NASA
Strategic Roadmap Summary Report
May 22, 2005
Strategic Roadmap Summary
Report

May 22, 2005
EXECUTIVE SUMMARY

Introduction
On January 14, 2004, President George W. Bush announced the Vision for Space Exploration. The Vision’s fundamental goal is to advance U.S. scientific, security, and economic interests through a robust space exploration program. To support this goal, the Vision stipulated that the U.S. would:

- Implement a sustained and affordable human and robotic program to explore the solar system and beyond;
- Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;
- Develop the innovative technologies, knowledge, and infrastructure both to explore and to support decisions about the destinations for human exploration; and
- Promote international and commercial participation in exploration to further United States scientific, security, and economic interests.

Roadmap Teams Commissioned
In response to the Vision, NASA commissioned strategic and capability roadmap teams to develop the pathways for turning the Vision into a reality. The strategic roadmaps were derived from the Vision for Space Exploration and the Aldrich Commission Report dated June 2004. NASA identified 12 strategic areas for roadmapping. The Agency added a thirteenth area on nuclear systems because the topic affects the entire program portfolio.

To ensure long-term public visibility and engagement, NASA established a committee for each of the 13 areas. These committees — made up of prominent members of the scientific and aerospace industry communities and senior government personnel — worked under the Federal Advisory Committee Act. A committee was formed for each of the following program areas:

- Robotic and Human Lunar Exploration
- Robotic and Human Exploration of Mars
- Solar System Exploration
- Search for Earth-Like Planets
- Exploration Transportation System
- International Space Station
- Space Shuttle
- Universe Exploration
- Earth Science and Applications from Space
- Sun-Solar System Connection
- Aeronautical Technologies
- Education
- Nuclear Systems

(The charter and membership of these committees are provided in the Appendix.)
Strategic Roadmap Committee Activities and Products

Eleven of the 13 strategic roadmap committees began meeting in early January. Formation of the Space Shuttle Committee, which was to focus on the transition from the Shuttle to a new exploration vehicle, was deferred pending the Shuttle’s return to flight. Formation of the Education Committee also was delayed until the others had begun their work. The rationale was that the Education Committee would benefit from the others’ discussions about long-term opportunities for educational and public outreach.

Completed Roadmaps

The 11 committees each met at least once between January 3 and May 17, 2005. Several committees benefited from early results and momentum from pre-existing focused planning outreach activities, and consequently, they developed roadmap before the roadmapping activities ended on May 22. Completed roadmaps are:

- Robotic and Human Exploration of Mars
- Solar System Exploration
- Search for Earth-Like Planets
- Universe Exploration
- Earth Science and Applications from Space
- Sun-Solar System Connection

The summaries presented in this volume are based on completed roadmaps in these areas. The completed roadmaps are collected in a separate Strategic Roadmaps volume.

Provisional Committee Findings

The remaining committees did not schedule all their meetings or complete work on their roadmaps. As a result, the summaries presented here are based on provisional committee findings and staff analyses. As such, the material from these committees here does not represent the formal findings of the chartered committees.

Other Roadmap Committees

Three of the roadmap areas for which committee activities were planned are not represented in this volume for diverse reasons.

The Shuttle Transition Committee was not established pending Return to Flight, and its creation has been overtaken by Agency events so no products are available in this area. The International Space Station Committee did meet, but a 60-day task force established by the Administrator has superseded its efforts and preliminary results. Finally, the first meeting of the Education Committee was deferred until preliminary findings of the other committees would be available to it, but will not now meet. As a result, there is no output from this committee.
Informing Capabilities Roadmaps
In addition to laying out options and decision points for implementing the Vision’s goals, an important objective of the strategic roadmap development process was to inform the development of the capabilities roadmaps. Because development proceeded in parallel, this was accomplished iteratively. The Agency will use the findings of the two roadmapping efforts to ensure that NASA’s long-range plans for technology development support the major flight programs.

Dr. Marc Allen, Team Lead
Strategic Roadmap Committees
Roadmap Summary

• NASA objective to which transportation roadmap responds:
  – Develop an exploration transportation system to deliver crew and cargo from the surface of the Earth to exploration destinations and to return the crew safely to Earth.

• Connection to Vision for Space Exploration:
  – Roadmap outlines decision pathways to meet the transportation requirements enabling the Vision for Space Exploration.
  – Roadmap cuts across nearly all other strategic roadmaps, particularly International Space Station, lunar, Mars, and solar system exploration.

• Top-level summary of anticipated achievements:
  – An operational crew exploration vehicle, post 2010
  – An operational launch vehicle for the Moon, post 2015
  – An operational launch vehicle for Mars, post 2030
  – A demonstration of nuclear propulsion, post 2015
  – An operational, crewed planetary descent/ascent capability, post 2015
## Roadmap Anticipated Achievements

|-------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| **Earth-to-Orbit Transportation** | - Move from Shuttle to new ISS-compatible crew and cargo systems  
- Develop, test, and operate crew exploration vehicle and associated launch vehicle  
- Develop lunar cargo launch vehicle | - Operate lunar cargo launch vehicle  
- Develop crewed Mars launch vehicle  
- Develop Mars cargo launch vehicle | - Develop, test, and operate Mars crewed launch vehicle  
- Develop, test, and operate Mars cargo launch vehicle |
| **In-Space Transportation**    | - Demonstrate nuclear electric propulsion  
- Develop propulsion alternatives (chemical/solar electric propulsion/aero-assist, solar sails, tethers)  
- Select lunar trajectories | - Operate nuclear electric propulsion for robotic missions  
- Operate lunar crew and cargo propulsion systems  
- Select Mars trajectories | - Operate Mars crew and cargo propulsion system (crew and cargo could be different systems)  
- Develop and operate Mars crew systems (life support, deep-space radiation protection, artificial gravity) |
| **Ascent/Descent Transportation** | - Develop and initially operate robotic ascent and descent systems | - Operate lunar descent and ascent systems (crew and cargo) | - Operate Mars descent and ascent systems (crew and cargo) |
| **Earth Capture and Reentry**  | - Operate robotic Earth capture and reentry systems  
- Operate crew exploration vehicle reentry systems | - Operate lunar-crewed Earth capture and reentry systems | - Operate Mars-crewed Earth capture and reentry systems |
The scope of the Transportation Systems Roadmap is based on committee discussions at the first meeting. Note that the committee’s activities ended before the committee could approve a complete and consistent product. The material presented in this package represents the results as of meeting #2 (April 18-19, 2005).

The Transportation Systems Roadmap is divided into the following categories:

- Earth-to-orbit (1 chart)
- Transfer to and orbital operations (2 charts)
  - Included as part of the “in-space transportation” goals and roadmap overview decisions summary
- Ascent/descent (1 chart)
- Destination orbital operations and transfer from (2 charts)
  - Included as part of the “in-space transportation” goals and roadmap overview decisions summary
- Earth capture and reentry (1 chart)

The Transportation Systems Roadmap:

- Includes transportation for crew, cargo, and robotic missions.
- Addresses the next 25- to 30-plus years, focused on the out years.
- Identifies key decision points and the alternative options for implementation of each decision.

Note: The Transportation Systems Roadmap is a simplified and limited representation of a large and complex decision space.

- An intricate web of interdependencies exists between questions, decision points, and milestones that is too complex to be represented on a few charts.
- Many decision points are not “either/or,” but may be a combination of the available options.
Destination Orbital Operations and Transfer From Roadmap (cont’d)

- Program Milestone
- Downselect Decision
- Initial Operational Capability
- Concept/Focused Technology
- Development/Production
- Operations/Support
- Transportation Elements

<table>
<thead>
<tr>
<th>05</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEV/Demo ISS Assembly Complete</td>
<td>Crew CEV Un-Crewed CEV Prom Demo</td>
<td>Human Lunar Landing ISS Research Complete Prometheus-Class Flight Discovery Missions</td>
<td>Long-Duration Lunar Missions New Frontier Missions</td>
<td>Flagship Missions</td>
<td>Mars Human Landing</td>
</tr>
</tbody>
</table>

**Trajectory**
- Earth Moon L1
- Low-Lunar Orbit
- Elliptical-Lunar Orbit

**Crew Support**
- Open ECLSS
- Partially Closed ECLSS
- Near-Earth Radiation Shielding (Many Options)

**Lunar Robotics / Cargo Trajectories**
- LEO / HEO
- Earth Moon L1
- High-Mars Orbit
- Low-Mars Orbit
- Elliptical-Mars Orbit

**Extended Lunar**
- Long-Duration Lunar

**Fully Closed ECLSS**
- Artificial Gravity
- Long Zero-G

**Interplanetary Radiation Shielding (Many Options)**

- Mars Human Landing
- Mars Transfer Stages
- Mars Axial Lander
- Mars Axial Rover
- Mars Robotics / Cargo Trajectories
Earth Capture/Reentry Roadmap

- Program Milestone
- Downselect Decision
- Initial Operational Capability
- Concept/Focused Technology
- Development/Production
- Operations/Support
- Transportation Elements

Earth Capture

- CEV/Demo
- ISS Assembly Complete
- Space Shuttle

Earth Reentry

- Parachutes
- Parafoils
- Gear/Skids
- Airbag
- Controlled Flight
- Prop Touchdown

Robotics Reentry Vehicle

- Robotics Transfer Stages

Mars Reentry Vehicle

- Robotics
- Mars Reentry Vehicle

Chemical SEP Aeroassist

Direct Entry
- Prop Capture
- Aerocapture
- Combination

Lunar

Direct Entry
- Prop Capture
- Aerocapture
- Combination

Long Lunar

Mars

- Prom Demo
- Prometheus-Class Flight
- Discovery Missions
- New Frontier Missions
- Flagship Missions

Exploration Transportation System

- CEV/Lunar Reentry Vehicle

- Mars Human Landing

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Transportation Systems Roadmap Overview - Decisions Summary

Earth-to-Orbit Launch Vehicles

- Shuttle – ISS Assembly
  - ISS Cargo/Research LV
- Foreign Launch Vehicles – ISS Crew/Cargo
  - Un-Crewed
  - Lunar Crewed Launch Vehicle
  - Lunar Cargo/Prometheus Launch Vehicle

In-Space Transportation

- Robotic/Un-Crewed Transportation Systems – Science, Lunar/Mars Robotics
  - Demo
  - NEP Prometheus - Outer Planet Science/Robotics
  - Un-Crewed
  - Crew Exploration Vehicle
  - Up to Extended
  - Lunar Cargo Vehicle
  - Mars Crew
  - Mars Cargo

Ascent/Descent

- Robotic Ascent/Descent Systems – Science, Lunar/Mars Robotics
  - Up to Extended
  - Lunar Ascent/Descent Systems
  - Mars

Earth Capture and Reentry

- Robotics Earth Capture and Reentry Systems – Sample Returns
  - Lunar Crew/Cargo
  - Mars

Milestones:
- 05
- 10
- 15
- 20
- 25
- 30+

Decision Points:
- ISS Assembly Complete
- Crew CEV
- Prometheus-Class Flight
- Long-Duration Lunar Missions

Initial Operational Capability:
- Operations / Support
## Launch Vehicle Decision Points from Roadmap Overview

<table>
<thead>
<tr>
<th>Decision Point</th>
<th>Decisions • Option Space</th>
<th>Other Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cargo launch vehicle for ISS post-Shuttle retirement? • Expendable Launch Vehicle (ELV)/commercial, Shuttle-derived, rely on foreign vehicles, clean sheet?</td>
<td>Commonality or expansibility to crew exploration vehicle (CEV) or lunar cargo launch vehicles?</td>
</tr>
<tr>
<td>2</td>
<td>Launch vehicle for crew exploration vehicle? • Shuttle-derived, ELV-derived, clean sheet?</td>
<td>Should the un-crewed CEV be the same as the crewed CEV? Commonality with cargo launch vehicles? Expansibility for Mars? Role of commercial/role of international?</td>
</tr>
<tr>
<td>3</td>
<td>Launch vehicle for lunar cargo? • Preserve Shuttle-derived or not?</td>
<td>Degree and timing of heavy lift? Commonality with crew launch vehicles? Extensibility for Mars? Autonomous rendezvous and docking? Role of commercial/role of international?</td>
</tr>
<tr>
<td>4</td>
<td>Launch vehicle for lunar cargo and “Prometheus-class” science mission? • Shuttle-derived, if preserved in 3, ELV-derived, clean sheet, commercial/entrepreneurial?</td>
<td>Degree and timing of heavy lift? Commonality with crew launch vehicles? Autonomous rendezvous and docking? Expansibility for Mars? Role of commercial/role of international?</td>
</tr>
<tr>
<td>5</td>
<td>Launch vehicle for Mars crew? • Shuttle-derived, ELV-derived, clean sheet?</td>
<td>Commonality with cargo launch vehicles? Role of commercial/role of international?</td>
</tr>
<tr>
<td>6</td>
<td>Launch vehicle for Mars cargo? • Shuttle-derived, ELV-derived, clean sheet?</td>
<td>Commonality with cargo launch vehicles? Autonomous rendezvous and docking? Role of commercial/role of international?</td>
</tr>
<tr>
<td>Decision Point</td>
<td>Decisions • Option Space</td>
<td>Other Considerations</td>
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<tr>
<td>----------------</td>
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<tr>
<td>7</td>
<td>Select crew exploration vehicle design concept?</td>
<td>Function and destination of crew exploration vehicle and other crewed vehicles?</td>
</tr>
<tr>
<td>8</td>
<td>Develop nuclear electric propulsion for science/robotic missions?</td>
<td>Nuclear electric propulsion?</td>
</tr>
<tr>
<td>Decision Point</td>
<td>Decisions • Option Space</td>
<td>Other Considerations</td>
</tr>
<tr>
<td>----------------</td>
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</tbody>
</table>
| 12             | Lunar ascent and descent systems?  
                • Cryogenic propellant, storable propellant? | Down mass/return mass?  
                Is the descent stage reusable?  
                Crew and cargo separate? Crew abort options?  
                Engine out capability required?  
                Landing systems? |
| 13             | Mars ascent and descent systems?  
                • Cryogenic propellant, storable propellant, parachute? | Down mass/return mass?  
                Is the descent stage reusable?  
                Crew and cargo separate? Crew abort options?  
                Engine out capability required?  
                Aerocapture, entry, descent, and landing systems? |
| 14             | Robotic Earth capture systems?  
                • Chemical, solar electric power, aeroassist?  
                • Robotic reentry systems?  
                • Parachutes parafoils, gear-/skid-controlled flight, prop touchdown? | Return mass? |
| 15             | Earth capture for lunar crew and cargo?  
                • Direct entry, prop capture, aerocapture?  
                • Combination?  
                • Earth reentry system?  
                • Parachutes parafoils, gear-/skid-controlled flight, prop touchdown? | Return mass?  
                Expendable or reusable system? |
| 16             | Earth capture and reentry systems for Mars crew and cargo?  
                • Direct entry, prop capture, aerocapture?  
                • Combination?  
                • Earth reentry system?  
                • Parachutes, parafoils, gear/skid, controlled flight, propulsive touchdown? | Return mass?  
                Expendable or reusable system?  
                Ablative and non-ablative high-temperature materials or active cooling? |
<table>
<thead>
<tr>
<th>Capability Roadmap</th>
<th>Capability Applicable for Transportation Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-Energy Power and Propulsion</td>
<td>Nuclear electric propulsion, nuclear thermal propulsion, solar electric propulsion</td>
</tr>
<tr>
<td>In-Space Transportation</td>
<td>Autonomous rendezvous and docking, aerocapture at Earth, on-orbit refueling, fluid transfer, tethers</td>
</tr>
<tr>
<td>Communication and Navigation</td>
<td>High-bandwidth communication</td>
</tr>
<tr>
<td>Human Planetary Landing Systems</td>
<td>Efficient entry and landing system</td>
</tr>
<tr>
<td>Human Health and Support Systems</td>
<td>Life-support systems, information systems (video, internet), exercise and health-management systems, spacesuits</td>
</tr>
<tr>
<td>Human Exploration Systems and Mobility</td>
<td>In-space assembly, deployment, and servicing</td>
</tr>
<tr>
<td>In-Situ Resource Utilization</td>
<td>Reduction of launch mass to low-Earth orbit and beyond; use of lunar regolith or ice for transportation propellants</td>
</tr>
<tr>
<td>Autonomous Systems and Robotics</td>
<td>Rendezvous and docking, repair and servicing, deployments, health monitoring, control and operation of systems, operations planning, and scheduling</td>
</tr>
<tr>
<td>Advanced Modeling, Simulation, and Analysis</td>
<td>Integrated simulation of long-term human missions</td>
</tr>
<tr>
<td>Systems Engineering Cost/Risk Analysis</td>
<td>Required to ensure an outcome and/or optimize performance within engineering, budget, and scheduling constraints</td>
</tr>
<tr>
<td>Transformational Spaceport</td>
<td>Ground-based infrastructure, launch frequency, vehicle mass, volume and processing, range capabilities, safety, and interface with national airspace</td>
</tr>
<tr>
<td>Nanotechnology</td>
<td>Ultra-high strength, lighter and multifunctional materials, high-temperature structural materials, damage-tolerant, self-healing materials, advanced power and propulsion materials, micro-electronics, highly miniaturized spacecraft systems, engines, airframes, and energy generation and storage</td>
</tr>
</tbody>
</table>
Other Information

• The Transportation Roadmap Committee received a summary of the Department of Defense’s space launch-related plans.
  – Assure access with two extended expendable launch vehicle (EELVs) providers.
  – Fly the remaining Delta II and Titan IV vehicles and transition to EELVs through 2020.
  – The existing Delta IV and Atlas V launch vehicle families meet all identified national security space launch requirements.
  – There is potential need for operationally responsive access to space.
  – Dependence on space for national security is becoming apparent.

• The Transportation Roadmap Committee recognized that on-going commercial entrepreneurial endeavors need to be considered.
  – A key issue is to balance pursuit of new paradigms versus the Agency’s tolerance for risk.
  – Consider unorthodox business terms, modular architecture with open standards, and balancing research investments against development activities.

• International participation and maintenance of a viable infrastructure were identified as critical issues, but the roadmap activity ended before specific recommendations could be made.
Nuclear Systems
Strategic Roadmap Summary Report
May 22, 2005
NASA Strategic Objective #13: **Demonstrate power, propulsion, life-support capabilities for long-duration, more distant human and robotic missions**

- Also potentially addresses the following NASA Strategic Objectives derived from the Vision for Space Exploration:
  6. Undertake **lunar exploration** to support sustained human and robotic exploration of Mars and beyond
  7. Series of **robotic missions to Moon** by 2008 to prepare for human exploration
  8. Expedition to the lunar surface as early as 2015, but no later than 2020
  9. Use lunar activities to further science and test approaches (including lunar resources) for exploration to Mars and beyond
  10. Conduct **robotic exploration of Mars** to prepare for future expedition
  11. Conduct **robotic exploration across the solar system** to search for life, understand history of universe, search for resources
  14. Conduct **human expeditions to Mars** after acquiring adequate knowledge and capability demonstrations
Roadmap Anticipated Achievements

• The Nuclear Systems Committee did not reach consensus on a strategic roadmap.
  – This package documents the interim products of the Nuclear Systems Roadmap.
  – Only committee materials through the end of meeting #2 (April 5-6, 2005) are reported.
  – A government-based working group generated most of the available “product material.”

