical detectors, lasers, and fine-pointing systems.

Deep-space communications facilities include a 34 m research and development antenna (at the DSN complex at Goldstone, California), and the Optical Communications Telecommunications Laboratory with a 1 m telescope (at the Table Mountain Observatory in Wrightwood, California).

The following areas, discussed below, represent the strategic focus within the deep-space communications technology area:

- High-rate communication techniques
- Optical communications

- Autonomous and cognitive radios
- Flight transponder technology
- Antenna arraying

## 8.1 High-Rate Communication Techniques

High-rate communication techniques are essential if future mission requirements are to be met. New methods are being investigated to allow current radio systems to accommodate the ever-increasing need to reliably move more bits between Earth and deep space. Specific areas of investigation include: very low complexity error correction coding to improve Ka-band link availability for gigabit per second (Gbps) links, software configurable radios that adaptively mitigate amplifier distortions throughout the life of long-duration missions, and integrated wideband array combiner and telemetry receivers for bandwidth-efficient signals.

Analysis of the NASA Agency Mission Planning Model and future mission concepts studies suggest that, by 2025, space missions will require a 100 times increase in communications capabilities. This level of capability can be achieved with radio-frequency technologies, including the adoption of Ka-band (26 to 40 GHz) as the deep-space workhorse communications frequency.

## 8.2 Optical Communications

At some point, spectral or performance needs will force missions to adopt optical communications. Several orders-of-magnitude increases in performance for the same power and mass are possible. Areas of emphasis at JPL in optical communications research and development include: long-haul optical communications; optical proximity link system development, and in-situ optical transceivers. These technologies will be essential to enable streaming video and data communications over the long distances involved in interplanetary distances.

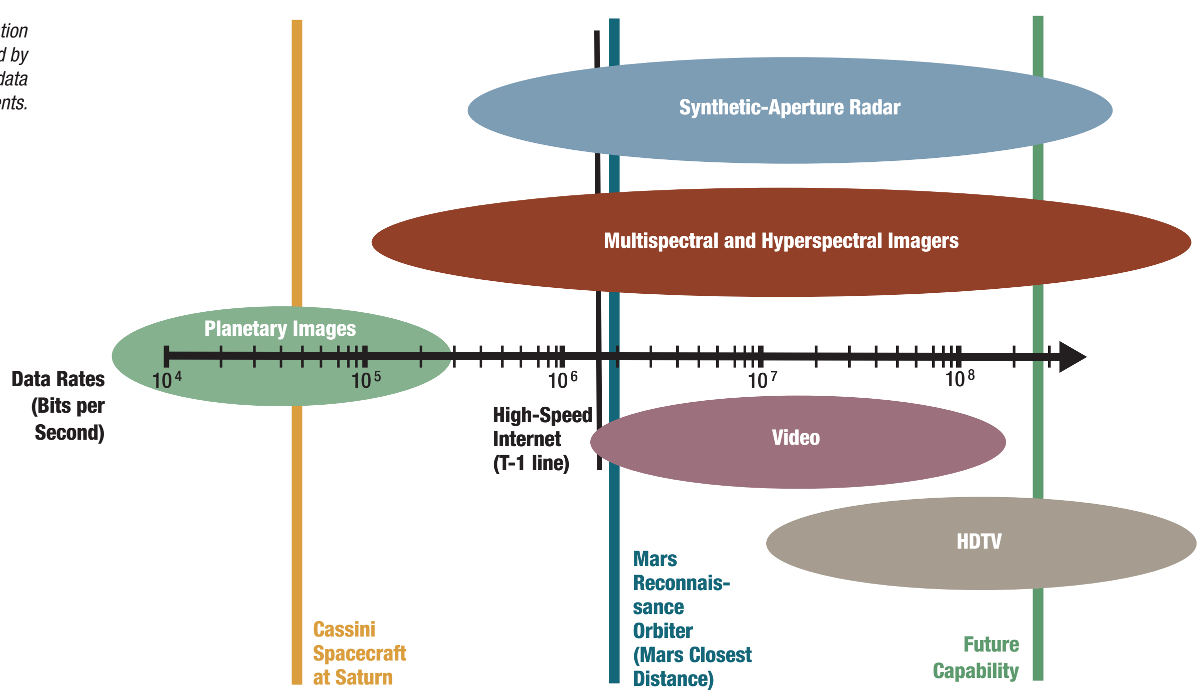
For long-haul communications over planetary ranges, JPL will need to develop the remaining critical subsystem technology to deliver a minimum of 20 dB improvement over conventional spacecraft telecommunications and navigation systems. Performance goals are in the range of 0.01–1 Gbps data rates; multiple-channel video high-definition television transfer; subcentimeter spacecraft position determination; and maximized bits/kg/watt system performance.

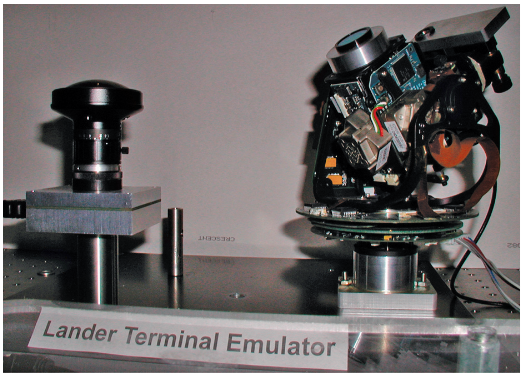
Optical proximity link system development will be required to meet future mission requirements of enabling high-rate communications translating into a minimum of 20 dB improvement over the state of the art. This improvement is needed for planetary and lunar orbiters to communicate with landed assets such as landers or rovers and to support optical navigation. The performance goal for optical proximity link systems is a 0.1–2.5 Gbps data rate.