• Unlike scientific/exploratory roadmaps in which discovery-based decisions are typical:
  – Key elements of the nuclear systems infrastructure are path-dependent limited resources that generally permit only serial (versus parallel) efforts requiring long development times.
  – Decision points for this Nuclear System Roadmap are generally requirements driven rather than “discovery” driven.
  – Activities in the nuclear part of nuclear systems are the statutory responsibility of the U.S. Department of Energy.
Roadmap Options and Alternatives: Key Questions Under Deliberation

The Nuclear Systems Committee did not reach a formal consensus. The following summarizes topics of deliberation at the time of the committee’s termination. (This does not reflect an exhaustive list of issues for nuclear systems)

- The committee had identified the following topics:
  - Radioisotope Thermoelectric Generator/ Radioisotope Power Sources
  - Fission (space-based power, surface power, nuclear electric propulsion)
  - Nuclear Thermal Propulsion
  - Outreach (public engagement and continued NASA support)

- ... about which the committee asked the following questions (list is not exhaustive) before the activity stopped:
  - What is the relevant history of the topic?
  - What activities are currently underway?
  - What are the design considerations?
    - Do safety standards exist or do they need to be developed or modified?
    - Do design standards exist, need to be developed or modified (including lifecycle, operations, disposal)?
    - Where are the logical breakpoints (power levels where a technological approach is no longer practical)?
    - When should this technology be used (surface, space, human, robotic)?
    - What capabilities are required to support activity (facilities, production systems, launch vehicles, test chambers, etc.)?
      - Do analogs (ground-based, space-based, or historical) exist and are they relevant?
      - What are the associated costs (consider only relative or at most order of magnitude)?
  - Which mission classes do the various technologies enable or enhance?
  - Regarding the roadmap, what decisions need to be made and when (technology development, fuel tests, fuel production, materials, launch systems, safety systems, etc.)?
  - How effective is NASA planning?
The Nuclear Systems Committee did not reach a formal consensus. The following summarizes possible “key decisions” that likely would appear on a Nuclear Systems Roadmap:

- Determination of first use for fission systems
  - Surface Power
  - Nuclear Thermal Propulsion
  - Nuclear Electric Propulsion (Jupiter Icy Moons Orbiter-type)
  - Nuclear Electric Propulsion (reduced capability)

- Determination of the need for nuclear thermal propulsion in a Mars transportation architecture

- Determination of the practicality of large-scale Radioisotope Power Source (RPS) systems for early surface architectures
  - Primarily: Does the Pu-238 fuel infrastructure support large-scale RPS use (such as for a habitat application)?
### Strategic Roadmap Interdependencies

<table>
<thead>
<tr>
<th>Roadmap</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robotic and human lunar expeditions</td>
<td>Nuclear Systems Roadmap receives technical requirements and schedule arising from the lunar planning. The roadmap may provide systems for sustained power generation irrespective of illumination. Possible in-space propulsion contributions for cargo transport. Lunar Robotic and Human Exploration Roadmap may provide opportunities for technical demos.</td>
</tr>
<tr>
<td>Sustained, long-term robotic and human exploration of Mars</td>
<td>Nuclear Systems receives technical requirements and schedule arising from Mars planning. The roadmap may provide systems for sustained power generation irrespective of illumination. Possible in-space propulsion contributions for human and cargo transport.</td>
</tr>
<tr>
<td>Sustained program of solar system exploration</td>
<td>Nuclear Systems receives mission class requirements. The roadmap may provide power and propulsion systems to enable or enhance exploration of outer solar system, interstellar space, near-sun environments, and multi-body tours.</td>
</tr>
<tr>
<td>Develop an exploration transportation system</td>
<td>Transportation architectures drive possible nuclear system deployment architectures. Nuclear-based propulsion systems may contribute to the space transportation repertoire.</td>
</tr>
<tr>
<td>Complete assembly of the International Space Station and focus utilization</td>
<td>Possible relevant on-orbit assembly experience from the International Space Station (ISS) may be applied to on-orbit assembly of nuclear systems (depending upon launch vehicle capabilities).</td>
</tr>
<tr>
<td>Safely transition from Space Shuttle to new exploration-focused launch systems*</td>
<td>Safety and risk management policy development at Kennedy Space Center (KSC) likely would affect launch of nuclear systems. National Environmental Policy Act and launch approval processes tightly couple the launch system with the nuclear spacecraft launched.</td>
</tr>
<tr>
<td>Explore the origin, evolution, structure, and destiny of the universe</td>
<td>Nuclear Systems receives mission class requirements. The roadmap may provide power and propulsion systems to enable or enhance exploration of outer solar system, interstellar space, and multi-body tours.</td>
</tr>
<tr>
<td>Explore Sun-Earth system to understand effects on Earth and implications for human exploration</td>
<td>Nuclear Systems receives requirements for power sources in near-sun missions. The roadmap may provide power and propulsion systems to enable or enhance exploration of near-sun environments.</td>
</tr>
<tr>
<td>Educate students and public, and expand national technical skills and capabilities</td>
<td>Nuclear Systems poses unique education challenges and opportunities. The Education Roadmap focus may contribute to national technical skills in support of Nuclear Systems activities.</td>
</tr>
</tbody>
</table>
Strategic Roadmap Interdependency Details (1 of 2)

• Transportation notionally provides to Nuclear Systems:
  – Launch capability for Jupiter Icy Moons Orbiter-type missions by 2017 (incidental from lunar launch vehicle requirements to surface power lift by 2019-2020)

• Nuclear Systems notionally provides to Transportation:
  – Nuclear electric propulsion (NEP) in-space transportation capability
    • Initial robotic mission demonstrates NEP capability in 2014 (planned JIMO precursor at the time of roadmap development)
    • Robotic missions to outer planets by 2017 (planned JIMO mission at the time of roadmap development)
  – Nuclear thermal propulsion in-space transportation capability
    • Cargo and piloted missions to Mars in 2025-2035 timeframe (per Mars roadmap)

• Other notional synergies/interactions between Nuclear Systems and Transportation:
  – Launch approval of nuclear power systems (radioisotope and fission) on existing and future launch vehicle systems
  – Human rating of nuclear in-space transportation systems
  – Architecture decision, including nuclear in-space transportation systems

The long development timeline of any nuclear system (surface or space) necessitates a stable and strong mission-class pull, otherwise the development will not come to fruition.
Nuclear Systems notionally provides to Lunar:

- Landing locations flexibility
  - Not defined
    - Equatorial most likely = 14-day lunar night
    - Uniquely supports permanent shadowed region
  - Decision in 2010-2012 (established by Lunar Roadmap)

- Robotic science power flexibility
  - Miscellaneous long-term surface science

- High-power orbiting assets:
  - Communications, navigation, synthetic aperture radar /notional opportunities

- Habitats
  - 30kWe by 2020 (first over-night human presence per Lunar Roadmap)

- Rovers
  - Short haul: radioisotope power source (RPS) may enhance, but not required
  - Long haul: 1-5 kW-class RPS may enable

- In-situ resource utilization (ISRU) — dependent on architecture
  - ISRU Testbed = 10kW
    - Option A: 2020-2022 (1-2year lag from first habitat assumed 2020)
  - ISRU Pilot = 50kW ("mostly thermal")
    - Option A: post 2025 (ISRU pilot per Lunar Roadmap)
  - ISRU Baseline = 50 to 100 kW ("mostly thermal")
    - Option C: 2017-2022 (pre-placement of ISRU ahead of humans)
  - ISRU Production >100kW ("mostly thermal")
    - Option C: post 2025 (extension of above)

- Lunar Transport
  - Chemical only – no nuclear in-space transport assumed

The long development timeline of any nuclear system (surface or space) necessitates a stable and strong mission-class pull, otherwise the development will not come to fruition.
Salient Points Arising in Committee Deliberations

(1 of 2)

The Nuclear Systems Committee did not reach a formal consensus. Below are significant points that one may reasonably infer from the committee deliberations. They are not in priority order.

- Strong and sustained mission pull is a requirement for space nuclear system development.
  - Focus on a deliverable engineered product is critical to program success.

- Key elements of the nuclear systems infrastructure are path-dependent limited resources that generally permit only serial (versus parallel) efforts that would require long development times.

- The U.S. has no fast flux-reactor test capability, necessitating use of foreign facilities for fuel test of in-space fast-flux reactors.

- The U.S. Department of Energy indicated that expansion of Pu-238 production and processing would be insufficient to support a radioisotope power source-based lunar surface power architecture.
  - Changes in U.S. policy and an extraordinarily large infrastructure investment would be required to support even a first use at 30kWe.
  - Current estimates of Russian Pu-238 supply are insufficient to support 30 kWe use.

- Significant differences may exist in mission classes (human versus robotic, in-space versus surface, mobile versus stationary). This may lead to significant differences in corresponding nuclear systems designs.
  - Nuclear system design relies heavily on requirements. One design for all applications should not be assumed.

- Expectations of “extensibility” of a nuclear system need to be tempered with practicality.
  - One hundred percent plug-and-play extensibility on the full-system level is unlikely.
  - Likelihood of extensibility increases at lower levels of integration (i.e. subsystem to component to material levels).

- The available human resources for nuclear systems development are very limited.
  - Enrollment rates in nuclear fields reached an all-time low in 2000.
The Nuclear Systems Committee did not reach a formal consensus. Below are significant points that one may reasonably infer from the committee deliberations. These are not in priority order.

- Existing nuclear thermal propulsion (NTP) infrastructure and knowledge base is an actively fading resource.
  - Reclamation of physical facilities, design media, and "corporate memory" will be more effective if initiated sooner than later.

- The main mission-class application for NTP is crew transport to Mars.
  - The role of NTP in lunar applications (crew and/or cargo) and Mars cargo applications is programmatically uncertain.
  - Human rating and systems operations remain open questions.

- Public perception of risk and accountability for safety is a complex issue that transcends memoranda of understanding between agencies.
  - The public most likely would hold NASA accountable for any incident pertaining to a space-nuclear system, regardless of time, statute location, or phase of development.
  - The relative roles of NASA and the U.S. Department of Energy in areas of safety, risk assessment, and risk mitigation are currently not clear to the public.
  - The degree and scope of analyses and testing needed to instill public trust in NASA's stewardship of nuclear systems have yet to be fully determined and may not be determined strictly by technical decisions.

- Launch safety and safety of space nuclear systems are tightly linked.

- The design, development, and operational challenges of a surface nuclear-reactor system are not as well understood as those of in-space reactor systems.
  - That includes concepts of operations, landing, future human interactions on the site of the power system and decommissioning.
Cooperation Opportunities

• International cooperation was discussed without resolution.
  – International cooperation regarding nuclear systems is not a straightforward matter (e.g., International Traffic in Arms Regulations, export control, etc.)

• Government (U.S. Department of Energy) cooperation was discussed.
  – The Energy Department’s involvement is both required by statute and provides required expertise to develop nuclear systems.
Roadmap Summary

**NASA Objective:**

“Conduct robotic and human lunar expeditions to further science and to test new exploration approaches, technologies, and systems that will enable future human exploration of Mars and other destinations.”

**Anticipated Accomplishments:**

- Two robotic precursor missions (one orbiter and one lander) between 2008-2012
- Demonstration of lunar transportation systems in low-Earth orbit around 2014
- Lunar sortie missions around 2017 (up to 7-day missions)
  - Outpost site selection
  - Transportation system test and verification
  - Surface system development
  - Apollo-class science investigations
- Single site lunar outpost around 2021 (up to 90-day missions)
  - Short-duration Mars simulations
  - Mars flight crew training and selection
  - In-depth scientific investigations
  - Initial in-situ resource utilization investigations (ISRU), proof-of-concepts, small-scale incorporation
- Extended duration outpost around 2025 (up to 1-year missions)
  - Long-duration Mars simulations
  - Mars flight crew training and selection
  - In-depth scientific investigations enhanced with long-distance surface mobility
  - ISRU
- Wide range of options to allow transition to Mars exploration
Roadmap Objectives – Trace to the Vision for Space Exploration

Space Exploration Beyond Low Earth Orbit

Moon

From Vision

Undertake lunar exploration activities to enable sustained human and robotic exploration of Mars and more distant destinations in the solar system

Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020

Use lunar exploration activities to further science, and to develop and test new approaches, technologies, and systems, including use of lunar and other space resources, to support sustained human space exploration to Mars and other destinations

Starting no later than 2008, initiate a series of robotic missions to the Moon to prepare for and support future human exploration activities

Pursue commercial opportunities for providing transportation and other services supporting the International Space Station and exploration missions beyond low Earth orbit

Pursue international participation

Pursue commercial opportunities for transportation and other services

NASA Objectives

Support Exploration of Mars

Programmatic Objective

Further Science

Test Approaches

Develop new approaches to support sustained human exploration to Mars and other destinations

Perform Lunar Science

National Interests

(To be Vetted Through Science Community via the LEAG)

Lunar Roadmap Committee Strategic Objectives

- Study Long-Duration Human Health and Physiology
- Demo. Operations Techniques
- Perform Tech. Test and Verification
- Demo. increased maintainability, reliability, supportability, ability to repair, etc.
- Develop, Demo. & Innovate future Mars Systems and Subsystem
- Identify, Develop & utilize lunar resources & understand their mapping to Mars
- Investigate the origin and evolution of the Moon
- Utilize the Moon as a guide to other planets
- Utilize the Moon as a unique platform for scientific investigation
- Perform astrobiology
- Study fundamental biology
- Stimulate U.S. Education
- Enable International Participation
- Enable business opportunities
- Enhance U.S. Strategic Interests
<table>
<thead>
<tr>
<th>Roadmap Goals</th>
<th>2015-2020</th>
<th>2020-2025</th>
<th>2025-2030+</th>
</tr>
</thead>
</table>
| **Develop new approaches to allow sustained human exploration of Mars and other destinations** | • Demonstrate and validate surface mobility designs and systems  
• Develop a proficiency with off-Earth spacecraft launch and landing operations  
• Demonstrate advanced chemical propulsion  
• Build partnerships with industry, government, and academia  
• Develop methods for managing organizational complexity (project management, program management, systems engineering, international partnerships)  
• Develop risk management methods for human exploration of deep space | • Understand long-term human adaptation to planetary environments (physiological)  
• Develop countermeasures to maintain crew health (e.g., exercise in a microgravity environment)  
• Understand the effectiveness of radiation shielding, biological interaction, human response.  
• Validate food systems, nutrition, and long-term storage  
• Validate and demonstrate medical diagnosis and treatment equipment  
• Develop and understand bio-isolation systems.  
• Develop and understand ISRU fundamentals  
• Develop regolith-excavation technology  
• Test and demonstrate test power systems.  
• Test and demonstrate closed life-support systems  
• Demonstrate and validate habitat design/systems.  
• Develop and understand logistics, maintenance, and repair capabilities  
• Develop and understand dust-mitigation techniques  
• Demonstrate nuclear power for human systems on Mars (if required)  
• Develop propellant storage and transfer capability to support surface refueling  
• Develop experience in planetary surface operations | • Understand long-term system reliability  
• Conduct psychosocial behavioral observations investigations  
• Select and train Mars crews |
| **Advance scientific knowledge** | • Investigate the origin and evolution of the Moon  
• Use the Moon as a guide to other planets  
• Perform astrobiology  
• Study fundamental biology  
• Use the unique features of the Moon as a platform for scientific investigation |  |  |
| **Advance national interests** | • Enable business opportunities  
• Enhance strategic interests  
• Stimulate U.S. education  
• Promote international participation |  |  |

NOTE: Objectives were identified for the three lunar goals that appear in the far left column; however, only those for the first row were time-phased. This was due to committee acceleration.
Graphic Representation of Roadmap
Option A: Lunar Evolution – Focus on Mars Preparation

2010-2015
- LRO
- Second Mission
- Landing Site Decision 2012

2010-2015
- Robotic Precursors
  - LRO 2008
  - Second Mission
  - Landing Site Decision 2012

2015-2020
- Robotic Precursors
  - LRO 2008
  - Second Mission
  - Landing Site Decision 2012

2020-2025
- Robotic Precursors
  - LRO 2008
  - Second Mission
  - Landing Site Decision 2012

2025-2030
- Robotic Precursors
  - LRO 2008
  - Second Mission
  - Landing Site Decision 2012

2030+
- Robotic Precursors
  - LRO 2008
  - Second Mission
  - Landing Site Decision 2012

Human Missions:
- LEO Demos: Human lunar capability
- Lunar Sorties: Outpost site selection
- Single Location Outpost: "Short-duration" Mars simulations
- Extended Duration Outpost: "Long-duration" Mars simulation (up to 1-year on surface)

Lunar Resources:
- Robotic Assistants

Science:
- "Apollo Class" Extensive Investigations (Outpost Class)
  - Drilling, trenching
  - Human physiology
- In-depth Investigations
  - Long-duration human physiology
  - Moon as an observing platform

Testbeds:
- Terrestrial Testbeds / Analogs in Preparation for Mars Exploration
  - Systems tests, test facilities, crew training

Capabilities:
- EVA
- Surface mobility (10s of km)
- Surface power (~30kw)
- Surface power (50-100kw) (supports ISRU)

Proof of Concepts Utilization
- Life Support augmentation
- Fuel cell reactants, etc.
- Regolith burial of habitat for shielding
- Additional consumables for "long-duration" Mars simulations
- Propellant production

NOTE: See next page for assumptions, descriptions, and transition options.
Assumptions:
• Lunar sortie crews perform final site verification and characterization before selecting outpost location.

Description:
• Emphasizes preparation for Mars exploration.
• Follows current Exploration Systems Mission Directorate baseline approach.
• U.S. government provided and managed.
• Extended lunar-sortie phase helps defer outpost development costs.
• Science opportunities grow as capabilities expand from sorties, to an outpost, and to a potential extended-duration outpost.
• Once a single location is found, lunar resource use is gradually included, leading to utilization.
• Modest surface mobility concentrates on a central site.

Transition Options:
• Decision point around 2025: Are we ready to go to Mars?
  – Phase out lunar outpost; complete test-bed/preparedness activities – focus on Mars.
  – Sustain outpost at appropriate levels to support more extensive Mars test-bed activities.
Three Additional Options:
(B) Early outpost (focus on science)
(C) Early lunar resource utilization
(D) Expedited moon to Mars

NOTE: See next page for assumptions, descriptions, and transition options for each alternative.
<table>
<thead>
<tr>
<th>Assumptions</th>
<th>Option-B</th>
<th>Option-C</th>
<th>Option-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Robotic obtained data is sufficient for selecting outpost site.</td>
<td>• Assumes the term “commercial” means a viable business case exists where NASA is not the sole customer. (Although NASA may provide “guaranteed buys” at the start to initiate the market.)</td>
<td>• Assumes that a decision to send humans to Mars is made early; influencing the launch vehicle decision</td>
<td>• Assumes limited commitment to a lunar presence.</td>
</tr>
<tr>
<td>• Assumes sortie phase is not required.</td>
<td>• Assumes commercial lunar navigation/telecommunication infrastructure to support commercial lunar robotic missions</td>
<td>• Assumes a minimal set of robotic missions because the use of resources and/or a sustained presence are not the objectives</td>
<td>• Assumes that robotically obtained data is sufficient for site selection</td>
</tr>
<tr>
<td></td>
<td>• Assumes U.S. government data-buy from commercial robotic missions</td>
<td>• Assumes that robotically obtained data is sufficient for propellant-scale resource extraction</td>
<td>• Assumes that robotically obtained data is sufficient for propellant-scale resource extraction</td>
</tr>
<tr>
<td></td>
<td>• Assumes robotically obtained data is sufficient for site selection</td>
<td>• Assumes resource extraction and propellant production are initiated through tele-operation before the crew's arrival</td>
<td>• Assumes resource extraction and propellant production are initiated through tele-operation before the crew's arrival</td>
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<tr>
<td></td>
<td>• Assumes lunar transportation system designed at outset to most efficiently leverage lunar-produced propellant</td>
<td>• Assumes lunar transportation system designed at outset to most efficiently leverage lunar-produced propellant</td>
<td>• Assumes lunar transportation system designed at outset to most efficiently leverage lunar-produced propellant</td>
</tr>
<tr>
<td></td>
<td>• Assumes propellant production and habitation are established with goal of &quot;privatization&quot;</td>
<td>• Assumes propellant production and habitation are established with goal of &quot;privatization&quot;</td>
<td>• Assumes propellant production and habitation are established with goal of &quot;privatization&quot;</td>
</tr>
<tr>
<td></td>
<td>• Assumes commercial nav/telecomm, propellant production, habitation, and reduced transportation costs because lunar resources are sufficient to enable commercial lunar transportation</td>
<td>• Assumes commercial nav/telecomm, propellant production, habitation, and reduced transportation costs because lunar resources are sufficient to enable commercial lunar transportation</td>
<td>• Assumes commercial navigation/telecommunication infrastructure to support commercial lunar robotic missions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>Option-B</th>
<th>Option-C</th>
<th>Option-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Emphasizes science</td>
<td>• Emphasizes early use of lunar resources</td>
<td>• Assumes &quot;Basic&quot; habitation capability – not necessarily extensible to long-duration Mars systems</td>
<td>• Assumes &quot;Basic&quot; habitation capability – not necessarily extensible to long-duration Mars systems</td>
</tr>
<tr>
<td>• McMurdo “Hub &amp; Spoke” model for expanded science/technology utilization accessed through surface mobility</td>
<td>• Leverages commercial markets</td>
<td>• Only selected surface systems and operations (EVA, surface mobility, etc.) and key transportation systems (precision landing, etc.) tested in lunar environment</td>
<td>• Only selected surface systems and operations (EVA, surface mobility, etc.) and key transportation systems (precision landing, etc.) tested in lunar environment</td>
</tr>
<tr>
<td>– Astronomical instruments</td>
<td>• Maximizes use of lunar resources</td>
<td>• Extensive terrestrial and ISS test beds for habitation, life support, crew physiology, etc.</td>
<td>• Extensive terrestrial and ISS test beds for habitation, life support, crew physiology, etc.</td>
</tr>
<tr>
<td>– Long-duration Mars simulation facility</td>
<td>• Maximizes use of commercial capabilities</td>
<td>• Demonstration of key ISRU subsystems only – no major utilization</td>
<td>• Demonstration of key ISRU subsystems only – no major utilization</td>
</tr>
<tr>
<td>– Other specialized remote facilities</td>
<td>• Outpost allows for Mars simulation and operational test</td>
<td>• Differences from Option-A:</td>
<td>• Differences from Option-A:</td>
</tr>
<tr>
<td>– Enhanced surface mobility for support – enabled by ISRU?</td>
<td>• Differences from Option-A:</td>
<td>– Requires up-front commitment to ISRU</td>
<td>– Requires no sortie missions</td>
</tr>
<tr>
<td>– Gradual incorporation of lunar resource utilization once single location determined</td>
<td>– Outpost is not decommissioned but rather transferred to commercial entity</td>
<td>– Outpost is not decommissioned but rather transferred to commercial entity</td>
<td>– Outpost is not decommissioned but rather transferred to commercial entity</td>
</tr>
<tr>
<td>• Outpost allows for Mars simulation and operational test</td>
<td>• Outpost is not decommissioned but rather becomes the “hub” of a McMurdo (Antarctica)-type model</td>
<td>• Exploration of Moon and Mars occurs in parallel in the out years</td>
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</tr>
<tr>
<td>• Differences from Option-A:</td>
<td>– Exploration of Moon and Mars occurs in parallel in the out years</td>
<td>• Assumes sortie is not required.</td>
<td>• Assumes sortie is not required.</td>
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<tr>
<td>– Requires no sortie missions</td>
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<tr>
<td>– Outpost is not decommissioned but rather becomes the “hub” of a McMurdo (Antarctica)-type model</td>
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<table>
<thead>
<tr>
<th>Transition Options</th>
<th>Option-B</th>
<th>Option-C</th>
<th>Option-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Decision point in 2025 time frame: <em>Are we ready to go to Mars?</em></td>
<td>• Decision point in 2025 time frame: <em>Are we ready to go to Mars?</em></td>
<td>[ damage to text ]</td>
<td></td>
</tr>
<tr>
<td>• If NASA emphasis is on Mars, then second decision point is whether U.S. government should pursue a McMurdo model under an National Science Foundation-style operation</td>
<td>• Commercial operation of lunar transportation, habitation capabilities; allows NASA to continue lunar presence, if required or desirable, as a tenant</td>
<td>• Decommission lunar outpost – focus on Mars as early as 2023</td>
<td>• Decommission lunar outpost – focus on Mars as early as 2023</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Decision point around 2023: <em>Are we ready to go to Mars?</em></td>
<td>• Decision point around 2023: <em>Are we ready to go to Mars?</em></td>
</tr>
</tbody>
</table>
The figure above represents the basic lunar exploration decision tree. Lunar Option-A (baseline) is depicted by the red dashed path. The three alternative roadmaps each represent a different path through the decision tree.
Criteria for Pathway Selection

These questions must be answered before selection of a pathway is possible:

**What is the objective for lunar exploration?**
- What is the definition of “sustained” exploration as applied to the Moon in the Vision for Space Exploration (e.g., Moon to stay or Moon as a stepping stone)?
- Is “sustained” an objective for returning to the Moon or a figure of merit?

**What is the transition strategy?**
- How should NASA transition from a lunar focus to a Mars focus once lunar objectives are achieved (including operationally, budget, workforce, vehicles, infrastructure, etc.)?
- How do we build in a transition strategy from the beginning, particularly for commercial interests?

**What are the other concerns?**
- How long do astronauts need to stay on the lunar surface to understand how well they adapt psychologically and physiologically to planetary environments? (e.g. reduced gravity, etc.)
- How should terrestrial analogs be used in conjunction with lunar activities?
- What is the best approach for international collaboration?
### Strategic Roadmap Interdependencies

<table>
<thead>
<tr>
<th>Strategic Roadmap</th>
<th>Dependency to Lunar Strategic Roadmap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exploration Transportation</td>
<td>- Cargo and crew transport</td>
</tr>
<tr>
<td>Nuclear Systems</td>
<td>- Power, energy storage and propulsion</td>
</tr>
<tr>
<td></td>
<td>- Mission duration, safety, human factors</td>
</tr>
<tr>
<td>Mars Exploration</td>
<td>- Scientific and engineering test beds (robotic)</td>
</tr>
<tr>
<td></td>
<td>- Operations concepts (robotic)</td>
</tr>
<tr>
<td></td>
<td>- Mars human exploration precursor needs</td>
</tr>
<tr>
<td>Sun-Solar System Connection</td>
<td>- Human health and safety</td>
</tr>
<tr>
<td></td>
<td>- Space environment for operations (forecasting and “now-casting”)</td>
</tr>
<tr>
<td>Space Station</td>
<td>- Space environment</td>
</tr>
<tr>
<td></td>
<td>- Human health and physiology, subsystem test (e.g., ECLSS)</td>
</tr>
<tr>
<td>Capability Roadmap</td>
<td>Capability Available for Lunar exploration</td>
</tr>
<tr>
<td>--------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>High-Energy Power and Propulsion</td>
<td>Energy storage; surface power, surface nuclear power (demo/ops)</td>
</tr>
<tr>
<td>In-Space Transportation</td>
<td>Autonomous rendezvous and docking; lunar descent/ascent systems</td>
</tr>
<tr>
<td>Communication and Navigation</td>
<td>Communications relay architectures; autonomous navigation systems; precision navigation systems and algorithms; tele-operations</td>
</tr>
<tr>
<td>Robotic Access to Planetary Surfaces</td>
<td>Lightweight, high-performance chemical landing systems; impact attenuation; precision landing and hazard avoidance; subsurface exploration techniques; surface mobility; sample acquisition and handling; techniques for landing large masses; surface systems that can survive in harsh environments (e.g., dust, thermal, etc)</td>
</tr>
<tr>
<td>Human Planetary Landing Systems</td>
<td>Precision landing and hazard avoidance; lightweight landing propulsion; landing systems (vehicles)</td>
</tr>
<tr>
<td>Human Health and Support Systems</td>
<td>Habitats and safe havens — in space and on surface; life-support systems, food, water; thermal control; dust management; information systems; spacesuits</td>
</tr>
<tr>
<td>Human Exploration Systems and Mobility</td>
<td>Robotic adjuncts; mobility systems (including rovers)</td>
</tr>
<tr>
<td>Autonomous Systems and Robotics</td>
<td>Traverse planning and hazard avoidance; repair and servicing; deployments; health monitoring, control and operation of systems; descent, landing and ascent; operations planning and scheduling</td>
</tr>
<tr>
<td>Scientific Instruments/Sensors</td>
<td>Landing site selection; resource assessment for ISRU</td>
</tr>
<tr>
<td>In-Situ Resource Utilization</td>
<td>Use of lunar regolith and ice for construction, oxygen &amp; propellant; scalable demos for validation of Mars techniques</td>
</tr>
<tr>
<td>Advanced Modeling, Simulation, Analysis</td>
<td>Integrated simulations of exploration architectures; science/engineering data processing and fusion</td>
</tr>
<tr>
<td>Systems Engineering Cost/Risk Analysis</td>
<td>Required for all complex engineering/scientific initiatives</td>
</tr>
<tr>
<td>Nanotechnology</td>
<td>Ultra-high strength, lighter, multi-functional materials, low power/mass electronic, human health monitoring, and life support; environmental monitoring; Biomimetic materials; Robotics; instrument systems</td>
</tr>
</tbody>
</table>
Commercial Opportunities for Lunar Exploration

To develop the public-private frontier:
• NASA is the catalyst

• Public and private stakeholders
  • Builders of the infrastructure
  • Users of the infrastructure
  • Benefactors from the use of the infrastructure

• Path to a sustainable frontier
  • Long term: all infrastructure owned commercially
  • Now: Mixed use projects; e.g., private rover, commercial payload, NASA science instruments

• Needed:
  • Welcoming attitude toward commerce
  • Appropriate, nurturing regulations
  • Planned transfer of management/ownership to private sector
  • Start as soon as possible, including lunar robotic missions

1 Chart provided by invited commercial panel chaired by Dr. Geoff Taylor (Univ. Hawaii) on behalf of Lunar Roadmap Committee
2 Radio Shack™ is a trademark of the Tandy Corporation and is not affiliated with NASA

Potential products and services:
• Propellant
• Satellite repair
• Power
• Tourism
• Communications
• Advertising

Private investment in lunar and cis-lunar infrastructure eliminates need for continued NASA funding of lunar operations once a decision is made proceed with human missions to Mars. No delay in humans to Mars; Private sector takes over lunar operations
National goal (from the Vision for Space Exploration):
• Advance U.S. scientific, security, and economic interests through a robust space exploration program.

NASA objective:
• Develop innovative technologies, knowledge, and infrastructure to explore and to support decisions about the destinations for human exploration.

Aeronautical technologies objective:
• Provide advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in atmospheres of other worlds. Specific research objectives follow.

This roadmap was canceled after one meeting. The committee, therefore, did not complete deliberations on significant areas, including workforce and facilities requirements.
Aeronautics Research - Objectives

Protect air travelers and the public
Decrease the aircraft fatality rate, reduce the vulnerability of the air transportation system to hostile threats, and mitigate the consequences of accidents and hostile acts.

Protect the environment
Protect local and global environmental quality by reducing aircraft noise and emissions.

Increase capacity and mobility
Enable more people and goods to travel faster and farther, with fewer delays.

Partnership for national security
Enhance the nation’s security through partnerships with Department of Defense, Department of Homeland Security, and other U.S. or international government agencies.

Explore revolutionary aeronautical concepts
Create novel aeronautical concepts and technology to support science missions and terrestrial and space applications.
# Roadmap Anticipated Achievements

<table>
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<tr>
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<tbody>
<tr>
<td><strong>Protect Air Travelers</strong></td>
<td>Network Enabled Optimizations for State-of-the-Art Systems</td>
<td>Proactive, Reconfigurable Systems for New and Enhanced Capabilities</td>
<td>Regenerative and highly reconfigurable hybrid organic structures and systems for real-time optimization, hazard avoidance, and security threat mitigation</td>
</tr>
</tbody>
</table>
| • Global integration of existing sensors for real-time global situational awareness (security, safety, and capacity) | • Integration of next-generation global sensors and communications for perspective situational awareness — seamless national defense integration  
• Inclement weather-proof systems  
• Embedded, multi-fault-tolerant security and safety systems, including self maintenance and repair | • Regenerative and highly reconfigurable hybrid organic structures and systems for real-time optimization, hazard avoidance, and security threat mitigation |
| **Protect the Environment**   | Evolutionary reductions of emissions and noise for current state-of-the-art systems | Revolutionary zero-emission power density and storage capabilities  
• Total elimination of some emission classes and significant reductions in noise | Total elimination of direct, unwanted emissions and noise |
| • Automation enhancements of business-as-usual-operations | • System-level automation with controlled zones of autonomous operations  
• Seamless National Airspace System unmanned aerial vehicle (UAV) fleet operations for a range of missions with controlled zones of autonomous operations | Collaborative autonomous systems (no human labor) for commercial, private multi-modal transportation and UAV operations  
• Ubiquitous, robust sensor nets and communications |
| **Increase Capacity and Mobility** | Global integration of existing sensors for real-time global situational awareness (security, safety, capacity) | Integration of next-generation global sensors and communications for perspective situational awareness — seamless national defense integration  
• Embedded, multi-fault-tolerant security and safety systems, including self maintenance and repair | Regenerative and highly reconfigurable hybrid organic structures and systems for real-time optimization, hazard avoidance, and security threat mitigations |
| • Automation enhancements of business-as-usual-operations | • Robust hypersonic and quiet supersonic operations demonstrations  
• Operational High Altitude, Long Endurance UAVs; Prototypes for autonomous cargo, firefighting, rescue, and other missions | • Regular hypersonic and supersonic operation, with seamless integration involving military and, as appropriate, launch operations | Micro Travel — individual flight gear or suits for urban, neighborhood, and nature hike-type excursions as well as entertainment and construction or operations-type activities |
| **Public Partnership for National Security** | Protect Air Travelers | Increase Capacity and Mobility | Protect the Environment |
| **Explore Revolutionary Aeronautical Concepts** | Cross-Cutting | Roadmap Anticipated Achievements |
| • Automation enhancements of business-as-usual-operations  
• Highly accurate predictive systems (safety, security, capacity, environment, and aircraft/infrastructure systems) for real-time human decision-support systems | • Micro- and nanotechnology structure, power, and control-surface enhancements to enable new vehicle classes and augmentation to existing vehicle fleets  
• Semi-reconfigurable, pro-active, on-demand systems (safety, security, capacity, and environment), subsystems (intelligent engines, gate robotics, and intelligent maintenance systems) | Highly distributed, with dynamic real-time system and vehicle optimizations |
## System Performance Metrics

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Reduce the aviation fatality rate per FY 90-96 average</td>
<td>50%</td>
</tr>
<tr>
<td>2010</td>
<td>Reduce aircraft vulnerability (exposure)</td>
<td>35%</td>
</tr>
<tr>
<td>2012</td>
<td>Identify and resolve air transportation system real-time risk and vulnerability</td>
<td>—</td>
</tr>
</tbody>
</table>

**Objective: Protect Air Travelers and the Public**

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Reduce NOx emission per the 1996 International Civil Aviation Organization (ICAO) standard.</td>
<td>70%</td>
</tr>
<tr>
<td>2010</td>
<td>Reduce aircraft community noise</td>
<td>10db</td>
</tr>
<tr>
<td>2010</td>
<td>Reduce Carbon Dioxide greenhouse emissions per 2000 SOA</td>
<td>25%</td>
</tr>
</tbody>
</table>

**Objective: Protect the Environment**

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>Increase terminal area throughput</td>
<td>5%</td>
</tr>
<tr>
<td>2009</td>
<td>Enable short-flied take-off and landing, and high-speed cruise capability</td>
<td>—</td>
</tr>
<tr>
<td>2009</td>
<td>Increase en route throughput per 1997 NAS capacity</td>
<td>10%</td>
</tr>
<tr>
<td>2013</td>
<td>Provide key enabling capabilities for a low cost, easy-to-fly personal air vehicle</td>
<td>—</td>
</tr>
</tbody>
</table>

**Objective: Increase Mobility**

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Transfer technology with the Department of Defense</td>
<td>—</td>
</tr>
<tr>
<td>2010</td>
<td>Reduce air transportation system vulnerability via partnership with the Department of Homeland Security and Transportation Security Agency</td>
<td>—</td>
</tr>
</tbody>
</table>

**Objective: Partnership for National Security**

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Enable un-inhabited air vehicle</td>
<td>14 day @ 60,000 ft. and 200kg payload</td>
</tr>
<tr>
<td>2010</td>
<td>Enable planetary flight vehicle technologies for exploration</td>
<td>—</td>
</tr>
</tbody>
</table>
Aeronautical Technologies

Roadmap for Safety

Fatal accident rate vs. 1990-96:
-50%       -70%       -90%       -98%

Aircraft self-protection and preservation
- 2005: Large-scale Homeland Security integration and Department of Defense (DoD)
- 2010: Reactive risk-mitigation systems that lessen abnormal operations
- 2015: Proactive risk-mitigation systems based on risk precursor identification
- 2020: Reactive risk-mitigation systems that lessen system failures
- 2025: Real-time learning/adaptive risk-mitigation systems
- 2030: Highly reconfigurable systems
- 2035: Advanced bio/nano personal protection systems

Environmental hazards awareness and mitigation
- 2005: Detection of natural hazards that compromise safe operations in the National Airspace System (NAS)
- 2010: Mitigation of the effects of detected natural hazards that compromise safe operations in the NAS
- 2015: Highly robust materials systems resistant to environmental hazards
- 2020: Impervious to environmental hazards through real-time, in-flight, self-healing and self-repairing systems

Human error avoidance
- 2005: Recovery from unsafe flight situations due to human error
- 2010: Onboard autonomous advisor — electronic co-pilot
- 2015: Recovery from unsafe flight situations due to the breakdown of the human/machine interface
- 2020: System-wide autonomous advisor – sentient NAS
- 2025: Recovery from unsafe flight situations due to machine error

Foundation Technologies—TRL 1-3, R&D with technology transition to mid-TRL programs

Digital Era
Sentient Era
Nano/Bio Era

Reduce Accident Rate by a Factor of 10 (per million departures)

5/22/2005
Roadmap for Security

Reduction in vulnerabilities: -35% -60% -90% -99%

2005 2010 2015 2020 2025 2030 2035

Hostile act intervention and protection
- Protection of critical assets from hostile aircraft takeovers
- Protection from man-portable air defense systems, other projectiles, and explosive devices
- Protection from electromagnetic effects/cyber attacks
- Protection of aircraft systems for information flow against hostile disruption
- Isolation, containment, and elimination of communicable diseases and chemical and biological agents aboard aircraft and in airports

System vulnerability discovery and management
- Detection and mitigation of deviations from flight path with hostile intent
- Discovery of potential security breaches at airport breaches at airports – Intelligent Sensors – Self replication sensor grids
- Data mining and detection of potential cargo threats
- Sensing of communicable diseases and chemical and biological agents aboard aircraft and in airports

Foundation Technologies - TRL 1-3, R&D with technology transition to mid-TRL Programs

Digital Era Sentient Era Nano-Bio Era
Roadmap for Environment

**Reduced aircraft emissions**
- NOx emissions vs. 1996: -70%, -80%
- CO₂ emissions vs. 1996: 25%, 35%
- Noise vs. 1997: -10 dB

**Reduced aircraft noise**
- Low-emission subsonic vehicles
- Low-emission supersonic vehicles
- Low-emission extreme short takeoff and landing vehicles
- Low-emission personal air vehicles
- Low-emission rotorcraft
- Low-emission unmanned aerial vehicles

**Foundation Technologies**
- TRL 1-3, R&D with technology transition to mid-TRL programs

**Zero emission, virtually silent aircraft**
- Electronically driven, Hydrogen-powered vehicles
- Lightweight structure for low-power requirements (30%)
- Active airframe surface response and air-flow control (inlets, boundary layer, jet exhaust, etc.) for aerodynamic efficiency and acoustic suppression
Roadmap for Capacity