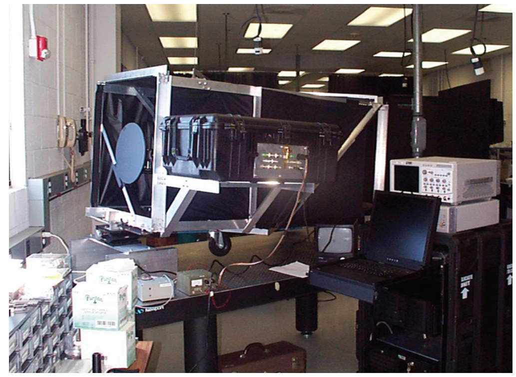
## 8.3 Autonomous and Cognitive Radios

Intelligent systems embedded in DSN communications terminals will allow significant operational cost savings while also offering the ability to adapt to new mission situations as they arise. Autonomous and cognitive radios will simplify operations by autonomously detecting data rates, modula-

*High communication rates are dictated by future science data requirements.*





*Lander-orbiter optical > 50 Mb/s for Mars or Moon.*

*Right: End-to-end field tests emulating deep-space signal levels.*

tion, and Doppler rates at space and ground receivers. These radios adaptively establish spectrum functionality, such as usage and data rate, based on dynamic probing (cognizance) of spectrum utilization and channel quality. Performance goals include 150 Mbps proximity links at Mars.

### 8.4 Flight Transponder Technology

The communications transponder is the mission's portal to the interplanetary network. It is also the element that requires the most reliability and longevity in the spacecraft system. Existing flight transponders are approaching their performance limit and are not expected to meet requirements of future missions. Improvements to this technology will enable the higher data rates required, support multiple spacecraft communications, and improve the precision of deep space navigation.

### 8.5 Antenna Arraying

JPL uses arrays of DSN antennas to form virtual antennas of a size effectively equal to the sum of its constituents. As we move to a future with orders-of-magnitude greater demand on space communications systems, arraying of DSN antennas will become pervasive, since arraying is more economical and more flexible than building ever-increasingly large monolithic antennas. Arraying will be essential to providing the highest data rates, and eliminating the communications bottleneck to the outer planets.

Critical technologies in this area include low-cost electronics, low-cost antennas, signal processing, and remote operations. This array approach will support the future communications need by operating at X-band and Ka-band frequencies at high data rates ( > 100 Mbps). Near-term performance targets are 25 Mbps uplink and 150 Mbps downlink data rates.

### Summary

*Deep-space communications are critical to the success of space missions that require data transmission from spacecraft to Earth, spacecraft tracking, and the ability to instruct the spacecraft to perform necessary actions. To overcome the enormous communication distance and spacecraft mass and power limitations in space, JPL's deep-space communications technologies developed for NASA's spacecraft and the Deep Space Network have enabled every JPL space mission ever flown and contributed to the development of exciting new mission concepts. To continue meeting the increasing demand on deep space communications systems, the Deep Space Network must increase its capability by a factor of 10 during each of the coming decades.*

9

# Mission System Software and Avionics

**Software and avionics that enable fundamental mission capabilities such as commanding and fault protection, and critical functions such as entry, descent, and landing, as well as emerging functionalities such as science-event detection and response.**

Mission system software and avionics, and autonomous capabilities in particular, have always been a central part of JPL missions, going back to the days of assembly programming languages, kilobits of memory, and central processing unit (CPU) performance barely measurable in modern terms.

A spacecraft and mission system's ability to plan, act, react and generally accomplish science and other mission objectives resides partly in the minds and skills of the engineers who designed them, and the operators who command them, and partly in the flight and ground software and computers that implement the vision and will of those engineers and operators.

The significant ongoing challenges of deep-space missions concern operating in a remote and imperfectly understood environment. Success depends on the ability to predict the fine details of the remote environment well enough to perform the mission safely and effectively. Also, a project team must have thought through carefully what may go wrong and must have a contingency plan, or a generalized response ready to go that will secure the spacecraft and mission reliably until next steps can be determined.

Balanced against these engineering realities are always-advancing science objectives, as each mission returns exciting new results and discoveries, leading naturally to new science questions that in turn demand greater capabilities from future spacecraft and missions.

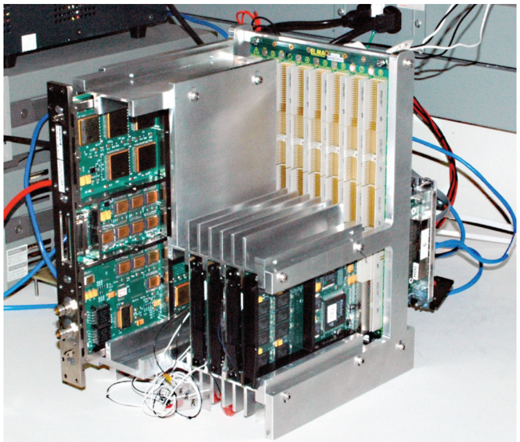
This healthy tension between engineering designs and science investigations results in increasing demands on the functionality of mission software and the performance of the (especially flight) computers that host the software. Mission software and avionics must become more sophisticated and, inevitably, complex to meet the needs of the science missions, while extreme reliability must be preserved in the engineered systems.

Mission software and computing are also inherently cross-cutting, in that capabilities developed for one mission are typically relevant to other missions as well, especially those within the same class, e.g., orbital or surface missions. Because of its cross-cutting nature, which impacts Earth, planetary, and astrophysical sciences, mission system software and avionics have the potential of high leverage and immediate and large advancements. This progress follows from advances in system software engineering as applied to space systems with current mission sets that have reached limits of what can be accomplished without these advances. Currently, there are four principal areas of technology development, maturation and infusion in mission system software and avionics:

- Spaceborne computing
- Mission system software
- Autonomous operations
- Software reliability

## 9.1 Spaceborne Computing

JPL spaceborne computing capabilities include flight computing architectures that support separation of sensor and instrument data processing from control functions of the spacecraft, that scale with mission class, and that apply generalized approaches to fault tolerance. When it comes to flight computing architectures and avionics, recent missions have used single radiation-hardened (rad-hard) processors of a few tens of up to a few hundred mega-operations per second with power consumption of 20 to 30 W. For most



*Flight-like Dependable Multiprocessor Testbed developed by Honeywell International for NASA's New Millennium Program. The testbed consists of four x-Pedite 6031 cards with 7447 processors and a radiation-hard controller. The testbed was used to analyze the performance of the fault-tolerant middleware software.*

missions, except to the most extreme of environments, such processors are reliable intrinsically enough that additional hardware redundancy need not be added to the system architecture.

For most guidance navigation and control mission functions, these processors have been more than adequate. However, emerging missions that require more complex entry, descent, and landing or onboard scientific data analysis and autonomy can drive the mission requirements for more onboard computing up by a factor of one hundred to one thousand. While such processors that support this exist in the commercial sector, it often takes years for these processors to migrate into rad-hard systems.

The trend in these systems is toward increasing the number of cores per chip, with decreasing power requirements. The very low power per core is the game-changer that can make these chips attractive for space applications. Rad-hard multicore chips are being developed by the U. S. Department of Defense in the range of 64 to 200 cores per chip, compared to the current state of the art of 4 to 8 cores per chip; the chips are expected to be released in the next 1 to 2 years. The challenge will be to architect these parallel computer parts into a highly reliable real-time embedded spacecraft avionics computing system that is easy to program, that controls software complexity, that is easy to verify and validate, that is able to predict real-time performance, and most important, that is highly fault tolerant. JPL must work with industry to influence the tools, standards, and components as much as possible to suit our highly reliable system needs; JPL may have to step in to fill technology gaps as needed.

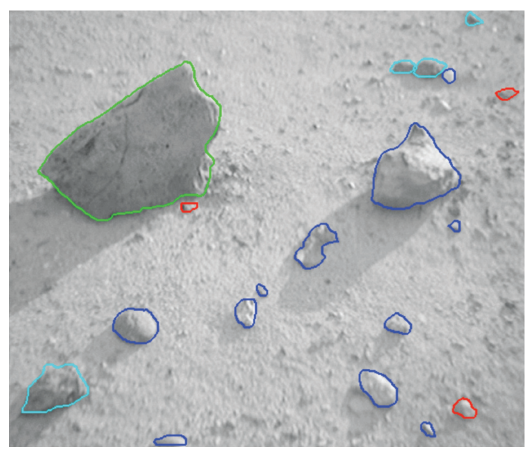
## 9.2 Mission System Software

Mission system software at JPL provides an integrated approach to systems and software engineering, with state-based designs leading seamlessly to goal-based operations, supported by a control system architecture. In the area of mission system software, JPL has developed a lifecycle approach that goes from state-based design (via so-called "state analysis") to behavior specifications that map onto verified software frameworks and goal-based operations concepts. All is integrated with a control architecture that supports autonomous capabilities. This work awaits final development and flight validation.

For mission system software, the primary objective is to enhance the reliability of our mission systems by creating them within a common framework that both systems and software engineers utilize. Additional objectives include a reusable set of software components for ground, flight, and test in addition to a well-conceived, stable control architecture for hosting autonomous capabilities.

## 9.3 Autonomous Operations

JPL's capabilities in autonomous operations include flight and ground automated planning integrated with fault protection, targeting both deep-space and human–robotic operations. These support capabilities like science-event detection and response. For autonomous operations, recent successes include the use of onboard vision-based processing to detect and compensate for horizontal (shear) winds during the landings of the Spirit and Opportunity rovers on Mars. JPL has also successfully deployed an automated planner in a flight system that routinely detects science events, such as volcanic eruptions from Earth orbit, and provides automated follow-up imaging. A version of this system recently detected and tracked dust devils on Mars.



*Characterizing features in an image is a challenging problem. Statistical identification of scientific features such as rocks within a scene will be important for future missions to Mars and the outer planets in which an autonomous spacecraft can automatically recognize important science targets.*

Autonomous capabilities will continue to advance to meet the needs of science investigations while maintaining the highest standard for system reliability and risk management. Precision landing along with rendezvous and docking are some anticipated future engineering functions. Science event detection and response is targeted to generalize to multiple platforms, supported by space networking.

## 9.4 Software Reliability

At JPL, software reliability takes a lifecycle approach, including requirements capture and analysis, verifiable software components, model-driven verification techniques, methodologies for software testing, and software fault containment. To enhance software reliability, JPL established the Laboratory for Reliable Software (LaRS) that is developing and deploying a lifecycle approach to software reliability and includes requirements analysis, behavior modeling, coding practices, model-based verification, testing methodologies, and fault containment. LaRS has made important contributions in its short history, improving software quality on several missions, including the Mars Exploration Rovers, Spitzer, the Mars Science Laboratory, Kepler, Dawn, and others.

The objective for software reliability can be stated simply: a tenfold reduction in software defects. The comprehensive lifecycle approach described above is required to realize it.

## Summary

*The functionality requirements of science missions will and must continue to evolve, while the need for extreme reliability in flight systems remains a critical factor. Heretofore, deep-space missions have been commanded almost entirely from the ground, with ingenuity and patience overcoming the difficulties of light-time delays. The only exceptions were certain scenarios where, because of latency, control loops simply had to be closed on board the spacecraft, such as during entry, descent, and landing on Mars. Other than for these critical sequences, reliability was achieved largely via safing responses in fault protection, while fault tolerance concepts were mostly based on radiation hardening of the avionics.*

*Now, with the advent of surface missions as an established mission class—and their concurrent realities of grappling with ongoing uncertainties of operating on a planetary surface—along with the above-mentioned evolution of science objectives, there are pressures to create more capability and to close more loops on board spacecraft. Inevitably, these new demands on functionality will be largely taken up by new kinds of software, especially those supporting autonomous capabilities. The flight computers must advance in capability to host such software, and both the flight software and the avionics must remain extremely reliable.*

*Stated differently, future spacecraft and space missions will rely more on software-based functionality, and flight computing must evolve to keep pace.*