ATS Capacity vs. 1997:
- 2.05 (x 1997)
- 2.5 (x 1997)
- 3 (x 1997)
- 4 (x 1997)

**Efficient traffic flow**
- Increase en-route commercial operations in the NAS
- Full system capability for general aviation during peak demand
- Full system capability public service aircraft during peak demand

**System-wide operations**
- Minimize system-wide disruptions from external events (thunderstorms, etc.)
- Harmonize equipment and operations globally
- Increase arrival and landing rates at commercial airports — advanced terminal, gate, and ramp automation as well as dynamic/reconfigurable airport structures
- More commercial operations from small and underused airports
- Commercial operations with short or no runways

**Aircraft/airport productivity**
- More commercial operations from small and underused airports
- Air traffic management procedures tailored to individual aircraft characteristics
- High-level optimization of system performance and full integration of en-route and terminal operations
- System impervious to disruptions from any source

**Fully integrated automated optimized National Airspace System (NAS)**
- Automated optimization of four-day flight path for all commercial aircraft
- Transparent integration of general aviation, public services, and unmanned aerial vehicles
- Air traffic management procedures tailored to individual aircraft characteristics
- High-level optimization of system performance and full integration of en-route and terminal operations
- System impervious to disruptions from any source

**Foundation Technologies**
- TRL 1-3, R&D with technology transition to mid-TRL programs

Digital Era  | Sentient Era  | Nano/Bio Era
Roadmap for Mobility

Goal: Continuously expanding choice of efficient air transportation

2005    2010    2015    2020    2025    2030    2035

- Efficient subsonic vehicles
- Efficient low-boom supersonic vehicles
- Air traffic management for unmanned aerial vehicles and other vehicle types (supersonics/hypersonics)
- Quiet and efficient all-weather extreme short takeoff and landing vehicles
- Efficient all-weather rotorcraft
- Low-cost, efficient, easy-to-fly personal air vehicles
- Highly configurable subsystems for continuous optimization of entire flight profile
- Autonomous personal air vehicles
- Highly accurate predictive decision-support systems for human operations
- Intelligent, proactive maintenance support systems
- Self-healing and regenerative systems
- Reconfigurable personal multi-modal modular vehicles
- Real-time transformation systems for continuous optimization of the entire flight profile
- Micro Travel — individual flight gear/suits for local neighborhood/urban/entertainment excursions

Optimized flight with reduced or no human intervention

Optimized ground ops and maintenance with reduced or no human intervention

Foundation Technologies - TRL 1-3, R&D with technology transition to mid-TRL programs

Digital Era  Sentient Era  Nano/Bio Era
Roadmap for New Missions

2005
- 14 days @ 60,000 ft., carrying 200-kg payload

2010
- 100 days @ 60,000 ft., carrying a 150-kg payload

2015
- 100 days @ 60,000 ft., carrying a 3,000-kg payload

2020

2025

2030

2035

Autonomous long-endurance unmanned flight
- Planetary flight vehicle technologies
  - Innovative applications of autonomous unmanned vehicles

Robust, re-useable demonstration vehicles and systems
- Operational vehicles
  - Earth launch assist system of systems

Hypersonic atmospheric flight
- System research and development for propulsion and vehicle options for efficient air-breathing hypersonic flight
  - Hypersonic cargo/sample return un-crewed return

Foundation Technologies
- TRL 1-3, R&D with technology transition to mid-TRL programs

Digital Era
- 14 days @ 60,000 ft., carrying 200-kg payload

Sentient Era
- 100 days @ 60,000 ft., carrying a 150-kg payload

Nano/Bio Era
- 100 days @ 60,000 ft., carrying a 3,000-kg payload
## Scenario Options for Elements of the National Airspace System

<table>
<thead>
<tr>
<th>Passenger/Cargo Demand</th>
<th>Fleet Mix/ Aircraft Types</th>
<th>Business Model/ Schedule</th>
<th>National Airspace Space Capability</th>
<th>Disruptions /Weather</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Current</td>
<td>1) Current scaled</td>
<td>1) Current (mostly hub and spoke)</td>
<td>1) Current</td>
<td>1) Good weather (Wx)</td>
</tr>
<tr>
<td>2) Terminal area forecast (TAF) growth to 2014 and 2025</td>
<td>2) More regional jets</td>
<td>2) 2014 Operation evolution plan (OEP)</td>
<td>2) Bad</td>
<td>2) Good weather (Wx)</td>
</tr>
<tr>
<td>3) 2X TAF-based constrained growth</td>
<td>3) New vehicles: Micro jets</td>
<td>3) Increased capacity of landside, surface runways, terminal en-route</td>
<td>3) Bad</td>
<td>3) Good weather (Wx)</td>
</tr>
<tr>
<td>4) 3X TAF</td>
<td>Uninhabited air vehicles</td>
<td>4) Systemic CNS, SWIM, and weather prediction</td>
<td>4) Disruption</td>
<td>4) Disruption</td>
</tr>
<tr>
<td></td>
<td>ESTOL/RIA</td>
<td></td>
<td></td>
<td>Sudden shutdown of an airport or region</td>
</tr>
<tr>
<td></td>
<td>Supersonic Transport (SST)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Investment decisions aim to optimize system performance for a robust range of scenarios.

- Protect air travelers and public
- Protect the environment
- Increase capacity and mobility
- Explore revolutionary aeronautical concepts
- Create a partnership for national security

Investment decisions aim to optimize system performance for a robust range of scenarios.
# Strategic Roadmap Interdependencies

<table>
<thead>
<tr>
<th>Roadmap</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustained, long-term robotic and human exploration of Mars</td>
<td>The roadmap receives technical requirements and schedules. It provides technologies for atmospheric flight on Mars.</td>
</tr>
<tr>
<td>Sustained program of solar system exploration</td>
<td>The roadmap receives technical requirements and schedules. It provides technologies for atmospheric flight on other worlds and for hypersonic/ unmanned aerial vehicle (UAV) sample and return to Earth.</td>
</tr>
<tr>
<td>Develop an exploration transportation system</td>
<td>The roadmap receives technical requirements and schedules. It provides technologies for atmospheric flight for both launch services and hypersonic/UAV reentry vehicles.</td>
</tr>
<tr>
<td>Safely transition from Shuttle to new exploration-focused launch systems</td>
<td>The roadmap receives technical requirements and schedules. It provides aero-assist launch technologies.</td>
</tr>
<tr>
<td>Determine how the living Earth system is affected by internal dynamics and understand the implications for life</td>
<td>The roadmap receives technical requirements and schedules. It provides a range of UAV technologies, including long-duration, high-altitude, robust atmospheric vehicles for data gathering as well as oceanic sensor deployment, water sample collection, and other Earth-monitoring and autonomous sampling missions.</td>
</tr>
<tr>
<td>Explore Sun-Earth system to understand effects on Earth and implications for human exploration</td>
<td>The roadmap receives technical requirements and schedules. It provides a long-duration, high-altitude, robust atmospheric vehicles to help carry out research and development on space weather forecasting and monitoring.</td>
</tr>
<tr>
<td>Educate students and public, and expand national technical skills and capabilities</td>
<td>The roadmap offers opportunities for students and the public to follow advanced technology systems and to augment math and science skills.</td>
</tr>
</tbody>
</table>
### Capabilities Roadmap Interdependencies

<table>
<thead>
<tr>
<th>Roadmap</th>
<th>Nature of the relationship: What the Capability Roadmap Provides for Aerospace</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-energy power and propulsion</td>
<td>• Energy storage</td>
</tr>
</tbody>
</table>
| Communication and navigation  | • High-bandwidth communication  
                                | • Secure inter-aircraft and ground and satellite command and control links                                                                      |
| Autonomous systems            | • Health monitoring and control and operation of systems  
                                | • Control of aircraft on the ground  
                                | • Air traffic control                                                        |
| Transformational spaceport/range | • Range safety  
                                | • Interface between national airspace system and space range                                                                                   |
| Advanced modeling/simulation  | • Advanced computational fluid dynamics techniques  
                                | • Advanced end-to-end system modeling                                                                                                         |
| Systems engineering           | • Required to ensure an outcome and/or optimize performance within engineering, budget, and schedule constraints for all enterprises  
                                | • Enable large system of systems (NAS) to transform                                                                                             |
| Nanotechnology                | • Ultra-high strength, lighter, and multifunctional materials (100 times stronger than steel)  
                                | • Micro-electronics 100 times smaller and less power consuming  
                                | • Highly miniaturized avionics and instrument systems  
                                | • Efficient electrical power systems                                         |
Earth Science and Applications
Strategic Roadmap Summary
May 22, 2005
Roadmap Summary

- NASA objective to which roadmap responds:
  - Advance scientific knowledge of the Earth system through space-based observation, assimilation of new observations, and development and deployment of enabling technologies, systems, and capabilities, including those with the potential to improve future operational systems.

- Connection to NASA vision:
  - “To Improve Life Here”
  - Responds to multiple presidential initiatives and directives, including Climate Change Research (June 2001), Global Earth Observation (July 2003), and Collaborative Oceans Research (December 2004)

- Top-level summary of themes:
  - Predictive understanding of the Earth as a system of interacting natural and human systems
    - Atmospheric composition: how the atmosphere protects and sustains us
    - Climate and weather: how climate and weather are evolving
    - Water: what controls the availability of water on the planet
    - Life: how life influences and responds to environmental processes
    - Solid Earth: what controls the changes to the Earth’s surface and interior
  - Synergistic integration of Earth observations and models (sensorweb/modelweb)
    - Exploration and discovery: new investigations using new insights, technologies, capabilities, and vantage points to explore unknown aspects of the Earth system
    - Continuous awareness: prompt recognition and adaptive observation of dynamic events through the networking of distributed observing and modeling systems for new scientific understanding of dynamic processes and to demonstrate the potential to improve future operational systems
    - Developing perspective: integration of sustained and comprehensive observations and models to understand long-term Earth processes and trends
## Roadmap Anticipated Achievements

<table>
<thead>
<tr>
<th>Exploration and Discovery:</th>
<th>2005-2015: Building a foundation for comprehensive observing and modeling</th>
<th>2015-2025: Expanding our view of Earth and benefits to society</th>
<th>2025-2035 and Beyond: Fully instrumented Earth system networked to predictive models serving scientists and decision-makers</th>
</tr>
</thead>
</table>
| Explore unknown aspects of the Earth system by carrying out new investigations, enhanced by new insights, technologies, capabilities, and vantage points | • Accurate assessment of carbon sequestration on land  
• Time-dependent deformation maps of fault zones, volcanoes, slopes, and ice sheets | • Characterize water distribution in root zone; improve weather and climate prediction  
• Upper ocean profiling to understand ocean biosphere | • Short-period magnetic field dynamics  
• Pursuing answers to new questions, enabled by distributed autonomy, biotechnology, nanotechnology, very large apertures, etc. |
| Continuous Awareness: | Improved understanding of natural and anthropogenic aerosols and their effects on climate  
• Ice sheets changes and ocean circulation tied to predictive climate models  
• Quantified snow deposition and water equivalent  
• CO₂ flux to constrain global sources and sinks | Quantified dynamics of major ice sheet motion  
• Tropospheric winds over land and ocean for weather and ocean circulation models  
• Quantified dynamics of cloud moisture, rainfall, surface and subsurface water storage, runoff, and fresh water availability  
• Vegetation/algal type and land/ocean carbon sequestration  
• Surface deformation dynamics, thermal/land-use changes, and surface beneath ice | Assessment of plant and algal physiological status and productivity  
• Improved global topography and, in conjunction with SRTM data, first global measurement of topographic change  
• Fully integrated Earth System model and assimilation system with data distribution portals for simple, high-speed access to all aspects of the Earth System |
| Developing Perspectives: | Calibrated operational weather/climate observations for science  
• National framework for linking Earth system models | Reduced uncertainties in global and regional climate models through cloud feedback and aerosol forcing  
• Models and data assimilation systems integral to the observing system and decision support systems, including future mission design | Global water cycle, including soil moisture, precipitation, linked to climate and weather models  
• Networked observations, models, and knowledge systems for science and operational systems |

**Goals**

- **Achievements**
- **2025-2035 and Beyond:** Fully instrumented Earth system networked to predictive models serving scientists and decision-makers
- **2015-2025:** Expanding our view of Earth and benefits to society
- **2005-2015:** Building a foundation for comprehensive observing and modeling

**Exploration and Discovery:**
- Explore unknown aspects of the Earth system by carrying out new investigations, enhanced by new insights, technologies, capabilities, and vantage points.

**Continuous Awareness:**
- Improved understanding of natural and anthropogenic aerosols and their effects on climate.
- Ice sheets changes and ocean circulation tied to predictive climate models.
- Quantified snow deposition and water equivalent.
- CO₂ flux to constrain global sources and sinks.

**Developing Perspectives:**
- Calibrated operational weather/climate observations for science.
- National framework for linking Earth system models.

**2025-2035 and Beyond:**
- Short-period magnetic field dynamics.
- Pursuing answers to new questions, enabled by distributed autonomy, biotechnology, nanotechnology, very large apertures, etc.

**2015-2025:**
- Characterize water distribution in root zone; improve weather and climate prediction.
- Upper ocean profiling to understand ocean biosphere.

**2005-2015:**
- Accurate assessment of carbon sequestration on land.
- Time-dependent deformation maps of fault zones, volcanoes, slopes, and ice sheets.
Strategic Roadmap Timeline

2005 2015 2025 2035

Atmospheric Composition
- Global Greenhouse Gases
- Tropopause Composition
- Aerosols
- Sea Level Rise
- Earth Observing System
- Ozone Changes

Climate/Weather
- Global Aerosol Radiation
- Cloud Feedback
- Ocean Circulation
- Aerosol Transport
- Ice Sheet Changes
- Global Precipitation
- Global Rainfall
- Global Soil Moisture
- Global Carbon Cycle
- Global Water Cycle

Water
- Ocean Carbon Storage
- Biodiversity
- Marine Ecosystems
- Ocean Dynamics
- Ocean Ecosystems

Life
- Plant Physiology & Function
- Ocean Biogeochemistry
- Ocean Primary Productivity
- Ocean Ecosystems
- Terrestrial Ecosystems
- Terrestrial Biogeochemistry

Solid Earth
- Surface Topography
- Surface Deformation
- Earth System Processes

New Lines of Inquiry
- Exploration
- Awareness
- Perspective
- Flagship

Transfer to operations
New line of science inquiry
Modeling and Computing Investment

- 2015
  - Loosely coupled global models
  - Earth System Modeling Framework implemented
- 2025
  - Fully integrated Earth system model
Roadmap Interdependencies
(1 of 2)

• Primary strategic roadmap linkages:
  – Shared desire with Sun-Solar System Connection Roadmap for joint investigations of the effects of solar variability on the Earth’s climate and upper atmospheric chemistry dynamics.
  – Shared scientific, modeling, and observation system interests with all three exploration roadmaps (Lunar, Mars, and Solar System), Earth-like planets, and Aeronautics.

• Key required technical capabilities:
  – Sensor web/model web autonomy
  – Capacity to connect multiple observing and modeling systems to synergistic networks or system of systems, with intensive modeling and analysis
  – Innovation in Earth observation instrument and system technology, as well as the capability to rapidly, reliably, and efficiently design, build, test, and operate new instrumentation
Major required infrastructure elements and facilities to support modeling and data management:

- Research and Development systems to observe all key Earth system variables and assimilate information into integrated, interacting models that include each of Earth’s major subsystems: oceans, atmosphere, cryosphere, biosphere, and solid Earth

- Earth system information easily accessible via high-bandwidth portal
Integration of Earth System Science

**Discover**

**Exploration and Discovery**

Discover new phenomena and develop new insights using innovative mission designs and technologies.

**Earth System Science**

Sustain and integrate the comprehensive observing and modeling systems required to serve science and societal needs.

Characterize dynamic events by networking interdisciplinary observation and modeling systems for science and decision-makers.

Understand

Developing Perspectives

Inform

Continuous Awareness
Partnerships

• Multiple interagency partnerships through presidential-level initiatives:
  – Climate Change Research (June 2001)
  – Global Earth Observation (July 2003)
    • U.S. Integrated Earth Observation System
  – Collaborative Oceans Research (December 2004)

• Transition important, time-series, Earth-system data records from the research to the operational domain:
  – Global land cover operations through Operational Land Imager on National Polar-Orbiting Operational Environmental Satellite System (NPOESS)
  – Global ocean color, vegetation properties, surface temperature, and atmospheric properties through Visible/Infrared Imager/Radiometer Suite on NPOESS Preparatory Project and then NPOESS

• Bilateral international partnerships:
  – Framework of the Global Earth Observation System of Systems

• Commercial value of Earth observations:
  – Presidential space policy on commercial remote sensing
  – Benefits of competition and feedback of the marketplace
Roadmap Objective

- **National objectives (from the Vision for Space Exploration):**
  - Implement a sustained and affordable human and robotic program to explore the solar system and beyond.
  - Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
  - Develop innovative technologies, knowledge, and infrastructure to explore and to support decisions about the destinations for human exploration.
  - Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.
  - Study the Earth system from space and develop new space-based and related capabilities for this purpose.

- **NASA objective:**
  - Explore the Sun-Earth system to understand the Sun and its effects on:
    - Earth
    - Solar system
    - Human explorers
  - Demonstrate technologies that can improve future operational systems.

- **These national and Agency objectives drive the objectives of our science discipline, as described on the following page.**
The Sun-Solar System Connection (SSSC) Roadmap is a plan to:

• **Develop the capability to predict space weather by:**
  – Understanding magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storms.
  – Understanding the plasma processes that accelerate and transport particles throughout the solar system.
  – Understanding the role of plasma-neutral interactions in nonlinear coupling of regions throughout the solar system.
  – Understanding the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary, and stellar environments.

• **Understand the nature of our home by:**
  – Understanding the causes and subsequent evolution of solar activity that affects the Earth’s space climate and environment.
  – Understanding changes in the Earth’s magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects.
  – Understanding the Sun's role as an energy source to the Earth’s atmosphere, particularly the role of solar variability in driving atmospheric and climate change.
  – Applying our understanding of space-plasma physics to the role of stellar activity and magnetic shielding in planetary system evolution and habitability.