# Lifecycle Integrated Modeling and Simulation

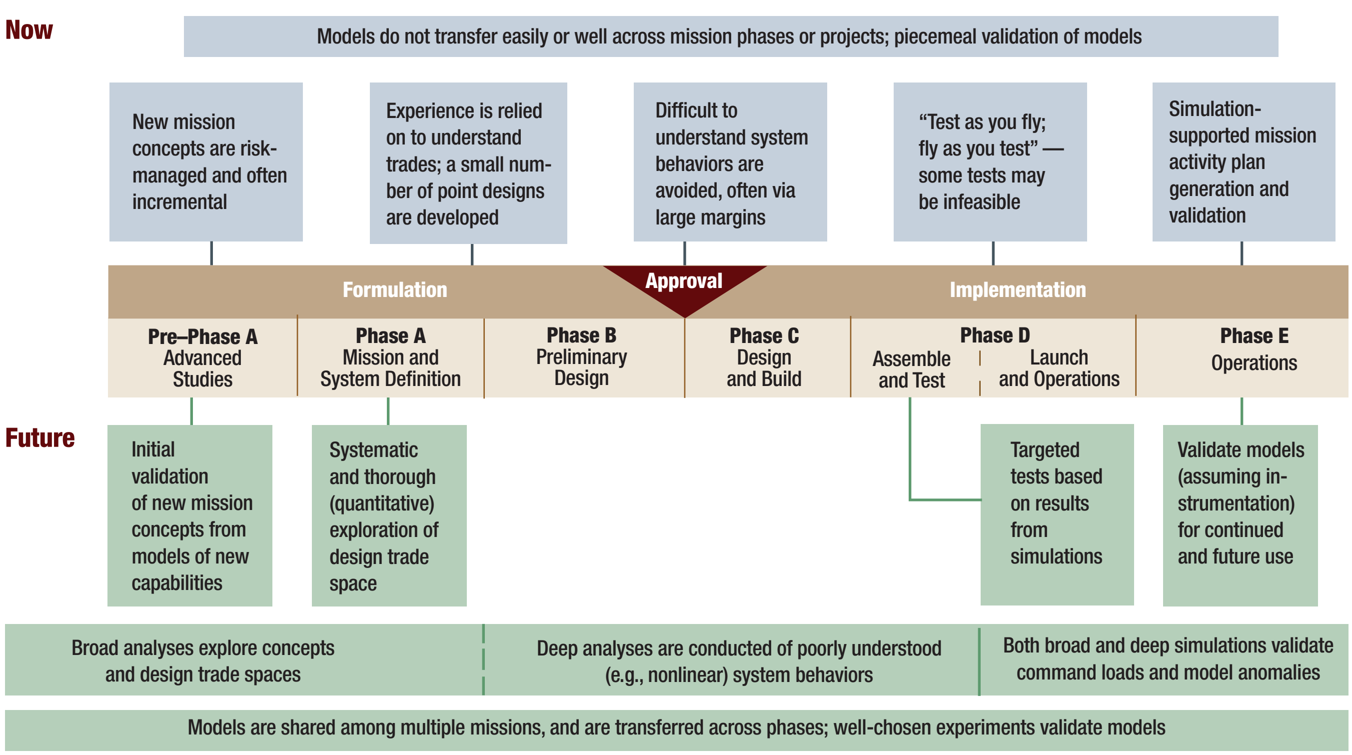
10

**Lifecycle integrated modeling and simulation enables rapid and thorough exploration of trade spaces during early mission design, validated high-fidelity simulations of specific engineering systems during detailed design, and validated computational science simulations in focused science disciplines. It targets the development of a formal framework of model verification and validation that includes quantification of uncertainties in model parameters to assess and establish performance margins.**

A deep-space or Earth-science mission starts with a set of questions about natural phenomena, which evolves into specific measurement objectives and science-return requirements. These objectives and science requirements drive the requirements, in turn, for the mission, spacecraft-system architecture, and instrument systems. As mission capabilities advance, so does overall system complexity. Testing and validating mission concepts and systems using conventional testbeds is becoming progressively more challenging and, in some cases, infeasible if testing on the ground is not possible. Large-scale, high-fidelity models and predictive simulations, when grounded by validation from available test data, can provide an important complementary testbed approach, enabling greater depth and breadth for exploring system designs and conducting engineering analyses, as well as driving selective physical testing. Similarly, predictive scientific simulations that assimilate observed data can be used to develop and assess instrument systems under development.

Several lifecycle modeling and simulation areas will benefit from technology advances, including broad analysis trade-

*Current and future states of integrated modeling and simulation at JPL.*



space-exploration capabilities, such as engineering design modeling, phenomenology modeling for engineering and science, performance and operation modeling, and visualization for design and systems engineering decisions. Advances must also be made in coupled and integrated physics-based modeling and high-fidelity simulations that provide deep level engineering analyses during detailed design. Model verification and validation capabilities that facilitate decision making about the system (similar to the decisions that would be made if it were feasible and cost-effective to experiment with and test the system itself) must be developed. Finally, model integration that provides a network-enabled, collaborative modeling and simulation environment of instrument, component, and spacecraft models is required.

These are areas where advances are needed to make possible bolder mission concepts and capabilities while managing risk and cost to acceptable levels, as well as to take progressively larger capability steps between missions, building on but not unduly constrained by legacy approaches. The "holy grail" would be a capability that could directly tie engineering parameters associated with flight and ground systems to advance science return, especially those parameters that drive schedule and cost.

Specific technology challenges in the area of lifecycle integrated modeling and simulation include: (1) determining the degree and coupling needed or feasible for model integration; (2) developing software integration between scalable (parallelizable) codes/tools and portability of code across multiple platforms; (3) developing mathematical, computational, and multiscale modeling scalability; (4) verifying (assessment of the numerical correctness of the code) and validating (assessment of simulation results with experiments) models; and (5) reusing models and codes libraries.

## 10.1 Trade-Space Exploration

Examples of advanced technologies in trade-space exploration include the following:

- Engineering design modeling
- Phenomenology modeling for engineering and science
- Performance and operation modeling
- Visualization for design decisions

These technologies are needed for early-mission design trade-space exploration, system trades, design validation and optimization, and requirement validation for broad analyses. Optimization and simulation tools are needed to both analyze and visualize new mission architectural solutions. Immediate performance targets include multiparameter design with rapid turnaround; systems trades that model and simulate nonlinear systems; design validation/optimization; scientific (phenomenology) modeling for in-situ remote sensing; spacecraft, instrument, and trajectory performance modeling for landers and orbiters; and incorporation of advanced visualization into the design optimization decision process.

## 10.2 Coupled and Integrated Physics-Based Modeling

Physically realistic models of complex behaviors of scientific phenomena, instruments, and spacecraft are essential for Earth, planetary, and astrophysics system simulations. However, such systems can be dominated by interactions between physical behaviors that can only be captured by tightly integrated, high-fidelity, multiphysics simulations. For example, most large apertures cannot be fully tested on the ground; therefore, technologists must rely on high-fidelity simulations, including a quantification of the margins and uncertainties in the simulation results, to fully model large apertures. Such simulations are beyond the capability of most codes today, and considerable investment is needed in this technology area for deep engineering analyses of complex space systems.

A key challenge is the development of the tools themselves. Current commercial tools cannot couple even two dissimilar physical models, because the model formulation in one domain is likely to be incompatible with that in another. Forcing unidisciplinary, commercial codes to form a quasi-integrated model may be possible, but that solution does not scale up to realistically detailed models, or to capture dynamics that arise in the coupling between two or more phenomenologies, such as structural, thermal, optical, and control dynamics of lightweight flexible structures. New tools are needed that couple and integrate models of multiple physical domains in a manner amenable to high-fidelity model meshes and dynamics integration.

A second key challenge is the quantification of uncertainty for these simulations. The codes must embed uncertainty descriptions for all model parameters in a manner that allows large-scale sensitivity studies. Uncertainty quantification methods must be scalable and parallelizable. The ability to handle spatially distributed uncertainty, such as variation in material properties, is especially important. Likewise, uncertainty quantification methods that avoid costly Monte Carlo simulation, such as metamodels or reduced-order models, would be of high value. Near-term performance targets against specific capabilities include multiple high-resolution coupled models with quantified uncertainty driving advanced instrument design, observations, and mission planning.

## 10.3 High-Fidelity Model Verification and Validation

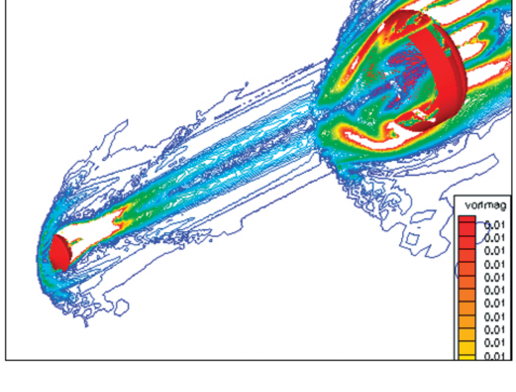
Confidence in a large-scale, high-fidelity simulation requires that model codes be rigorously verified and test-validated. Model verification is the process of determining the degree to which a computational model accurately represents the underlying assumed mathematical model and its solution. Model validation, which usually follows model verification, is the process of determining the degree to which the assumed mathematical model represents an accurate representation of the real world from the perspective of the intended application of the model. Verification of complex, integrated modeling codes is necessary to ensure that uncertainty in simulation results from software errors and numerical effects is minimized or eliminated.

Development of verification capabilities is challenging because of the coupled and integrated nature of the codes. Validation is likewise very difficult because it requires test data for the precise space environment; in the case of space systems (e.g., entry, descent, and landing; large deployable telescopes; space interferometers), it is not possible to replicate the environment on the ground in every detail. The challenge and promise is that by modeling the differences, one can establish that the domain of validity of the numerical-simulation models extends to flight conditions where it must apply.

Far right, simulation of an optical interferometry testbed using Cielo, an integrated structural, thermal, and optical modeling system.

Extrapolation outside a limited test domain means that the models themselves have to get the right answer for the right reason. A traditional "tuning" or "calibration" of the model can make it fit a given test on the ground, but that does not mean the model is any more credible for another application. Only validating the model at the level of its basic physics can lend credibility beyond the domain of ground tests.

Consequently, investments in new methods and technologies are needed to verify and validate models so they can be relied upon to extensions from ground tests to flight. Rigorous validation methods are needed that are compatible with flight practices for gathering system data during integration and test. Test methods are needed that target the dominant model uncertainties in validating models, so that limited test resources can be focused where they will have the most impact in establishing model reliability. Methods for inferring model uncertainty from comparison with test data are needed, including the development and demonstration of statistical metrics for validation in multidisciplinary regimes. Lastly, for models validated in lower-level tests, technologists must have methods to roll up the uncertainties into system-level models. Performance targets include inverse statistical analyses for extrapolating model uncertainty beyond a test

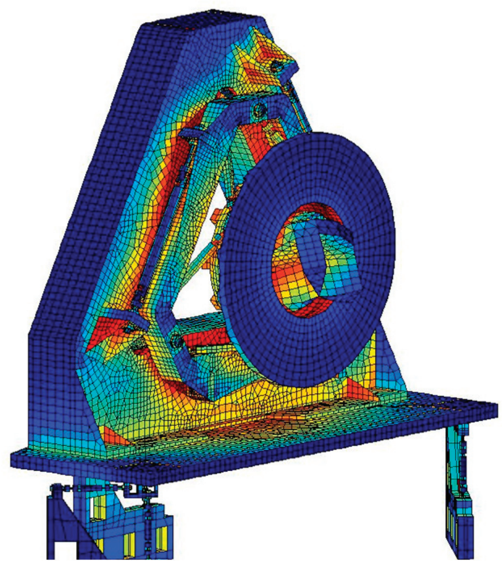



Computational fluid dynamics model for Mars Science Laboratory parachute qualification.

to another test with different inputs, and demonstration of specific methods on coupled, integrated high-fidelity models of complex systems.

## 10.4 Model Integration

Science and engineering models today do not transfer easily or well across mission phases or projects. A desired future state is an environment in which models are shared among multiple missions and are readily transferred from phase to phase in an integrated, synergistic fashion, covering a broad range of multidisciplinary problems associated with science and engineering. The integration of models and simulations developed independently presents a daunting challenge. In terms of model integration, an assessment of what degree of coupling is needed or feasible must be ascertained, and interoperability standards need to be defined that will allow the conforming models and data sources to be integrated.



In addition, a framework and architecture for integration must be agreed upon by the modeling and simulation community in order to produce a flexible, reusable system that will enable multidisciplinary, multiscale model- and simulation-based analyses and design throughout the project lifecycle. This includes the adoption of a set of model service protocols and information-exchange mechanisms so that discipline models can interoperate seamlessly with other discipline models. Specific technology needs include a scalable, model-centric information infrastructure to support semantic integration, model transformations, formal specifications and ontologies, and state of the art in interoperability standards. These technologies are considered cross-cutting as they are needed for both broad analyses involved in early trade space exploration as well as deep analyses required for detailed design. Current modeling languages, environments, tools, and standards are restrictive in some aspects of expressiveness, lack formal semantics (which impedes the ability to integrate information), and lack mechanisms of model validation. Advances in formal specifications and ontologies provide the basis for robust and sound model sharing. Performance targets against specific capabilities include a semantically rich model integration framework that can integrate representations from a dozen or so models, coupled with high-fidelity and predictive simulations and the ability to connect the models through a full project lifecycle. These models would represent varying degrees of fidelity in a multidisciplinary context.