• **Safeguard our outward journey by:**
  – Characterizing the environmental extremes that human and robotic explorers will encounter in space.
  – Developing the capability to predict the origin of solar activity and disturbances associated with potentially hazardous space weather.
  – Developing the capability to predict the acceleration and propagation of energetic particles to enable safe travel for human and robotic explorers.
  – Understanding how space weather affects planetary environments in order to minimize risk in exploration activities.
## Sun-Solar System Connection Anticipated Achievements

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Develop the capability to predict space weather</strong></td>
<td>Characterize</td>
<td>Understand</td>
<td>Predict</td>
</tr>
<tr>
<td></td>
<td>magnetic reconnection at the Sun and Earth</td>
<td>the magnetic processes that drive space weather</td>
<td>solar magnetic activity and energy release</td>
</tr>
<tr>
<td></td>
<td>Determine the dominant processes and sites of particle acceleration</td>
<td>Quantify particle acceleration for the key regions of exploration</td>
<td>Predict high-energy particle flux throughout the solar system</td>
</tr>
<tr>
<td></td>
<td>Identify key processes that couple solar and planetary atmospheres to the heliosphere and beyond</td>
<td>Understand non-linear processes and couplings for prediction of the space environment and atmosphere</td>
<td>Understand the interactions of disparate astrophysical systems</td>
</tr>
<tr>
<td><strong>Understand the nature of our home</strong></td>
<td>Understand how solar disturbances propagate to Earth</td>
<td>Identify precursors of important solar disturbances</td>
<td>Image activity in other stellar systems</td>
</tr>
<tr>
<td></td>
<td>Identify how space weather effects are produced in geospace</td>
<td>Quantify mechanisms and processes required for geospace forecasting</td>
<td>Provide a scientific basis for continuous forecasting of conditions throughout the solar system</td>
</tr>
<tr>
<td></td>
<td>Discover how space plasmas and planetary atmospheres interact</td>
<td>Determine how magnetic fields, solar wind, and irradiance affect the habitability of solar system bodies</td>
<td>Determine how stellar activity and plasmas affect planetary formation and evolution governing habitability through time.</td>
</tr>
<tr>
<td></td>
<td>Identify the effects of solar variability on Earth’s atmosphere</td>
<td>Integrate solar variability effects into Earth-climate models</td>
<td>Predict climate change (joint with Earth Science)</td>
</tr>
<tr>
<td><strong>Safeguard our outward journey</strong></td>
<td>Determine extremes of the variable radiation and space environments at Earth, Moon, and Mars</td>
<td>Characterize the near-Sun source region of the space environment</td>
<td>Analyze the first direct samples of the interstellar medium</td>
</tr>
<tr>
<td></td>
<td>Now-cast solar and space weather and forecast “all-clear” periods for space explorers near Earth</td>
<td>Reliably forecast space weather for the Earth-Moon system; make first space weather now-casts at Mars</td>
<td>Provide situational awareness of the space environment throughout the inner solar system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Determine Mars atmospheric variability relevant to Exploration activities</td>
<td>Reliably predict atmospheric and radiation environment at Mars to ensure safe surface operations</td>
</tr>
</tbody>
</table>

*Develop technologies, observations, and knowledge systems that support operational systems*
Joint Sun-Earth Science

Phase 1
Sun-Earth-Moon System
Characterization of System
- Magnetic reconnection
- Particle acceleration processes
- Drives of cis-lunar space weather

Phase 2
Sun-Terrestrial Planets
Modeling of System Elements
- Effects of solar variability on Earth and Mars
- Measure near-Sun space environment
- Atmospheric response to external drivers

Phase 3
Sun-Solar System
System Forecasting
- Predict solar, heliospheric, and stellar activity
- Physical models of important space weather processes
- Inner heliosphere radiation and space weather forecasts
- Drivers of climate and habitability
- Sample interstellar medium

Model Systems
- Forecast space weather for public and explorers

Local Space Weather Forecasts for Operations
- Reliable weather predictions for all exploration and science in space

Characterize Environments
- Sample interstellar medium
- Effects of solar variability on Earth and Mars

Space Weather Impacts on System Design
- Informs Lunar Exploration
- Informs Extended Human Exploration
- Space Weather Operations

Exploration Systems Timeline
- Crew exploration vehicle
- Robotic lunar exploration
- Human/robotic lunar surface exploration
- Extended human operations on lunar surface
- Human exploration near Mars or other solar system locale
- Human exploration of Mars or other solar system locale

2005 2015 2025 2035
Candidate Mission Sets

**Solar-Terrestrial Probes (STP) — fundamental science missions:**

- Auroral Acceleration Multi-Probe (AAMP)
- Dayside Boundary Constellation (DBC)
- Geospace Electrodynamics Cluster (GEC)
- GEospaee Magnetosphere-Ionosphere Neutral Imagers (GEMINI)
- Heliostorm
- Heliospheric Imager and Galactic Observer (HIGO)
- Interstellar Probe (IP)
- Ionosphere-Thermosphere-Mesosphere Coupler (ITMC)
- Ionosphere-Thermosphere-Mesosphere Waves (ITMW)
- Magnetospheric Constellation (MC)
- Magnetospheric Multi-Scale (MMS)
- Magnetic TRAnsition region Probe (MTRP)
- Reconnection and Micro-scale (RAM)
- Sun-Earth Coupling by Energetic Particles (SECEP)
- Stellar Imager (SI)
- Solar Polar Imager (SPI)
- Solar TErrestrial RElations Observatory (STEREO)
- Telemachus

**Living with a Star — missions to study the effects of space weather:**

- Far-Side Sentinels (FS)
- Inner Heliospheric Sentinels (HIS)
- Ionosphere-Thermosphere Imager (ITImager)
- Ionosphere-Thermosphere Storm Probes (ISTP)
- Radiation Belt Storm Probes (RBSP)
- Solar Dynamics Observatory (SDO)
Candidate Mission Sets

**Explorer Missions (EXP)** — openly competed smaller missions addressing timely scientific investigations:

- Aeronomy of Ice in the Mesosphere (AIM)
- Time History of Events and Macroscale Interactions during Substorms (THEMIS)

**NASA, externally funded, or other mission candidates:**

- Lunar Reconnaissance Orbiter (LRO)
- Mars Aeronomy/Mars Dynamics
- Mars Science Laboratory (MSL)
- Neptune Orbiter (NO)
- Pluto/Kuiper
- Solar-B
- Solar Connection Observatory for Planetary Environments (SCOPE)
- Solar Heliospheric and Interplanetary Environment Lookout for Deep Space (SHIELDs)
- Solar Orbiter
- Solar Probe (SP)
- Solar Sail
- Solar Wind Buoys (SWB)
- Titan Explorer (TE)
- Venus Aeronomy Probe (VAP)
Sun-Solar System Missions Roadmap

### Phase 1
Sun-Earth-Moon System
Characterization of System

### Phase 2
Sun-Terrestrial Planets
Modeling of System Elements

### Phase 3
Sun-Solar System
System Forecasting

#### Future Mission Candidates

**Solar:**
- SDO, Solar-B

**CMEs and Heliosphere:**
- STEREO, Sentinels, Solar Sail Demo

**Radiation:**
- RBSP, Sentinels

**Geospace Impacts:**
- MMS, RBSP, THEMIS, ITSP/ITImager

**Climate Impacts:**
- SDO, AIM

**Moon, Mars Awareness:**
- LRO, MSL

**Interstellar Boundary:**
- IBEX

**Inner Boundary:**
- Solar Probe

**Solar Processes:**
- Solar Orbiter

**Geospace System Impacts:**
- GEC, GEMINI, MagCon

**Climate Impacts:**
- L1 Earth-Sun, SECEP

**Mars Atmosphere:**
- Mars Aeronomy/Mars Dynamics

**Space Weather Stations:**
- Heliostorm

**Solar System Space Weather:**
- SEPP, Solar Wind Buoy

**Planetary Orbiters:**
- Pluto/Kuiper, JPO

**Solar Processes:**
- MTRAP, RAM

**Heliospheric Structure & Disturbances:**
- HIGO, SPI/Telemachus

**Geospace System Impacts:**
- AAMP, ITMC, ITMW

**Solar System Space Weather:**
- DBC, FS/Shields

**Planetary Orbiters:**
- SCOPE, NO, TE, VAP

**Interstellar Medium:**
- Interstellar Probe

**Habitability:**
- Stellar Imager

**Forecast Hazards:**

Distributed assets form an evolving sensor web to sample the vast connection from the Sun to planetary environments and beyond.

Key:
- In Development;
- Recommended;
- Recommended;
The roadmap is designed around scientific investigations:
- Robust and flexible to changes in technology or new discoveries
- Re-evaluation occurs as new understanding is achieved
- Explorers advance knowledge to change future missions

### Phase 1 achievement

**Technology achievement**
- **Yes**
  - Increased space weather-warning times (Heliostorm)
  - Out-of-ecliptic solar imaging (Solar Polar Imager)
  - Sampling interstellar medium (Interstellar probe)
  - Out-of-ecliptic solar imaging (Telemachus–chemical propulsion)
  - Sampling interstellar medium (Interstellar probe — using nuclear electric propulsion?)
- **No**
  - Space weather warnings (L1 Solar wind)
  - Out-of-ecliptic solar imaging (Solar Polar Imager)
  - Sampling interstellar medium (Interstellar probe)
  - Out-of-ecliptic solar imaging (Telemachus–chemical propulsion)
  - Sampling interstellar medium (Interstellar probe — using nuclear electric propulsion?)

### Phase 2 decisions

**Science achievement**
- Understand propagation of solar events (STEREO, Solar orbiter, and inner heliosphere sentinels)
  - Further study of propagation of solar events (Solar wind buoys)
  - Energetic particle impacts on atmosphere and inner magnetosphere (SECEP, GEMINI)
**Phase 1 & 2 achievements**

**Science achievement**

Understand magnetosphere and ionosphere processes and coupling (RBSP, ITSP, GEC, MMS, and MC)

**Phase 3 decisions**

**Particle acceleration by parallel electric fields (AAMP)**

**Coupling of ITM system to upper atmosphere (ITM-Coupler/ITM Waves)**

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**Science achievement**

Understand propagation of solar events (SDO, STEREO, Solar Orbiter, and Inner Heliosphere Sentinels, SWB)

**Science**

**Out-of-ecliptic solar event imaging (SPI/Telemachus)**

**In-ecliptic solar event imaging (FarSide/SHIELDs)**
Strategic Roadmap Interdependencies

- **Lunar exploration**
  - Provide:
    - Specifications for materials and technology development
    - Forecast of solar activity and its effect on lunar environment and astronaut productivity
    - Electrostatics and dust-charging processes
  - Benefit from studying the history of solar wind through regolith-core studies

- **Mars exploration**
  - Provide:
    - Space environment specifications for materials and technology development
    - Forecast of solar activity and its effect on the Mars environment and exploration productivity
    - Data on Mars aeronomy, ionosphere, atmospheric loss, and habitability
  - Benefit from platforms for scientific investigations

- **Exploration transportation**
  - Provide:
    - Space environment specifications for materials and technology development
    - Forecast solar activity and its effect on planetary and interplanetary environments

- **Earth systems and dynamics**
  - Provide:
    - Sun/climate connection
    - Societal effects of space weather processes

- **Exploration of the universe**
  - Provide:
    - Understanding of the Sun as a magnetic variable star
    - Understanding of fundamental plasma processes
Capability Roadmap Interdependencies

- **Answering our science questions will sometimes require measurements at unique vantage points and in non-Keplerian orbits, within and outside the solar system. Capability requirements include:**
  - Cost-effective, high-$\Delta V$ propulsion and deep-space power.
  - High-energy power and propulsion — advanced radioisotope thermoelectric generators
  - In-space transportation — solar sails
  - Nanotechnology — carbon-nanotube membranes for solar sails
  - In situ measurements using clusters and constellations, combined with remote sensing (sensor webs); compact, affordable instruments and spacecraft; low-power high-radiation electronics; autonomous maintenance of precision flight formations (important for Stellar Imager mission).
    - Advanced telescopes and observatories
    - Scientific instruments and sensors
  - Low-cost access to space (secondary payloads, sounding rockets)
    - Transformational spaceport

- **Return and ingest large solar system research data sets**
  - Next-generation or follow-on to Deep Space Network
    - Communication and navigation

- **Visualize, analyze, and model space plasmas**
  - Advanced modeling, simulation, and analysis

- **New measurement techniques — compact instrumentation and imagers**
  - Next generation of Sun-Solar System instrumentation
    - Advanced telescopes and observatories
    - Scientific instruments and sensors
    - Nanotechnology
Paradigm-Shifting Events – Needed Infrastructure and Facilities

- **Paradigm-shifting events:**
  - Low-cost access to space
    - Major effects on how science experiments can be deployed
    - Revolutionize access to space

- **Infrastructure needs:**
  - Upgrade Deep Space Network to collect more data throughout the solar system
  - Supercomputing
  - Reinforce/revitalize sounding rocket/balloon program

- **Facilities:**
  - Facilities related to the development of science instruments and sensors

- **People:**
  - Develop and maintain skills through a broad range of competed funding opportunities for the scientific community
  - Outreach to attract workers to Earth-Sun system science
Other Information

Key cooperation opportunities

• Partnership Forums:
  – International Living with a Star
  – International Heliophysical Year
  – International Space Environment Service
  – National Space Weather Program

• Science objectives broadly shared with national partners:
  – National Science Foundation
  – National Oceanic and Atmospheric Administration
  – Department of Commerce
  – Department of Defense
  – Department of Transportation
  – Department of Energy
  – Department of the Interior
Roadmap Summary

From the Vision for Space Exploration:

• Conduct robotic exploration of Mars
  – To search for evidence of life
  – To understand the history of the solar system
  – To prepare for future human exploration
• Conduct human expeditions to Mars
  – After acquiring adequate knowledge about the planet using robotic missions
  – After successfully demonstrating sustained human exploration missions to the Moon

The activities and investigations described in this roadmap will allow the nation to:

• Determine if Mars was ever habitable and if life ever developed there.
• Understand the climate and the geological evolution of Mars and use that knowledge to better understand the formation and evolution of the terrestrial planets and life in the solar system.
• Make informed decisions about human exploration of Mars and prepare the key capabilities required for safe and effective human missions.
• Deliver elements and infrastructure to Mars to serve as a robotic outpost prior to the arrival of human explorers.
• Undertake the first human expeditions to Mars.
### Roadmap Anticipated Achievements

|---------------------------------------------------|-------------------------------------------------------|-------------------------------------------------------|-------------------------------------------------------|
| Determine if Mars was habitable and if life developed there | - Evidence of past water and aqueous processes  
- Habitable environments  
- Biosignatures | - Lab study of Mars samples  
- Subsurface exploration  
- Intensive search for life  
- Intensive search for life  
- Discovery-driven opportunistic science |  
- Intensive search for life  
- Discovery-driven opportunistic science |
| Understand the climate of Mars                    | - History of water  
- Atmosphere chemistry and dynamics  
- Polar-layered deposits | - Long-term climate change  
- Understand and predict Mars weather  
- Discovery-driven opportunistic science |  
- Discovery-driven opportunistic science |
| Understand the geological evolution of Mars       | - High-resolution surface mapping  
- Global/local mineralogy  
- Surface-atmosphere interactions  
- Role of water | - *In situ* exploration of compelling sites  
- Lab study of Mars samples |  
- Discovery-driven opportunistic science |
| Prepare for human exploration                     | - Search for usable water  
- Environment, dust, surface characteristics  
- Atmosphere variability and models  
- Establish initial telecom infrastructure | - Downselect architectures  
- Identify and explore candidate landing sites  
- Confirm resources  
- Biohazards, toxicity  
- Validate key |  
- Establish robotic outpost at preferred human site  
- Emplace infrastructure (power, ISRU, communications, etc)  
- Develop key capabilities, build and test |
Phase 1 Mission Recommendations

The robotic missions planned for the coming decade will revolutionize our understanding of Mars and will lay the groundwork for key decisions on future human exploration.

<table>
<thead>
<tr>
<th>Opportunity</th>
<th>Mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>Mars Reconnaissance Orbiter</td>
</tr>
<tr>
<td>2007</td>
<td>Phoenix Lander (Mars Scout)</td>
</tr>
</tbody>
</table>
| 2009        | Option 1: Mars Science Lab (MSL) #1  
Option 2: Mars Telecom Orbiter (MTO) #1, plus Mars Scout |
| 2011        | Option 1: MSL #2, plus Mars Scout, plus MTO #1  
Option 2: MSL #1 plus MSL #2 |
| 2013        | Mars Environmental Mission (MEM) #1, plus Mars Scout |
| 2016        | Mars Sample Return |
**Mars Exploration Roadmap Schematic**

### 2005 - 2016
- **2005**: MRO, Phoenix
- **2007**: MSL #1
- **2009**: MTO, Scout
- **2011**: MSL #2, MTO, Scout
- **2013**: MEM #1, Scout
- **2016**: MSR

### 2018 - 2022
- **2018**: Continued Robotic Science
  - MTO #2, Scout
  - Astrobiology Field Lab
- **2020**: Capability Development and Validation
- **2022**: MEM #2

### 2025
- **Decision**
  - Robotic Outpost, prepare for human exploration
  - Robotic science only; defer human exploration

### ~2025 - 2030
- **Decision**
  - Capability Development
  - Robotic Outpost
  - Emplace Elements
- **Verification**
  - Yes: Crew Systems Test and Validation
  - No: Continue Development/Test; Later Launch

### ~2035 - 2040
- **Human Mission Launch**
Roadmap Options and Alternatives

- As specified in the Vision, the roadmap team focused on defining priorities for a program in which robotic science missions pave the way for human explorers.

- Three natural decision points have been identified that:
  - Define the end of each phase of the roadmap
  - Determine the degree of readiness to proceed to the next series of investments leading to human Mars exploration, and
  - Are informed by discoveries, developments, and many other intermediate decisions.

End of Phase 1 (~2016):
- Continue with robotic science and preparation for human exploration, or
- Focus on continued/expanded robotic science; defer or de-emphasize human exploration planning.

Decision criteria may include:
- Positive indications of usable sub-surface water
- Indications that human health hazards of long-duration flight and Mars environment are tolerable and can be mitigated
- Successful development and test of Entry Descent and Landing (EDL) technology and progress in the development of Mars surface nuclear power technology, and
- Programmatic and budget factors.
End of Phase 2 (~2025):

• Establish a robotic outpost for comprehensive study and emplace infrastructure at potential human landing site(s), or
• Defer further planning for human Mars exploration; continue vigorous robotic exploration program.

**Decision criteria may include:**

- Successful validation of in situ resource utilization (ISRU) capability for human consumables and propellant production
- Analysis of first Mars samples, indicating low level of bio- or toxic hazards and continuing to enhance scientific interest
- Successful “dress rehearsal” of major human mission elements, including entry descent and landing, ISRU, Mars ascent, and planetary protection systems
- Satisfactory progress toward the development of human life support and habitation, surface power systems, and other key capabilities
- Successful validation of human exploration systems and concepts on the Moon, and
- Programmatic, budgetary, and international factors.
Roadmap Options and Alternatives (cont.)

Mid-Point and/or End of Phase 3 (~2030-2035):

- Confirm readiness for human missions; continue emplacement of infrastructure, develop flight systems, and proceed toward human mission launch, or
- Readiness not confirmed; continue capability development and validation, additional flight system development and test.

Decision criteria may include:

- Successful validation of key human flight elements
- Development of fission-power system for Mars surface
- Lunar mission demonstration of sustained human exploration systems and concepts
- Risk management
- Identification of active Mars biology in region of robotic outpost, and
- Programmatic, budgetary, and international factors.
Summary: Key Roadmap Decision Points

Decisions of architectural significance:

• Select a new human Mars Design Reference Mission to guide capability investments and future mission planning.

• Select the capability of new heavy-lift launch system and determine development timeframe.

• Determine the feasibility of safely landing large (~40 metric ton) mass elements on the surface of Mars.

• Decide on the preferred method of in situ resource utilization by confirming the presence of usable subsurface water and conducting system tests and validation.

• Identify the Mars mission elements for which validation on the Moon is critical.

• Decide whether to proceed with a fission-reactor system for Mars surface power.

• Determine the nature and degree of human health hazards likely to be encountered on the surface of Mars.

• Determine the need for high-efficiency in-space propulsion based on fission power.