## Summary

*JPL seeks new ways to propose compelling new mission and instrument concepts while understanding and containing risks in their development. Testing and validation of these concepts as well as system designs using conventional testbeds are becoming progressively more challenging, and in some cases, infeasible. As a consequence, investment in lifecycle integrated modeling and simulation technologies and capabilities is needed to enable greater depth and breadth in exploring system designs and conducting engineering and scientific analyses.*

*A lifecycle emphasis is important because technologies and capabilities are needed to support the development and integration of not only models and simulations to be used for broad analyses in exploring concepts and design trade spaces with rapid turnaround demands, but also high-fidelity models coupled with predictive simulations in order to perform deep analyses during detailed system design. Finally, novel techniques are needed for validation of models and simulations as engineers and scientists become increasingly dependent on the modeling and simulation discipline to explore system designs and conduct engineering and scientific analyses.*

# Appendices

## A Science to Technology Traceability

Key science questions and exploration goals with traceability to Strategic Technologies.
The approach and methods for this mapping follow from the 2005 Strategic Technology Plan.

## B Acronyms and Abbreviations

## C Bibliography

APPENDIX A

# Science to Technology Traceability

Key science questions and exploration goals with traceability to Strategic Technologies. The approach and methods for this mapping follow from the 2005 Strategic Technology Plan.

| Solar System Exploration Science Goals | | | | | | | | Science Key Technology Needs | Strategic Technology | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Solar System Exploration | 1. Large-Aperture Systems | 2. Detectors and Instrument Systems | 3. Advanced Propulsion and Power | 4. In-Situ Planetary Exploration Systems | 5. Survivable Systems for Extreme Environments | 6. Deep Space Navigation | 7. Precision Formation Flying | 8. Deep Space Communi-cations | 9. Mission System Software and Avionics | 10. Lifecycle Integrated Modeling and Simulation |
| Origin of the Solar System | | Solar System Evolution | | Origin of Life in the Solar System | | Evolution of Life in the Solar System | Preparation for Human Exploration | | | | | | | | | | | |
| Solar System Exploration Mission Realizations | | | | | | | | | | | | | | | | | | |
| Science Orbiters | In-Situ Landers | In-Situ Landers | In-Situ Aerobots | In-Situ Landers | In-Situ Aerobots | In-Situ Landers | Science Orbiters | | | | | | | | | | | |
| | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | Entry, Descent, and Landing, (EDL), Precision Landing, and Hazard Avoidance | | | ✓ | ✓ | | ✓ | | | | |
| | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | Telecom (Proximity) | | | | | | | | ✓ | | |
| ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | Planetary Protection | | | | ✓ | | | | | | |
| | | | ✓ | | ✓ | | | Aerobot Technology | | | ✓ | ✓ | ✓ | | | | | |
| ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | Sample Acquisition, Transfer, and Encapsulation | | | | ✓ | | | | | | |
| ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | Autonomy | | | | | | | | | ✓ | ✓ |
| | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | In-Situ Remote Sensing and Analytical Instruments | | ✓ | | ✓ | ✓ | | | | | |
| ✓ | | | | | | | ✓ | Remote Sensing Instruments | | ✓ | | | | | | | | |
| | ✓ | ✓ | | ✓ | | ✓ | | Subsurface Access | | | | ✓ | ✓ | | | | | |
| | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | Avionics | | | ✓ | | ✓ | | | | ✓ | |
| ✓ | | | | | | | ✓ | Aerocapture | | | ✓ | | | ✓ | | | | |

| Science Key Technology Needs | Mars Exploration Science Goals | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mars Exploration | Life Goal | | | | Climate Goal | | | Geology/Geophysics Goal | | | | | Preparation for Human Exploration Goal | | | |
| | Mars Exploration Mission Realizations | | | | | | | | | | | | | | | |
| | Science/ Telecom Orbiters | In-Situ Landers | In-Situ Rovers | Mars Sample Return (Lander & Orbiter) | Science/ Telecom Orbiters | In-Situ Landers | Network Landers | Science/ Telecom Orbiters | In-Situ Landers | In-Situ Rovers | Network Landers | Mars Sample Return (Lander & Orbiter) | Science/ Telecom Orbiters | | In-Situ Rovers | Mars Sample Return (Lander & Orbiter) |
| Entry, Descent, and Landing, (EDL) Precision Landing, and Hazard Avoidance | | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ |
| Telecom (Proximity) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ |
| Planetary Protection | | ✓ | ✓ | ✓ | | ✓ | | | ✓ | ✓ | | ✓ | | | ✓ | ✓ |
| Back Planetary Protection | | | | ✓ | | | | | | | | ✓ | | | | ✓ |
| Rover Technology | | | ✓ | ✓ | | | | | | ✓ | | ✓ | | | ✓ | ✓ |
| Sample Acquisition, Transfer, and Encapsulation | | ✓ | ✓ | ✓ | | ✓ | | | ✓ | ✓ | | ✓ | | | ✓ | ✓ |
| Autonomy | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ |
| In-Situ Remote Sensing and Analytical Instruments | | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ |
| Remote Sensing Instruments | ✓ | | | | ✓ | | | ✓ | | | | | ✓ | | | |
| Subsurface Access | | ✓ | ✓ | ✓ | | ✓ | | | ✓ | ✓ | | ✓ | | | ✓ | ✓ |
| Avionics | | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ |
| Rendezvous and Sample Capture | | | | ✓ | | | | | | | | ✓ | | | | ✓ |
| Mars Ascent Vehicle (MAV) | | | | ✓ | | | | | | | | ✓ | | | | ✓ |

| Science Key Technology Needs | Strategic Technology | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Mars Exploration | 1. Large-Aperture Systems | 2. Detectors and Instrument Systems | 3. Advanced Propulsion and Power | 4. In-Situ Planetary Exploration Systems | 5. Survivable Systems for Extreme Environments | 6. Deep Space Navigation | 7. Precision Formation Flying | 8. Deep Space Communications | 9. Mission System Software and Avionics | 10. Life-cycle Integrated Modeling and Simulation |
| Entry, Descent, and Landing, (EDL) Precision Landing, and Hazard Avoidance | | | ✓ | ✓ | | ✓ | | | | |
| Telecom (Proximity) | | | | | | | | ✓ | | |
| Planetary Protection | | | | ✓ | | | | | | |
| Back Planetary Protection | | | | ✓ | | | | | | |
| Rover Technology | | | ✓ | ✓ | ✓ | | | | | |
| Sample Acquisition, Transfer, and Encapsulation | | | | ✓ | | | | | | |
| Autonomy | | | | | | | | | ✓ | ✓ |
| In-Situ Remote Sensing and Analytical Instruments | | ✓ | | ✓ | ✓ | | | | | |
| Remote Sensing Instruments | | ✓ | | | | | | | | |
| Subsurface Access | | | | ✓ | ✓ | | | | | |
| Avionics | | | ✓ | | ✓ | | | | ✓ | |
| Rendezvous and Sample Capture | | | ✓ | ✓ | | ✓ | | | | |
| Mars Ascent Vehicle (MAV) | | | ✓ | ✓ | | ✓ | | | | |