• Confirm the ability of humans to live and work safely in deep space long enough to travel to Mars and return to Earth.
Strategic Roadmap Interdependencies

• **Lunar Exploration**
  – Systems and concepts for living and working in a planetary environment over an extended period
  – “Mars-like” exploration tools and concepts for use on the Moon
  – Challenge: Joint Moon-Mars program planning to identify requirements and plan for their evolution and infusion into lunar missions in an intelligent manner

• **Exploration Transportation System**
  – Heavy-lift launch capability, ~100 metric tons to low-Earth orbit for crew and cargo
    • Use on a lunar mission before using on Mars
  – Mars descent and ascent systems compatible with human mission masses
  – Possible need for high-efficiency in-space propulsion— to be determined via trade studies as a part of architecture definition and selection

• **International Space Station**
  – Knowledge of human health and performance in space
  – Fully equip and use the International Space Station to conduct physiological and biological research
  – Must support architecture decisions by ~2015

• **Nuclear Systems**
  – Surface power for human missions (~60-100 kW total, possibly in blocks of 20-40 kW)
    • Fission power appears to be the most beneficial implementation
    • Support architecture decisions by 2015; implementation readiness by ~2030
  – Surface power for robotic missions — ensure availability of improved Radioisotope Power Source systems
  – Possible need for fission power to support in-space propulsion
Capability Roadmap Interdependencies

**Required:**
- Hypersonic parachute to allow landing Mars Sample Return-class assets at high elevations on Mars
- Human-scalable entry, descent, and landing systems capable of safely and precisely landing 40 metric tons
- Heavy-lift launch vehicle (~100 metric tons to low-Earth orbit)
- Robust ~20-40 kW power plant for use on the surface of Mars
- Validation of capabilities needed for human expeditions, using appropriate venue
  - Strategically select opportunities to validate key capabilities in relevant environments
  - Includes Earth analog environments, International Space Station, Moon, and Mars (via robotic missions)

**Possibly Required:**
- In-situ resource utilization for human consumables and propellant production
  - Downselect among candidate methods based on Mars environment knowledge (especially the presence of water), feasibility tests, and architecture studies
- Nuclear propulsion for Mars missions
  - If the cost benefit for Mars is established via trade studies, or if required by other overriding Agency/national needs
Core Competency and Infrastructure Interdependencies

- The NASA workforce and national talents must be energized and defined to meet the challenge of Mars exploration.
  - Survey engineering talent and facilities to establish baseline and identify gaps.
  - Create strategic partnerships among government, industry, and academia.

- **Key areas of emphasis for workforce:**
  - Systems engineering and mission planning
  - Robotics, mobility, instrument/system integration
  - Physiological research
  - Nuclear systems
  - Atmospheric entry and dynamics
  - Planetary science

- **Key areas of emphasis for facilities:**
  - Mars sample receiving, handling, and curation
  - Atmospheric entry simulation and test
  - Nuclear systems testing (in partnership with U.S. Department of Energy)
  - Mars simulation with realistic surface material/environmental properties
  - Physiological/biological testing (radiation, gravity adaptation, etc.)
  - Testing, simulation, and modeling of large-scale complex systems
  - End-to-end in-situ resource utilization system operations in a simulated Mars environment
Goals and Objective

Agency goal from the Vision for Space Exploration:

Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore the moons of Jupiter, asteroids, and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources.

Roadmap objectives:

1. Learn how the Sun’s family of planets and minor bodies originated.
2. Determine how the solar system evolved to its current diverse state, including the origin and evolution of the Earth’s biosphere.
3. Explore the space environment to discover potential hazards and search for resources that would enable a permanent human presence.
4. Understand the processes that determine the fate of the solar system and life within it.
5. Determine if there is or ever has been life elsewhere in the solar system.
Roadmap Summary Science Threads

How does a planetary system become habitable?

• Habitability in other planetary environments
  - Earth-like planet:
    • Venus-Earth-Mars: Venus is a baked-dry version of Earth; Mars is frozen solid.
    • Venus and Earth are the same size; when did Venus become uninhabitable?
    • Did life ever start and does life still exist on Mars?
  - Blue Moons: Habitable worlds around the giant planets:
    • Europa-Titan-Triton are another warm-to-cold trio.
    • What does organic chemistry on Titan tell us about how life began?
    • Is there life on Europa?

• Habitability in the architectures of planetary systems:
  - How do giant planets determine the arrangement of terrestrial planets near the habitable zone? (Focus on Jupiter and Neptune.)
  - Can giant planets in the habitable zones of other stars have habitable moons?
  - How were the ingredients for life supplied and when?
  - How have impacts affected the survival and evolution of life through time?

(Note: This roadmap does not include Moon/Mars flight missions.)
## Roadmap Anticipated Achievements

**Agency Strategic Goal:** Conduct robotic exploration across the solar system for scientific purposes and to support human exploration.

|-------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
| 1: Learn how the Sun’s family of planets and minor bodies originated. | a) Probe the interior of a comet (Deep Impact)  
b) Return samples of dust from a comet’s coma (Stardust)  
c) Conduct detailed studies near a differentiated and a primitive asteroid (Dawn)  
d) Conduct detailed studies of a cometary nucleus (Rosetta) | a) Complete the reconnaissance of the solar system with a flyby of Pluto  
b) Explore the diversity of small bodies with such missions as multiple comet and Trojan/Centaur asteroid flybys  
c) Study individual small bodies intensively by means of sample-return missions | a) Return cryogenically preserved samples from a comet  
b) Characterize the diversity of Kuiper Belt objects |
| 2: Determine how the solar system evolved to its current diverse state, including origin and evolution of the Earth’s biosphere. | a) Conduct an intensive orbital study of Mercury to understand how and where it formed (Messenger)  
b) In conjunction with the expected achievements of Roadmap objective 1, investigate the origin of Earth’s water, organics, and other volatiles  
c) Investigate the earliest life on Earth through studies of Earth’s oldest rocks as well as modern analogous microbial communities | a) Land on a Venusian highland to search for granitic or andesitic rocks consistent with an early Earth-like tectonic evolution  
b) Search for evidence of past massive oceans of water on Venus  
c) Characterize the past and present population of asteroid impacts to understand their impact on terrestrial planets | a) Drill into various places on Venus to determine the mechanisms by which Venusian highlands were formed  
b) Return selected geologic samples from Venus |
| 3: Explore the space environment to discover potential hazards and search for resources that would enable a permanent human presence | a) Complete (>90 percent) the inventory of Near-Earth Objects (NEOs) larger than 1-km in diameter  
b) Characterize potentially hazardous objects via telescopic remote sensing  
c) Study remotely the resource potential of a sample of accessible small bodies | a) Precisely track and characterize any near-Earth object that could impact the Earth  
b) Explore near-Earth asteroid mineralogy in situ to determine resource potential | a) Develop technologies to alter trajectories of large, potential Earth-impacting bodies  
b) Study an L2 and NEO human-visit capability to understand the need for robotic and piloted extraction of asteroidal resources for use in space and on Earth |
## Roadmap Anticipated Achievements (continued)

Agency strategic goal: Conduct robotic exploration across the solar system for scientific purposes and to support human exploration.

|-------------------|--------------------|--------------------|-----------------------|
| **4: Understand the processes that determine the fate of the solar system and life within it.** | a) Determine the nature of interactions and balance of processes on/in Titan's surface, interior, and atmosphere  
b) Quantify the nature of changes in Saturn’s atmosphere  
c) Understand the evolution of satellite surfaces and ring structure | a) Study the nature of Pluto’s surface and its evolution over time  
b) Look for clues to the origin of the Pluto-Charon system  
c) Determine the composition of the surface of a typical Kuiper Belt object and hence understand its origin | a) Determine the range of detailed properties of Kuiper Belt objects  
b) Quantify the composition and conditions within the giant planets, particularly Jupiter and Neptune  
c) Determine the origin of Triton’s volatiles and the origin of this body’s apparent early episode of melting/resurfacing |
| **5: Determine if there is or has ever been life elsewhere in the solar system.** | a) Through the astrobiology program, determine plausible pathways for the origin of life on Earth  
b) Determine if organics exist on Titan distinct from those made by photochemistry and whether they are accessible for study | a) Determine if material from Europa’s subsurface ocean is accessible to a surface or near-surface-drilling study  
b) Deploy a mobile platform to study the detailed structure and composition of biogenically relevant organics on Titan | a) Determine if evidence of biological activity exists in selected materials samples directly on Europa  
b) Drill into cryovolcanic flows on Titan to search for organic material that evolved in the presence of liquid water  
c) Explore for life throughout the outer solar system |
Solar System Exploration Roadmap

2005 - 2015
Europa Geophysical Observer

2015 - 2025
Venus Surface Explorer

2025 - 2035
Europa Astrobiology or Neptune System

Flagship Missions

New Frontiers
- New Horizons (Pluto)
- Lunar SPAB
- Jupiter Polar Orbiter
- Comet Surface SR
- Jupiter FB/DP
- Venus Atmosphere

Discovery
- 3/decade

Power

- 5/decade

Hypervolocity/Aero Entry

High-Temperature/High-Pressure Operations

Low-Temperature Operations

Technology Development

Ground-Based Observations

Research and Analysis

Education and Public Outreach
Roadmap Options and Alternatives

- A budget-balanced portfolio of Discovery, New Frontiers, and Flagship-class missions is the foundation for this roadmap. It also is built on robust research and analysis programs, critical technology developments, supporting ground observations, and education and public outreach.

- Three categories make up the options for flight missions:
  - **Discovery ($300M - $500M)**
    - Open, unrestricted competition to address broad solar system objectives
    - Budget projection supports flying five per decade
  - **New Frontiers ($500M - $800M)**
    - Open competition to address solar system objectives consistent with Decadal Survey recommendations
    - Budget projection supports flying three per decade
  - **Flagship missions ($800M - $1400M or $1400M - $2800M)**
    - Major campaigns to address fundamental questions in solar system exploration consistent with Decadal Survey recommendations
    - Investigations address distant and/or extreme environments
    - Budget projection supports flying two $800-1400M or one $1400-2800M mission(s) per decade
Roadmap Mission Set Options

• **New Frontiers**
  - Kuiper Belt/Pluto
  - Lunar South Pole Aitken Basin
  - Comet Surface Sample Return
  - Venus Buoyant Station
  - Jupiter Polar Orbiter with Probes

• **Flagship Missions**
  - Europa Geophysical Orbiter
  - Venus Surface Explorer
  - Titan Explorer
  - Europa Astrobiology Lander
  - Titan Orbiter/Lander
  - Neptune Orbiter with Probes
  - Comet Cryo Nucleus Sample Return
  - Venus Sample Return
Flagship Decision Criteria

• Decision points are influenced by the confluence of three major factors:  
  - Scientific priorities and knowledge  
  - Technological readiness or capability, and  
  - Programmatic considerations.

• Preceding missions influence the destination(s), the campaign architecture, and the approach.

• Selected Discovery and New Frontiers missions can influence other priorities.

• A focused investment in critical technologies and capabilities will enable the missions and dictate the timetable for their implementation.
**Key Roadmap Decisions for Flagships**

**2005 - 2015**
- **Europa Geophysical Orbiter (f)**

1. **2015 - 2025**
   - **Titan (f) Explorer**
   - **Venus (f) Surface Explorer**
   - **2018/2019**
     - Start the second of two flagship missions — a Venus Surface Explorer.

2. **2025 - 2035**
   - **Europa Astrobiology**
   - **Titan Orbiter/Lander**
   - **Neptune Orbiter with Probes**
   - **Comet Cryo Nucleus Sample Return**
   - **Venus Sample Return**
   - **Decision 2 (2023/2024)**
     - Start a flagship mission in the $1400M to $2800M range.

**Decision 1 (2012/2013)**
- Start the first of two flagship missions for the period (2015-2025).
- If the technology is ready, fly Titan Explorer ahead of a Venus Surface Explorer.

(f) = $800M - $1400M
(F) = $1400M - $2800M
Roadmap Technology Interdependencies

• **Highest-priority investments:**
  - Radioisotope Power Source technologies (milliwatts up to 10s to 100s of watts, high efficiency)
  - Technologies for extreme environments:
    • High radiation tolerance (Europa, Jupiter)
    • Very high (Venusian surface) and very low (Titan mid-atmosphere) temperatures
    • Extreme pressure (hundreds of bars: Venus, Jupiter, and Neptune)
    • Atmospheric entry probes for outer planets and Venus (very high heating rates in helium/hydrogen atmosphere for outer planets and high heating rates in carbon dioxide for Venus)

• **Further assessment of the following technology areas:**
  - Closer evaluation of optical communications, ultra-high bandwidth, and ultra-high pressure communication/survival technologies that could enhance and possibly enable deep giant planet probes
  - Further study to determine specific needs for technologies in autonomous systems, science instruments, nanotechnology, or advanced modeling and analysis to enhance solar system exploration missions
# Technology Links

## Radioisotope Power Source (RPS)

- Radioisotope power supplies are critical for missions at extreme distances or in extreme environments
- Ongoing evaluation of efficient RPS designs (e.g., Stirling cycle rather than Radioisotope Thermoelectric Generator)
- Highest-priority critical path item for Europa and future outer-planet missions

## Technologies for Extreme Environment

- **High Radiation Tolerance**
  - Different energy and particle distribution distinct from military applications
  - Implies need for electronics, structures, and shielding, which can provide a minimum 30-day operation to one lasting many months

- **Extreme Temperatures**
  - High: 700K
  - Low: 70-90K

- **Extreme Pressures**
  - Hundreds of bars

- Extremely high-temperature technologies are needed for Venus atmosphere mission with surface access
  - Electronics and surface mobility at ~500 degrees Celsius
- Extremely low-temperature technologies are needed for Comet Surface Sample Return missions and Titan Explorer

- Missions that require operations at > 100 bars
  - Deep atmosphere of Neptune (up to one kilobar)
  - Surface of Venus (90 bars)
  - Deep atmosphere of Jupiter (100 bars)

- Implies special attention to structure and design of surface vehicles and pressure vessels in hazardous environment (hydrogen in outer-planet atmospheres, high-temperature corrosive chemicals in Venus)

## Technology for Outer-Planet and Venus Probes

- Extreme entry velocity/heating rates in hydrogen/helium atmosphere for Jupiter and Neptune probes and very high heating rates in carbon dioxide atmosphere for Venus
- Requires extreme environment thermal protection systems and testing in relevant environments
- Extreme depth for Venus, Jupiter, and Neptune probe missions
- Requires special attention to entry probe design, including pressure vessel structure to deal with ≥ 100 bar pressures, and thermal management of sensors, electronics, and batteries
- Communications technology needed for data transfer from extreme depths
- Aerocapture for a Neptune and Triton Orbiter probe
- Requires targeting precision and extreme environments thermal protection system
### Strategic Roadmap Interdependencies

<table>
<thead>
<tr>
<th>Strategic Roadmap</th>
<th>Links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lunar Robotic and Human Exploration</td>
<td>Studying solar system processes preserved in lunar surface materials through sample analysis and field studies is critical in understanding the processes under which the solar system developed</td>
</tr>
<tr>
<td>Mars Robotic and Human Exploration</td>
<td>Understanding Mars from both a historical and current perspective is critical to understanding the solar system's development</td>
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<tr>
<td></td>
<td>• Understanding the current state and evolution of the Martian atmosphere, surface, and interior</td>
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<tr>
<td></td>
<td>• Determining the nature of any habitable environments on Mars and whether life exists or ever existed on Mars</td>
</tr>
<tr>
<td>Earth-Like Planets and Habitable Environments</td>
<td>Studying the giant planets in our solar system and understanding how they affect habitability</td>
</tr>
<tr>
<td></td>
<td>Studying extrasolar planetary systems and understanding how they become habitable</td>
</tr>
<tr>
<td>Exploration Transportation</td>
<td>Exploring the outer solar system will require longer transit times. To gather more sophisticated science data, instruments will require larger launch mass and volume</td>
</tr>
<tr>
<td></td>
<td>• Heavy-lift launch for high-mass robotic missions</td>
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<tr>
<td></td>
<td>• Precision entry/descent and landing</td>
</tr>
<tr>
<td></td>
<td>• In-space propulsion</td>
</tr>
<tr>
<td></td>
<td>• In-space automated rendezvous and docking (depending on design of launch and transfer vehicles)</td>
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<tr>
<td></td>
<td>• Pre-deployed surface/orbit assets (fuel, power, instruments, etc.)</td>
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<tr>
<td></td>
<td>• Surface ascent/sample return to Earth</td>
</tr>
</tbody>
</table>
## Strategic Roadmap Interdependencies

<table>
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</table>
| **Sun-Solar System Connection** | Specifying and predicting space weather at solar system destinations and along interplanetary routes. Includes planetary atmospheric state (ascent, aerobraking, aerocapture, descent, landing), ionospheric state (communications, navigation), and energetic radiation morphology and spectral content (reliability of electronics and materials)  
  • Predicting, detecting, and warning of solar and galactic radiation environment  
  • Characterizing upper atmosphere (e.g., Titan, Neptune) for aerocapture  
  • Study magnetosphere around other planetary bodies |
| **Aeronautical Technologies**    | Future atmospheric vehicles                                          |
| **Nuclear Systems**             | Radioisotope Power Sources are critical for missions at extreme distances or in extreme environments in providing propulsion to and from the outer solar system, communications, and for planetary surface investigations |
Search for Earth-Like Planets
Strategic Roadmap Summary
May 22, 2005
The Vision statement contains the objective: “Conduct advanced telescope searches for Earth-like planets and habitable environments.”

Objectives:

- Find planets and nearby Earth-like worlds.
- Profile planetary characteristics and biomarkers.
- Understand planet formation and habitability.

Anticipated accomplishments will answer universal questions:

- What is the number of planets around nearby stars?
- What is the location of the nearest terrestrial planets?
- What are the properties of these planets, including indicators of the existence of life?
- What is the relationship between star formation and planet formation?
- What conditions are needed for the formation of life on planets?
- What evidence is needed to determine if life exists on any planet beyond the Earth?
Mission Set

Planet Search and Characterization Missions

- Space Interferometer Mission (SIM PlanetQuest), 2011: Indirect astrometric detection of planets M > 3 Earth masses
- Terrestrial Planet Finder-Coronagraph (TPF-C), 2014: Direct visible-light detection of planets and planetary systems around other stars
- Terrestrial Planet Finder-Interferometer (TPF-I), 2019: Direct infrared detection and spectroscopy of planets and their atmospheres
- Life Finder: Unambiguous signs of life around nearby stars
- Planet Imager: Multi-pixel resolution images of nearby planets

Planet Formation and Habitability

- Stratospheric Observatory for Infrared Astrophysics (SOFIA), 2005: Circumstellar disks, star, and planet formation
- James Webb Space Telescope (JWST), 2011: Formation of planets, stars, and galaxies
- Single Aperture Far Infrared (SAFIR): Formation of planetary systems
- Large Ultraviolet Visible Observatory (LUVO): Chemical evolution of the early universe
- Far Infrared Space Interferometer (FIRSI): High-resolution imaging of proto-planetary disks

Competed Missions

Address focused science questions through scientist-led investigations

- Kepler (2008): Accurate determination of the statistical frequency of earth-mass planets around solar-type stars
- Additional Origins probe missions
### Roadmap Anticipated Achievements

**Conduct advanced telescope searches for Earth-like planets and habitable environments**

<table>
<thead>
<tr>
<th>Objective</th>
<th><strong>Phase 1: 2005-2015</strong></th>
<th><strong>Phase 2: 2015-2025</strong></th>
<th><strong>Phase 3: 2025 Beyond</strong></th>
</tr>
</thead>
</table>
| **Planet Detection** | a) Measure the frequency of Earth-like planets in a statistically representative sample [COROT, Kepler]  
   b) Radial velocity surveys detect additional Jupiter analogs and nearby planets with mass approaching $10 M_{\text{earth}}$ [Ground]  
   c) First SIM planet detections | a) Astrometric detection of $M > 3 M_{\text{earth}}$ planets in habitable zone within 10 parsecs [SIM]  
   b) Photometric detection of $M > 0.5 M_{\text{earth}}$ planets in stellar habitable zone within 10 parsecs [TPF-C]  
   c) Photometric detection of $M > 0.5 M_{\text{earth}}$ planets in stellar habitable zone within 100 parsecs [TPF-I] | a) At least an order-of-magnitude increase in the number of directly detected Earth-like planets [LF]  
   b) Detection of planetary moons in nearby extrasolar system [LF] |
| **Planet Characterization** | a) Measure atmospheric spectra of hot Jupiters seen in transiting events [Ground, HST, Spitzer, JWST]  
   b) Measure spectra of brown dwarfs and giant planets [JWST] | a) Measure planetary masses [SIM]  
   b) Measure radius and surface temperature [TPF-C+TPF-I]  
   c) Detect basic atmospheric composition and presence of clouds [TPF-C+TPF-I]  
   d) Measure gross surface properties [TPF-C, TPF-I]  
   e) Detect new classes of planets [SIM, TPF-C, TPF-I]  
   f) Detect provisional indications of life [TPF-I] | a) Confirmation of biomarkers [LF]  
   b) Search for life on a larger sample of planets  
   c) Search for variety of different metabolisms [LF]  
   d) Improved characterization of planetary systems [LF] |
| **Planet Formation and Habitability** | Observe the formation and evolution of stars, galaxies, and planetary systems from the first luminous objects to debris disks [Spitzer, SOFIA, Herschel, JWST] | Observe the development of conditions for life, from the first release of the chemical elements in the first stars, through the formation of protoplanetary disks, to the chemistry and physics of the solar system [SOFIA, JWST, SAFIR] | a) Observe proto-planetary disks with the resolution needed to detect Earth-like planets in formation [FIRSI]  
   b) Trace the chemical evolution of the early universe [Large UV/Optical Imager] |
Key Decision – Search Strategy

- Choice of the most effective strategy to find Earth-like planets depends on whether they are common or rare.
  - The Frequency of Earth-like Planets (FEP) is currently unknown
    - Earth-mass planets fall below the detection threshold of ground-based observatories.
  - The Kepler and European COROT missions are designed to accurately determine this parameter within the next five years.
  - For planning, FEP is estimated to be at least 10 percent.