| Astronomy and Physics Goals | | | | | | | | | | | Science Key Technology Needs | Strategic Technology | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cosmology | | | Dark Energy | Gravity Waves | Exoplanets | | | Local Universe Astrophysics | Fundamental Physics | Our Solar System | Astronomy and Physics | 1. Large-Aperture Systems | 2. Detectors and Instrument Systems | 3. Advanced Propulsion and Power | 4. In-Situ Planetary Exploration Systems | 5. Survivable Systems for Extreme Environments | 6. Deep Space Navigation | 7. Precision Formation Flying | 8. Deep Space Communi-cations | 9. Mission System Soft-ware and Avionics | 10. Lifecycle Integrated Modeling ns Simulation |
| Astronomy and Physics Mission Realizations | | | | | | | | | | | | | | | | | | | | | |
| Polarimetry | Multi-Object Spectroscopy | Lunar Radio Astronomy | Weak Lensing | LISA | Interferometry | Corona-graphy | Combined Light Spectros-copy | Ultraviolet to Submillimeter Telescopes, Instruments, and Detectors | Solar System Ranging | Telescopic Missions | | | | | | | | | | | |
| | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | | ✓ | 0.1–3 µm Detectors/ Focal Planes | | ✓ | | | ✓ | | | | | |
| ✓ | | | | | | | | ✓ | | | 30 µm–1mm Detec-tors/Focal Planes/ Amplifiers | | ✓ | | | ✓ | | | | | |
| ✓ | | | | | ✓ | | ✓ | ✓ | | | Cryogenics | ✓ | ✓ | | | ✓ | | | | | |
| | | | | | | | | ✓ | | | Large Optics | ✓ | | | | | | | | | |
| | | | | ✓ | ✓ | ✓ | | ✓ | ✓ | | Precision Structures & Metrology | ✓ | | | | | | ✓ | | | |
| | | | | ✓ | ✓ | ✓ | | | | | Formation Flying | | | ✓ | | | | ✓ | | | |
| | | | ✓ | ✓ | | | ✓ | | | ✓ | Onboard Processing and Com-pression | | | | | | | ✓ | ✓ | ✓ | |
| | ✓ | | | | | | ✓ | ✓ | | | Gratings | | ✓ | | | | | | | | |
| | | | | | ✓ | ✓ | | | | | Stray Light Control | ✓ | ✓ | | | | | | | | |
| | | ✓ | | | | | | | ✓ | | Transponder Deployment | | | | | | | ✓ | ✓ | | |
| | | ✓ | | | | | | | ✓ | | Thin-Film Antennas | ✓ | ✓ | | | | | | | | |
| | | ✓ | | | | | | | | | Rover Deployment | | | ✓ | ✓ | ✓ | | | | | |

| Earth Science and Technology Science Goals | | | | | | Science Key Technology Needs | Strategic Technology | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Climate Variability and Change | Atmospheric Composition | Carbon Cycle, Ecosystem, and Biogeochemistry | Water and Energy Cycle | Weather | Earth Surface and Interior | Earth Science and Technology | 1. Large-Aperture Systems | 2. Detectors and Instrument Systems | 3. Advanced Propulsion and Power | 4. In-Situ Planetary Exploration Systems | 5. Survivable Systems for Extreme Environments | 6. Deep Space Navigation | 7. Precision Formation Flying | 8. Deep Space Communi-cations | 9. Mission System Software and Avionics | 10. Lifecycle Integrated Modeling and Simulation |
| Solar System Exploration Mission Realizations | | | | | | | | | | | | | | | | |
| Spectrometry | Sub-mm Radiometer/ Spectrometry | Lidar/ Spectrometry | Radar/Ranging | Radar/Radiometry | Radar/ Spectrometry/ Ranging | | | | | | | | | | | |
| | ✓ | ✓ | | | ✓ | Greater than Petabye Data Production | | | | | | | | | ✓ | ✓ |
| | | | ✓ | ✓ | ✓ | Optimized Signal Chain (L/X/Ku) | | ✓ | | | | | | | ✓ | |
| | | | ✓ | | | Optimized Signal Chain (Ka/W/G) | ✓ | ✓ | | | | | | | | |
| | ✓ | | ✓ | ✓ | | Heterodyne Detection: 18, 50, 183 GHz, sub-mm | | ✓ | | | | | | | | |
| ✓ | ✓ | ✓ | | | ✓ | Multi/ Hyperspectral: High QE, FPA Uniformity and Polarization, ROIC, 2 μm Lidar | | ✓ | | | | | | | ✓ | |
| ✓ | ✓ | ✓ | | | ✓ | Data Compression, Formation Flying, Digital Spectrometer | | | | | | | | | ✓ | |
| | | | ✓ | | ✓ | Microthruster/ Avionics | | | ✓ | | | | ✓ | | ✓ | |
| ✓ | ✓ | ✓ | | ✓ | ✓ | Modeling and Simulation: OSSE, Climate Model, Coupled Models | | | | | | | | | | ✓ |

| Exploration Systems and Technology Office Support to Human Space Flight Goals | | | | | | Science Key Technology Needs | Strategic Technology | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Human Presence Precursor Missions | | | Human Presence Beyond LEO | | | Exploration Systems and Technology | 1. Large-Aperture Systems | 2. Detectors and Instrument Systems | 3. Advanced Propulsion and Power | 4. In-Situ Planetary Exploration Systems | 5. Survivable Systems for Extreme Environments | 6. Deep Space Navigation | 7. Precision Formation Flying | 8. Deep Space Communi-cations | 9. Mission System Software and Avionics | 10. Lifecycle Integrated Modeling and Simulation |
| Exploration Systems and Technology Mission Realizations | | | | | | | | | | | | | | | | |
| Robotic Lunar Orbiters | Robotic Lunar-Landed Missions | Other Precursor Missions (e.g., Asteroids, Libration Points) | ISS Experiments | Precision Lunar Landing Systems | Robotics Systems for Human Exploration | | | | | | | | | | | |
| | | | ✓ | | ✓ | Environmental Monitoring and Control | | ✓ | | | | | | | | |
| | ✓ | | | | ✓ | Long-Life Systems for Lunar Environment | | | | | ✓ | | | | | |
| | ✓ | | | | ✓ | Surface Mobility Systems | | | | ✓ | | | | | | |
| | | | ✓ | | ✓ | Human–Robotic Lunar Surface Operations | | | | | | | | | ✓ | |
| ✓ | ✓ | | ✓ | | ✓ | Lunar Science and Exploration Instruments | | ✓ | | ✓ | ✓ | | | | | |
| | ✓ | ✓ | ✓ | ✓ | ✓ | Autonomous Onboard GN&C | | | | | | ✓ | | | | |
| | ✓ | | | ✓ | ✓ | Precision and Safe (Hazard Avoidance) Landing | | | | ✓ | | ✓ | | | | |
| | ✓ | | | | ✓ | Surface Navigation | | | | ✓ | | | | | | ✓ |
| | | ✓ | | ✓ | ✓ | End-to-End GN&C Simulation | | | | | | ✓ | | | | |

APPENDIX B

# Acronyms and Abbreviations

| | |
|---|---|
| ACS | attitude control system |
| ATHLETE | All-Terrain Hex-Legged Extra-Terrestrial Explorer |
| AutoGNC | autonomous guidance, navigation, and control |
| AutoNav | autonomous navigation |
| COSMIC | Constellation Observing System for Meteorology, Ionosphere, and Climate |
| CTE | coefficient of thermal expansion |
| DARTS | Dynamics Algorithms for Real-Time Simulation |
| DOR | differential one-way range |
| delta-v | change in velocity |
| DSN | Deep Space Network |
| EDL | entry, descent, and landing |
| ESA | European Space Agency |
| FAST | formation algorithms and simulation testbed |
| FOV | field of view |
| FSC | fractionated spacecraft |
| GEO | geosynchronous orbit |
| GIRE | Galileo Interim Radiation Electron |
| GLONASS | Global'naya Navigatsionnaya Sputnikovaya Sistema, or Global Navigation Satellite System |
| GNSS | global navigation satellite system |
| GPS | global positioning system |
| IR | infrared |
| $I_{sp}$ | specific impulse |
| JPL | Jet Propulsion Laboratory |
| JWST | James Webb Space Telescope |
| LaRS | Laboratory for Reliable Software |
| LEO | low-Earth orbit |
| LIBS | laser-induced–breakdown spectroscopy |
| Lidar | light detection and ranging |
| MER | Mars Exploration Rover |
| MLE | Mars landing engine |
| MLS | Microwave Limb Sounder |
| MRO | Mars Reconnaissance Orbiter |
| MSL | Mars Science Laboratory |
| NASA | National Aeronautics and Space Administration |
| NEXT | NASA's Evolutionary Xenon Thruster |
| NSTAR | NASA Solar Electric Propulsion Technology Application Readiness |
| PFF | precision formation flying |
| POD | precision orbit determination |

| | |
|---|---|
| rad-hard | radiation hardened |
| RF | radio frequency |
| RPS | radioisotope power systems |
| SAR | synthetic-aperture radar |
| SIR | spaceborne imaging radar |
| SIS | superconductor-insulator-superconductor |
| SPIRE | Spectral and Photometric Imaging Receiver |

# Bibliography

APPENDIX C

Anthes, R., et al. (eds.) 2007 *Earth Science and Applications from Space: National Imperative for the Next Decade and Beyond.* National Academies Press (Washington, DC).

Balint, T. S., E. A. Kolawa, J. A. Cutts, and C. E. Peterson 2008 Extreme Environment Technologies for NASA's Robotic Planetary Exploration. *Acta Astronautica.* 63(1-4):285–298.

Garrett, H. B., J. M. Ratliff, and R. W. Evans 2005 *Saturn Radiation (SATRAD) Mode*. JPL Publication 05-9. National Aeronautics and Space Administration, Jet Propulsion Laboratory, California Institute of Technology (Pasadena, CA).

Jet Propulsion Laboratory 2005 *Strategic Technology Plan 2005*. JPL Publication 400-1203. Jet Propulsion Laboratory, California Institute of Technology (Pasadena, CA).

Jet Propulsion Laboratory 2006 *Solar System Exploration: This Is the Solar System Exploration Roadmap for NASA's Science Mission Directorate.* Technical Report JPL D-35618. Jet Propulsion Laboratory, California Institute of Technology (Pasadena, CA).

Kolawa, E. A., et al. 2007 *Extreme Environment Technologies for Future Space Science Missions.* Technical Report JPL D-32832. National Aeronautics and Space Administration (Washington, DC).

Mars Advanced Planning Group 2006 *Robotic Mars Exploration Strategy 2007-2016*. Jet Propulsion Laboratory, California Institute of Technology (Pasadena, CA).
http://mepag.jpl.nasa.gov/reports/3715_Mars_Expl_Strat_GPO.pdf

Mars Advanced Planning Group 2006 Update to the Robotic Mars Exploration Strategy 2007-2016. Jet Propulsion Laboratory, California Institute of Technology (Pasadena, CA), http://mepag.jpl.nasa.gov/reports/MAPG_2006_Update_Final-1.pdf

National Aeronautics and Space Administration 2006 *2006 NASA Strategic Plan*. National Aeronautics and Space Administration (Washington, DC).
http://www1.nasa.gov/pdf/142302main_2006_NASA_Strategic_Plan.pdf

National Aeronautics and Space Administration. 2007 *Science Plan for NASA's Science Mission Directorate 2007–2016.* Technical report NP-2007-03-461-HQ. National Aeronautics and Space Administration (Washington, DC).

National Aeronautics and Space Administration. 2007 *The Global Exploration Strategy: The Framework for Coordination.* National Aeronautics and Space Administration (Washington, DC).
http://www.nasa.gov/pdf/178109main_ges_framework.pdf

National Research Council Committee on the Scientific Context for Exploration of the Moon. 2007 *The Scientific Context for Exploration of the Moon: Final Report.* The National Academies Press (Washington, DC).

National Research Council, 2003 *New Frontiers in the Solar System: an Integrated Exporation Strategy*. The National Academies Press (Washington D.C.)

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