- If FEP is 10 percent or greater, the baseline TPF-C/TPF-I strategy is ideal.
  - Terrestrial Planet Finder-Coronagraph (TPF-C) and Terrestrial Planet Finder-Interferometer (TPF-I) each support roadmap objectives and are scientifically complementary.

- If FEP is close to 100 percent, performance requirements could be relaxed or detailed characterization could be emphasized because a nearby Earth analog becomes very likely.

- Although unlikely, if FEP is significantly less than 10 percent, TPF-C does not have enough target stars within its range to detect a useful sample of Earth-mass planets.
Other Decisions

• The planned mission sequence builds knowledge acquisition logically, but other mission sequences will achieve the overall objectives.
  – Space Interferometer Mission (SIM) finds planetary systems.
    • Obtains planetary mass, which is a key physical characteristic.
    • Enriches the target set for Terrestrial Planet Finder (TPF) missions and improves their efficiency.
  – Terrestrial Planet Finder-Coronagraph (TPF-C) measures planet size.
  – Terrestrial Planet Finder-Interferometer (TPF-I) obtains planet temperature.

• The plan recognizes the possibility of setbacks
  – For various reasons, the Frequency of Earth-Like Planets (FEP) might not be successfully measured.
  – Earth-massed planets might be extremely rare — FEP ~ 1 percent or fewer.
  – Programmatic or technical difficulties could degrade the SIM.

• The following chart maps out examples of alternate architectures and the events that would trigger their selection.
  – Specific alternate paths, if needed, would be designed and evaluated based on the driving issues.
Baseline Architecture
Assumes Earth-like planets occur in about 10 percent of systems — FEP ~ 0.1

Alternates 1 & 2
1) Earth-like planets are rare FEP ~ 0.01 or COROT and Kepler fail to measure FEP
2) TPF-C fails on-orbit

Alternate 3
No SIM mission — cancellation or early on-orbit failure

Alternate 4
Early discovery — a nearby Earth-like planet is found by ground-based observations or other means

European

Probe Missions

Add specialized probe missions to characterize the discovery.
Roadmap Interdependencies

• **Science Requirements**
  – A complete set of astrometric data and visible and infrared measurements are needed to fully characterize the planets in orbit around other stars.
    • Maintaining the development pace of the Space Interferometer Mission (SIM), Terrestrial Planet Finder-Coronagraph (TPF-C), and Terrestrial Planet Finder-Interferometer (TPF-I), is key to this requirement.

• **Capability Requirements**
  – Develop the enabling detectors, optics, structures, formation flight, specialized test facilities, and model-augmented verification capabilities identified in the capability roadmaps.
    • Advanced telescopes and observatories
    • Sensors and scientific instruments
    • Advance simulation and modeling

• **Ground Data, Interagency Partnerships, and International Collaborations**
  – Use ground-based observatories to continue the discovery of planetary systems and carry out target star surveys.
  – Partner with the European Space Agency (ESA)’s active planet-finding program.
    • Explore the possibility of a joint TPF-I-Darwin mission.
  – Continue to advance large, lightweight space optics capabilities using dual-use partnerships with the national security community.

• **Future Workforce Requirements**
  – A strong technical workforce, including scientists and engineers, is critical to the sustainable future of the roadmap initiatives.
    • Encourage undergraduate- and graduate-level training in physical sciences, mathematics, and engineering.
Other Information

National Academy of Sciences Decadal Survey:

- Reaffirms the high priority of the Space Interferometer Mission (SIM).
  - Decadal Survey Committees have endorsed SIM.

- Supports the search for planetary systems around nearby stars and the Terrestrial Planet Finder mission as high priorities.
Universe Exploration Summary

**Vision:** Implement a sustained and affordable human and robotic program to explore the solar system and **beyond.**

**Exploring Beyond**
- How did the universe begin?
- How will it end?
- How did we get here?

**Objective:** Explore the universe to understand its **origin, structure, evolution, and destiny.**

**Roadmap achieves the Objective and advances the Vision**

**Origin and Destiny: Beyond Einstein Program**
Objective 1: Determine what powered the Big Bang.
Objective 2: Understand the properties of space, time, and matter at the edge of a black hole.
Objective 3: Investigate dark energy, the mysterious force that is driving apart the cosmos.

**Structure and Evolution: Pathways to Life Program**
Objective 4: Follow the growth of the universe from its infancy to the creation of planets, stars, galaxies, and ultimately life itself.
Universe Exploration Mission Set

Strategic Observatories

- Gamma-ray Large Aperture Space Telescope (GLAST), 2007: Jets from black holes and dark matter decay; signatures of first galaxies and stars
- Laser Interferometer Space Antenna (LISA), 2014: Gravitational waves from many sources; how space and time behave around black holes and constrain dark energy
- Constellation-X (Con-X), 2017: Observe matter falling into black holes and address the mysteries of dark matter and dark energy
- Competed Einstein Probes
  - Joint Dark Energy Probe (JDEM)
  - Black Hole Finder Probe (BHFP)
  - Inflation Probe (IP)
- Vision Missions
  - Big Bang Observer (BBO)
  - Black Hole Imager (BHI)

Pathways to Life

Explorers: Missions linked to universe strategic goals
- Competed Explorer Missions
- Vision Missions
  - Pathways to Life Observatories
## Universe Roadmap Goal Structure

**Agency Strategic Objective:** Explore the universe to understand its origin, structure, evolution, and destiny

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Determine the nature of cosmic inflation by detecting its signature gravitational waves</td>
<td>a) Investigate alternate approaches for the Inflation Probe WMAP, and suborbital</td>
<td>a) Measure gravitational waves from inflation [Inflation Probe]</td>
<td>a) Detect all important sources of gravitational waves since the Big Bang, and directly detect quantum effects during inflation. [Big Bang Observer]</td>
</tr>
<tr>
<td>b) Tighten constraints on inflationary models [Suborbital, WMAP, and Planck]</td>
<td></td>
<td>b) Detect gravitational waves and perhaps radiation from the first picosecond [LISA]</td>
<td></td>
</tr>
</tbody>
</table>

**Roadmap Objective 2: Black Holes**

**Validate the predictions of Einstein’s Theory of General Relativity at the extremes of gravity**

| a) Observe acceleration processes of jets emerging from black holes [GLAST] | a) Investigate General Relativity close to black holes | a) Directly image matter falling into a black hole [Black Hole Imager] |
| b) Determine if General Relativity correctly describes the massive black holes at the centers of galaxies [LISA] | b) Constrain how black holes evolve [Con-X] | b) Investigate stellar mass black hole formation [Black Hole Observer] |
| c) Determine the number of black holes in the local universe [Black Hole Finder Probe] | c) Investigate General Relativity close to black holes | |
| a) Investigate General Relativity close to black holes | b) Constrain how black holes evolve | |
| c) Determine the number of black holes in the local universe | a) Measure precise cosmological parameters, such as global curvature [WMAP] | a) Increases precision of cosmic yardsticks [Con-X] |
| b) Ground observations constrain the nature of dark energy [HST and ground observations] | b) Measure distance measurements to cosmological black holes [LISA] | b) Measure distance measurements to cosmological black holes [LISA] |
| c) Precisely constrains the nature of dark energy [JDEM] | c) Precisely constrains the nature of dark energy [JDEM] | c) Precisely constrains the nature of dark energy [JDEM] |

**Roadmap Objective 3: Dark Energy**

**Determine the ultimate fate of the universe**

| a) Detect hot intergalactic medium (IGM) [Chandra, HST] | a) Confirm baryon content of hot IGM, and dispersion of heavy elements | a) Map missing baryons in the IGM |
| b) Investigate protostellar disks [HST, Chandra, Spitzer, JWST, SOFIA] | b) Probe galactic black holes | b) Understand the factors critical to formation of galaxies, stars, planets, and life |
| c) Characterize the evolution of surface activity of solar-type stars. Understand our “Sun in Time” [Chandra, XMM] | c) Study stellar dynamos and stellar activity [Cox-X] | c) Understand the effects of stellar activity on conditions for emergence of life [Path of Life Observatories] |
| a) Map missing baryons in the IGM | d) Study star formation history [JWST] | d) Study star formation history [JWST] |

**Roadmap Objective 4: Structure and Evolution**

**Determine how the universe grew to contain galaxies, stars, and elements, setting the stage for life**

| a) Confirm baryon content of hot IGM, and dispersion of heavy elements | a) Confirm baryon content of hot IGM, and dispersion of heavy elements | a) Map missing baryons in the IGM |
| b) Investigate protostellar disks [HST, Chandra, Spitzer, JWST, SOFIA] | b) Probe galactic black holes | b) Understand the factors critical to formation of galaxies, stars, planets, and life |
| c) Characterize the evolution of surface activity of solar-type stars. Understand our “Sun in Time” [Chandra, XMM] | c) Study stellar dynamos and stellar activity [Cox-X] | c) Understand the effects of stellar activity on conditions for emergence of life [Path of Life Observatories] |
| d) Study star formation history [JWST] | d) Study star formation history [JWST] | d) Study star formation history [JWST] |
Universe Exploration Timeline

### Beyond Einstein

Objectives 1, 2, & 3

- **Beyond Einstein**
  - PLANCK
  - LISA
  - CHANDRA
  - Con-X
  - GLAST
  - NuSTAR

- Competed Probe Missions
- Competed Explorer Missions

### Pathways to Life

Objective 4

- **Pathways to Life**
  - WISE
  - Con-X
  - JWST
  - Herschel
  - SOFIA

Con-X contributes to both Beyond Einstein and Pathways to Life objectives

Pathways to Life Observatories

- Operations / Support
- Downselect Decision
- Launch Date
- Development / Production
- Operations / Support
Discoveries, primarily during Phase 2, will inform the direction of research emphasis and mission selection for Phase 3.

Option 1

Unexpected detection of a cosmological gravitational wave background by LISA increases priority for the Big Bang Observer.

Option 2

JWST, Constellation-X or other programs discover unexpected objects increasing the priority for Pathways to Life Observatory.

Option 3

Constellation-X and LISA show effects that do not follow the predictions of general relativity and increase the priority for Black Hole Imager.
Capability Roadmap Interdependencies

- Capability Requirements
  - Develop the enabling detectors, optics, structures, and formation flight capabilities identified in the capability roadmaps:
    - Advanced telescopes and observatories
    - Sensors and scientific instruments
    - Advanced simulation and modeling
  - Develop the requisite facilities required to support future universe exploration initiatives.
Universe Exploration Requirements

• **Interagency Partnerships**
  – A cornerstone investigation, the Joint Dark Energy Mission, is dependent on a successful partnership between NASA and the Department of Energy.

• **Future Workforce Requirements**
  – A strong technical workforce, including both scientists and engineers, is critical to the sustainable future of the roadmap initiatives.
    • Encourage undergraduate- and graduate-level training in physical sciences, mathematics, and engineering.
The National Academy of Sciences Decadal Survey identified JWST, GLAST, Constellation-X, LISA, and the Black Hole Finder Probe as high priority missions.

The National Academy Committee, chaired by Michael Turner, prepared a science assessment and research strategy for research, giving high priority to the Dark Energy Probe, Inflation Probe, Con-X, and LISA.

The White House Office of Science and Technology Policy (OSTP) Interagency Working Group (DOE, NASA, and NSF) on “The Physics of the Universe” responded to “Quarks to the Cosmos” and gave high priority to inter-agency collaboration.
ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Exploration Transportation System Strategic Roadmap Committee (the “Committee”), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on developing a new launch system and crew exploration vehicle to provide transportation to and beyond low Earth orbit. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.

2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.

3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation’s space policy.

2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.
ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.

2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.

3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.

4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

________________________________________     __________________
Administrator                      Date
MEMBERSHIP ROSTER

Exploration Transportation System
Strategic Roadmap Committee

Committee Members
Craig E. Steidle, Admiral USN (Ret), NASA Exploration Systems Mission
Directorate, co-chair
James Kennedy, NASA Kennedy Space Center, co-chair
Charles Bolden, Jr., General USMC (Ret), TechTrans International, Inc., co-chair
John Campbell, NASA Goddard Space Flight Center/Wallops Flight Facility
Edward F. Crawley, Massachusetts Institute of Technology
Peter Diamandis, X-Prize Foundation
Delma Freeman, NASA (retired)
Wes Harris, Massachusetts Institute of Technology
Sydney Michael Hudson, Rolls Royce North American (retired)
Tamara Jernigan, Lawrence Livermore National Laboratory
Dave King, NASA Marshall Space Flight Center
Wayne Littles, NASA (retired)
Max Nikias, University of Southern California
Karen Poniatowski, NASA Space Operations Mission Directorate
Robert Sieck, NASA (retired)

Mark Borkowski, Directorate Coordinator
Dana Gould, Advanced Planning and Integration Office Coordinator (LaRC), Designated
Federal Official

Ex Officio and Liaison
Lynn Cline, NASA Space Operations Mission Directorate
Doug Cooke, NASA Exploration Systems Mission Directorate
Lisa Guerra, NASA Exploration Systems Mission Directorate
Susan Hackwood, Executive Director of the California Council on Science and
Technology, liaison with the Education Strategic Roadmap Committee
Colonel Jim Knauf, Secretary of the Air Force, Undersecretary of the Air Force for
Launch, National Security Space liaison
Garry Lyles, NASA Exploration Systems Mission Directorate

Final December 23, 2004
Updated March 28, 2005
ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Nuclear Systems Strategic Roadmap Committee (the “Committee”), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on utilization of nuclear systems for the advancement of space science and exploration. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.

2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.

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MEMBERSHIP ROSTER

Nuclear Systems Strategic Roadmap Committee

Committee Members
Craig E. Steidle, Admiral USN (Ret), NASA Exploration Systems Mission Directorate, co-chair
Chris J. Scolese, NASA Goddard Space Flight Center, co-chair
John F. Ahearne, Sigma Xi Center, Duke University, co-chair
Doug Allen, Schafer Corporation
Ken Anderson, NASA Goddard Space Flight Center
George Apostolakis, Massachusetts Institute of Technology
Dave Bartine, NASA Kennedy Space Center
Stephen Bowen, NASA Johnson Space Center
Theron Bradley, NASA (retired)
Andy Christensen, Northrop Grumman
Tom Gavin, Jet Propulsion Laboratory
Roger Kasparsen, Clark University
Andy Klein, Oregon State
Gerald Kulcinski, University of Wisconsin
Jim Mosquera, Department of Energy
Ted Swanson, NASA Goddard Space Flight Center
Earl Wahlquist, Department of Energy
Ann Whitaker, NASA Marshall Space Flight Center

Perry Bankston, Advanced Planning and Integration Office Coordinator (JPL)
Victoria Friedensen, NASA Exploration Systems Mission Directorate, Designated Federal Official
Jason Jenkins, Directorate Coordinator

Ex Officio and Liaison
Dennis Berry, Department of Energy, Sandia National Laboratories
John-Luc Cambier, Air Force Research Laboratory, National Security Space liaison
Don Cobb, Department of Energy, Los Alamos National Laboratory
Bret Drake, NASA Exploration Systems Mission Directorate
Daniel Gauntner, NASA Glenn Research Center
Lisa Guerra, NASA Exploration Systems Mission Directorate
David Hill, Department of Energy, Oak Ridge National Laboratory
James Lake, Department of Energy, Idaho National Laboratory
Gary Martin, NASA Advanced Planning and Integration Office
Ajay Misra, NASA Science Mission Directorate
Joe Nainiger, NASA Glenn Research Center
Curt Niebur, Jet Propulsion Laboratory
ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Robotic and Human Lunar Exploration Strategic Roadmap Committee (the “Committee”), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on undertaking robotic and human exploration of the Moon to further science and to enable sustained human and robotic exploration of Mars and other destinations. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.

2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.

3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation’s space policy.

2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.
ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.

2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.

3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.

4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

________________________     __________________
Administrator         Date
MEMBERSHIP ROSTER

Robotic and Human Lunar Exploration
Strategic Roadmap Committee

Committee Members
Craig E. Steidle, Admiral USN (Ret), NASA Exploration Systems Mission
Directorate, co-chair
William F. Readdy, NASA Space Operations Mission Directorate, co-chair
Jefferson D. Howell, Jr., General USMC (Ret), Johnson Space Center, co-chair
Thomas P. Stafford, General, USAF (Ret), co-chair
CAPT Bruce Abbott, United States Navy, National Reconnaissance Office
Michael Duke, Colorado School of Mines
Mike Hawes, NASA Space Operations Mission Directorate
James Head, Brown University
Milt Heflin, NASA Johnson Space Center
John Horack, NASA Marshall Space Flight Center
Howard McCurdy, American University
Thomas Morgan, NASA Science Mission Directorate
Firouz Naderi, Jet Propulsion Laboratory
Bradford Parkinson, Stanford University
Donald Pettit, NASA Johnson Space Center
R. Edwin Smylie, Grumman (retired)
Paul Spudis, Applied Physics Laboratory
Tom Tate, House of Representatives Committee on Science and Technology (retired)
Jeff Taylor, University of Hawaii
Brenda Ward, NASA Johnson Space Center

Scott Wilson, Mission Directorate Coordinator, Designated Federal Official
Frank Bauer, Advanced Planning and Integration Coordinator

Ex Officio and Liaison
Doug Cooke, NASA Exploration Systems Mission Directorate
Tom Cremins, NASA Space Operations Mission Directorate
Orlando Figueroa, NASA Science Mission Directorate
James Garvin, NASA Chief Scientist
Lisa Guerra, NASA Exploration Systems Mission Directorate
Tom Jasim, NASA Science Mission Directorate
Michael Lembeck, NASA Exploration Systems Mission Directorate
Wendell Mendell, NASA Johnson Space Center
Cassandra Runyon, College of Charleston, liaison with the Education Strategic
Roadmap Committee
Charlie Stegemoeller, NASA Johnson Space Center
Richard Vondrak, NASA Goddard Space Flight Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
AERONAUTICAL TECHNOLOGIES
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Aeronautical Technologies
Strategic Roadmap Committee (the “Committee”), having determined that it is in the
public interest in connection with the performance of Agency duties under the law, and
with the concurrence of the General Services Administration, pursuant to the Federal
Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to
provide advice and recommendations to NASA on providing advanced
aeronautical technologies to meet the challenges of next-generation systems in
aviation, for civilian and scientific purposes, in our atmosphere and in the
atmospheres of other worlds. Recommendations to be provided by the Committee
will help guide Agency program prioritization, budget formulation, facilities and
human capital planning, and technology investment.

2. The Committee shall function solely as an advisory body and will comply fully
with the provisions of the FACA.

3. The Committee reports to the Associate Deputy Administrator for Systems
Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The
remaining Committee members will be appointed by the ADA-SI. Membership
will be selected to assure a balanced representation of expertise and points of
view within the government, academia, and private industry in scientific and
technological areas relevant to the Nation’s space policy.

2. Members will be appointed for a 15-month term, renewable at the discretion of
the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring
an effort of limited duration. Such subcommittees and/or task forces will report their
findings and recommendations to the Committee. However, if the committee is
terminated, all subcommittees and/or task forces will terminate.
ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.

2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.

3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.

4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.
MEMBERSHIP ROSTER

Aeronautical Technologies
Strategic Roadmap Committee

Committee Members
Terry Hertz, NASA Aeronautics Research Mission Directorate, *co-chair*
Jim Jamieson, The Boeing Company, *co-chair*
Nicholas Altiero, Tulane University
Frank Cappuccio, Lockheed Martin
Randall Friedl, Jet Propulsion Laboratory
Frank Frisbie, Northrop Grumman
Richard Golaszewski, GRA, Incorporated
William Lebegern, Metropolitan Washington Airport Authority
Nancy Levenson, Massachusetts Institute of Technology
John O’Brien, Air Line Pilots Association
Col Stuart Rodgers, Air Force Research Laboratory
Nick Sabatini, Federal Aviation Administration
Roger Wall, FedEx Corporation
Terry Weisshaar, Defense Advanced Research Projects Agency

Yuri Gawdiak, Mission Directorate Coordinator, *Designated Federal Official*
Vicki Regenie, Advanced Planning and Integration Office Coordinator (JPL)

Ex Officio and Liaison
Rich Christiansen, NASA Glenn Research Center
Tom Edwards, NASA Ames Research Center
Bob Meyer, NASA Dryden Flight Research Center
Jerry Newsom, NASA Langley Research Center
Mary Ann Thompson, Aerospace Foundation, liaison with the Education Strategic Roadmap Committee

*Draft 2/4/05*
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
EARTH SCIENCE AND APPLICATIONS FROM SPACE
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Earth Science and Applications from Space Strategic Roadmap Committee (the “Committee”), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on research and technology development to advance Earth observation from space, improving scientific understanding, and demonstrating new technologies with the potential to improve future operational systems. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.

2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.

3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation’s space policy.

2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.
ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.

2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.

3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.

4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

________________________     __________________
Administrator         Date
MEMBERSHIP ROSTER

Earth Science and Applications from Space
Strategic Roadmap Committee

Committee
Orlando Figueroa, NASA Science Mission Directorate, *co-chair*
Diane Evans, Jet Propulsion Laboratory, *co-chair*
Charles Kennel, Scripps Institution of Oceanography, *co-chair*
Waleed Abdalati, Goddard Space Flight Center
Leopold Andreoli, Northrop Grumman Space Technology
Walter Brooks, Ames Research Center
Jack Dangermond, ESRI
William Gail, Vexcel Corporation
Colleen Hartman, National Oceanic and Atmospheric Administration
Christian Kummerow, Colorado State University
Joyce Penner, University of Michigan
Douglas Rotman, Lawrence Livermore National Laboratory
David Siegel, University of California, Santa Barbara
David Skole, Michigan State University
Sean Solomon, Carnegie Institution of Washington
Victor Zlotnicki, Jet Propulsion Laboratory

Gordon Johnston, Mission Directorate Coordinator, *Designated Federal Official*
Azita Valinia, Advanced Planning and Systems Integration Coordinator

Ex Officio and Liaison
Roberta Johnson, University Corporation for Atmospheric Research, liaison
with the Education Strategic Roadmap Committee

*Final December 17, 2004*
*Updated March 28, 2005*
ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Sun-Solar System Connection Strategic Roadmap Committee (the “Committee”), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on exploring the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.

2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.

3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation’s space policy.

2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.
ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.

2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.

3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.

4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

________________________     __________________
Administrator         Date
MEMBERSHIP ROSTER

Sun-Solar System Connection
Strategic Roadmap Committee

Committee Members
Al Diaz, NASA Science Mission Directorate, co-chair
Franco Einaudi, NASA Goddard Space Flight Center, co-chair
Thomas E. Moore, NASA Goddard Space Flight Center, co-chair
Timothy Killeen, National Center for Atmospheric Research, co-chair
Scott Denning, Colorado State University
Jeffrey Forbes, University of Colorado
Stephen Fuselier, Lockheed Martin
William C. Gibson, Southwest Research Institute
Donald Hassler, Southwest Research Institute
Todd Hoeksema, Stanford University
Craig Kletzing, University of Iowa
Edward Lu, NASA Johnson Space Center
Victor Pizzo, National Oceanic and Atmospheric Administration
James Russell, Hampton University
James Slavin, NASA Goddard Space Flight Center
Michelle Thomsen, Los Alamos National Laboratory
Warren Wiscombe, NASA Goddard Space Flight Center

Barbara Giles, Mission Directorate Coordinator, Designated Federal Official
Azita Valinia, Advanced Planning and Integration Office Coordinator (GSFC)

Ex Officio and Liaison
Donald Anderson, NASA Science Mission Directorate
Alan Shaffer, Office of the Secretary of Defense, Network Information Integration, National Security Space liaison
Richard Fisher, NASA Science Mission Directorate
Rosamond Kinzler, American Museum of Natural History, liaison with Education Strategic Roadmap Committee
Michael Wargo, NASA Exploration Systems Mission Directorate
Mark Weyland, NASA Johnson Space Center

Final 12/22/04
Updated 3/14/05
ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Robotic and Human Exploration of Mars Strategic Roadmapping Committee (the “Committee”), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on Mars exploration, including robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. The purview of the Committee also includes advice and recommendations on human expeditions to Mars after acquiring adequate knowledge about the planet using these robotic missions and after successfully demonstrating sustained human exploration missions to the Moon. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.

2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.

3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation’s space policy.

2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.
SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.

2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.

3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.

4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

________________________     __________________
Administrator         Date
MEMBERSHIP ROSTER

Robotic and Human Exploration of Mars Strategic Roadmap Committee

Committee Members
Alphonso Diaz, NASA Science Mission Directorate, *co-chair*
Charles Elachi, Jet Propulsion Laboratory, *co-chair*
A. Thomas Young, Lockheed Martin (retired), *co-chair*
Ray Arvidson, Washington University
Robert Braun, Georgia Institute of Technology
James Cameron, producer/writer/director
Aaron Cohen, Texas A & M University
Steven Dorfman, Hughes Electronics (retired)
Linda Godwin, NASA Johnson Space Center
Noel Hinners, Lockheed Martin (retired)
Kent Kresa, Northrop Grumman
Gentry Lee, Jet Propulsion Laboratory
Laurie Leshin, Arizona State University
Shannon Lucid, NASA Johnson Space Center
Paul Mahaffy, NASA Goddard Space Flight Center
Christopher McKay, NASA Ames Research Center
Sally Ride, University of California, San Diego
Lawrence Soderblom, U.S. Geological Survey
Steven Squyres, Cornell University
Margaret (Peggy) Whitson, NASA Johnson Space Center

*Michael Meyer, Directorate Coordinator, Designated Federal Official*
Judith Robey, Advanced Planning and Integration Office Coordinator

*Ex Officio and Liaison*
Douglas Cooke, NASA Exploration Systems Mission Directorate
Orlando Figueroa, NASA Science Mission Directorate
James Garvin, NASA Chief Scientist
William Gerstenmaier, NASA Johnson Space Center
Michael Hawes, NASA Space Operations Mission Directorate
Daniel McCleese, Jet Propulsion Laboratory
Douglas McCuistion, NASA Science Mission Directorate
Firouz Naderi, Jet Propulsion Laboratory
Michelle Viotti, Jet Propulsion Laboratory, liaison with the Education Strategic Roadmap Committee Liaison
Joseph Wood, NASA Advanced Planning and Systems Integration Office
ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Solar System Exploration Strategic Roadmap Committee (the “Committee”), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on conducting robotic exploration across the solar system to search for evidence of life, to understand the history of the solar system, to search for resources, and to support human exploration. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation’s space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.
ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.

2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.

3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.

4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

________________________     __________________
Administrator         Date
MEMBERSHIP ROSTER

Solar System Exploration
Strategic Roadmap Committee

Committee Members
Orlando Figueroa, NASA Science Mission Directorate, co-chair
G. Scott Hubbard, NASA Ames Research Center, co-chair
Jonathan Lunine, University of Arizona Lunar and Planetary Laboratory, co-chair
Andrew B. Christensen, Northrop Grumman
Jerry Chodil, Ball Aerospace (retired)
Ben Clark, Lockheed Martin Astronautics
Greg Davidson, Northrop Grumman
David DesMarais, NASA Ames Research Center
Douglas Erwin, National Museum of Natural History
Wes Huntress, Carnegie Institution of Washington
Torrence V. Johnson, Jet Propulsion Laboratory
Thomas D. Jones, Consultant
Melissa McGrath, NASA Marshall Space Flight Center
Karen Meech, University of Hawaii
John Niehoff, Science Applications International Corporation
Robert Pappalardo, University of Colorado
Ellen Stofan, Proxemy Research, Inc.
Meenakshi Wadhwa, The Field Museum

Carl Pilcher, Directorate Coordinator, Designated Federal Official
Judith Robey, Advanced Planning and Integration Office Coordinator

Ex Officio and Liaison
Andrew Dantzler, NASA Science Mission Directorate
Heidi Hammell, Space Science Institute, Education Roadmap Committee Liaison
Chris Jones, Jet Propulsion Laboratory
Jason Jenkins, NASA Exploration Systems Mission Directorate

Final 12/22/04
Updated 3/4/05
ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Search for Earth-like Planets Strategic Roadmap Committee (the “Committee”), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on searching for Earth-like planets and habitable environments around other stars using advanced telescopes. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.

2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.

3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation’s space policy.

2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.
ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.

2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.

3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.

4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

________________________     __________________
Administrator         Date
MEMBERSHIP ROSTER

Search for Earth-like Planets
Strategic Roadmap Committee

Committee Members
Ghassem Asrar, NASA Science Mission Directorate, co-chair
Adam Burrows, University of Arizona, co-chair
David Spergel, Princeton University, co-chair
Jerry Chodil, Ball Aerospace (retired)
Tom Greene, NASA Ames Research Center
Maureen Heath, Northrop Grumman Space Technology
John Mather, NASA Goddard Space Flight Center
Victoria Meadows, Jet Propulsion Laboratory
Geoff Marcy, University of California
Frank Martin, Lockheed Martin (retired)
Neil Tyson, American Museum of Natural History
Alycia Weinberger, Observatories of the Carnegie Institution of Washington

Eric P. Smith, Directorate Coordinator, Designated Federal Official
Rich Capps, Advanced Planning and Integration Office Coordinator (JPL)

Ex Officio and Liaison
Charles Beichman, Jet Propulsion Laboratory
Mike Devirian, Jet Propulsion Laboratory
Edna Devore, SETI, liaison with the Education Strategic Roadmap Committee
Anne Kinney, NASA Science Mission Directorate
Col Steve Petersen, National Reconnaissance Office, National Security Space liaison

Final 12/6/04
Updated 3/29/05
ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Universe Exploration Strategic Roadmap Committee (the “Committee”), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on exploring our Universe to understand its origin, structure, evolution, and destiny. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.

2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.

3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation’s space policy.

2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.
ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.

2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.

3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.

4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.
MEMBERSHIP ROSTER

Universe Exploration Strategic Roadmap Committee

Committee Members
Anne Kinney, NASA Science Mission Directorate, co-chair
Nick White, NASA Goddard Space Flight Center, co-chair
Kathy Flanagan, Massachusetts Institute of Technology, co-chair
Chuck Bennett, NASA Goddard Space Flight Center
Craig Hogan, University of Washington
Steve Kahn, Stanford University, Stanford Linear Accelerator Center
Rene Ong, University of California, Los Angeles
Sterl Phinney, California Institute of Technology
Ron Polidan, Northrop Grumman Space Technology
Michael Shull, University of Colorado
Bob Stern, Lockheed Martin
Michael Turner, National Science Foundation
Jakob van Zyl, Jet Propulsion Laboratory

Michael Salamon, Mission Directorate Coordinator, Designated Federal Official
Rich Capps, Advanced Planning and Integration Office Coordinator (JPL)

Ex Officio and Liaison
Louis Barbier, NASA Goddard Space Flight Center
Roy Gould, Harvard Center for Astrophysics, liaison with the Education Roadmap Committee
Steve Maran, American Astronomical Society
Colonel Steve Petersen, National Reconnaissance Office, National Security Space liaison

Final 12/17/04
Updated 2/3/05
ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Space Shuttle Strategic Roadmap Committee (the “Committee”), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on returning the Space Shuttle to flight, completing assembly of the International Space Station, and safely transitioning from the Space Shuttle to a new exploration transportation system. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.

2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.

3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation’s space policy.

2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.
ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.

2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.

3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.

4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

________________________     __________________
Administrator         Date
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
INTERNATIONAL SPACE STATION
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA International Space Station Strategic Roadmap Committee (the “Committee”), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on completing assembly of the International Space Station and focusing research on supporting space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.

2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.

3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation’s space policy.

2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

DRAFT 12/1/2004
ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.

2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.

3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.

4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

________________________________________  ______________________
Administrator                                    Date
MEMBERSHIP ROSTER

International Space Station
Strategic Roadmap Committee

Committee Members
Mark Uhran, NASA Space Operations Mission Directorate, co-chair
Robert Cabana, NASA Johnson Space Center, co-chair
Thomas C. Betterton, Admiral USN (Ret), Naval Postgraduate School, co-chair
John-David Bartoe, NASA Johnson Space Center
William Bastedo, Booz Allen Hamilton
Jon Bryson, Aerospace Corporation (retired)
Nick Kanas, University of California at San Francisco
Terri Lomax, NASA Exploration Systems Mission Directorate
Ronald Merrell, Virginia Commonwealth University
Charles Oman, Massachusetts Institute of Technology
Jeffrey Sutton, National Space Biomedical Research Institute
Charles Walker, Boeing Aerospace Corporation

Michele Gates, Directorate Coordinator
Stacey Edgington, Advanced Planning and Integration Office Coordinator, Designated Federal Official

Ex Officio and Liaison
Michael Lembeck, NASA Exploration Systems Mission Directorate
Edward Lu, NASA Johnson Space Center
Marlene MacLeish, Morehouse School of Medicine, liaison with Education Strategic Roadmap Committee
Richard Williams, NASA Chief Medical Officer

Final January 24, 2005
Updated February 17, 2005
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
EDUCATION STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Education Strategic Roadmap Committee (the “Committee”), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on using NASA missions and other activities to inspire and motivate the nation’s students and teachers, to engage and educate the public, and to advance the nation’s scientific and technological capabilities. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.

2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.

3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation’s space policy.

2. Members will be appointed for a 21-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.
ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 21-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.

2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.

3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.

4. The operating costs for its expected duration of 21 months are estimated to be $500,000 including 1.0 work years of staff support.

DURATION

The Committee shall terminate 21 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

____________________________________  ____________________
Administrator                             Date
MEMBERSHIP ROSTER

Education Roadmap Committee

Committee
Adena Williams Loston, NASA Chief Education Officer, co-chair
Julian Earls, NASA Glenn Research Center, co-chair
France A. Córdova, University of California, Riverside, co-chair
Edna DeVore, SETI Institute
Roy Gould, Harvard Center for Astrophysics
Susan Hackwood, California Council on Science and Technology
Heidi Hammel, Space Science Institute
Roberta Johnson, University Corporation for Atmospheric Research
Wayne C. Johnson, Hewlett-Packard
Douglas R. King, St. Louis Science Center
Rosamond Kinzler, American Museum of History
Lt. Col. Timothy Lea, National Security Space
Marlene MacLeish, Morehouse University
Jeff Rosendhal, NASA (retired)
Cassandra Runyon, College of Charleston
Mary Anne Thompson, Aerospace Education Foundation
Michelle Viotti, Jet Propulsion Laboratory

Shelley Canright, Directorate Coordinator, Designated Federal Official
Ashley Stockinger, Advanced Planning and Integration Office Coordinator

Ex Officio and Liaison
Bill Anderson, NASA Education Division
Larry Bilbrough, NASA Education Division
Katie Blanding, NASA Education Division
Larry Cooper, NASA Education Division
Jason Freeman, NASA Education Division
Angie Johnson, NASA Education Division
Mayra Montrose, NASA Exploration Systems Division
Nitin Naik, NASA Assistant Chief Technology Officer
Melissa Riesco, NASA Office of Human Capital Management
Carla Rosenberg, NASA Education Division
James Stofan, NASA Education Division
Ming-Ying Wei, NASA Education Division

Staff
(as identified)
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>AAMP</td>
<td>Auroral Acceleration Multi-Probe</td>
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<td>AIM</td>
<td>Aeronomy of Ice in the Mesosphere</td>
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<td>AOA</td>
<td>Analysis of Alternative</td>
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<td>Advanced Planning and Integration Office</td>
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<td>ATM</td>
<td>Air Traffic Management</td>
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<td>ATS</td>
<td>Application Technology Satellite</td>
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<td>BBO</td>
<td>Big Bang Observer</td>
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<td>Bio</td>
<td>Biological</td>
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<td>BHFP</td>
<td>Black Hole Finder Probe</td>
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<td>BHI</td>
<td>Black Hole Imager</td>
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<td>Committee on Environment and Natural Resources</td>
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<td>CEV</td>
<td>Crew Exploration Vehicle</td>
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<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>Communication, Navigation, and Surveillance</td>
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<td>Climate Change Technology Program</td>
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<td>Constellation X</td>
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<td>EDL</td>
<td>Entry, Descent, and Landing</td>
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<td>Evolved Expendable Launch Vehicle</td>
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<td>EME</td>
<td>Electromagnetic Effects</td>
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<td>Exploration Systems Mission Directorate</td>
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<td>E-STOL</td>
<td>Extreme Short Takeoff and Landing</td>
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<td>EVA</td>
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<td>Frequency of Earth-Like Planets</td>
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<td>Group on Earth Observations</td>
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GLAST  Gamma-ray Large Area Space Telescope
GOS   Geospatial One-Stop
GPM   Global Precipitation Measurement
GRC   Glenn Research Center
HEO   High-Earth Orbit
HIGO  Heliospheric Imager and Galactic Observer
HST   Hubble Space Telescope
IFR   Instrument Flight Rules
IGM   Intergalactic Medium
IHS   Inner Heliospheric Sentinels
IOC   Initial Operational Capability
IP    Inflation Probe
IP    Interstellar Probe
IPCC  Intergovernmental Panel on Climate Change
IR    Infrared
ITSP  Ionosphere-Thermosphere Storm Probes
ISRU  In Situ Resource Utilization
ISS   International Space Station
ITAR  International Traffic in Arms Regulations
ITImager Ionosphere-Thermosphere Imager
ITMC  Ionosphere-Thermosphere-Mesosphere Coupler
ITMW  Ionosphere-Thermosphere-Mesosphere Waves
IWGEO Interagency Working Group on Earth Observations
JDEM  Joint Dark Energy Mission
JIMO  Jupiter Icy Moons Orbiter
JPO   Jupiter Polar Orbiter
JWST  James Webb Space Telescope
KBO   Kuiper Belt Object
KSC   Kennedy Space Center
LCDM  Landsat Continuity Data Mission
LEAG  Lunar Exploration Analysis Group
LEO   Low Earth Orbit
LF    Life Finder
LISA  Laser Interferometer Space Antenna
LRO   Lunar Reconnaissance Orbiter
LUVO  Large Ultraviolet Visible Observatory
LV    Launch Vehicle
ManPADS Man Portable Air Defense System
MC    Magnetospheric Constellation
MMS   Magnetospheric Multi-Scale
MSFC  Marshall Space Flight Center
MSL   Mars Science Laboratory
MSR   Mars Sample Return
MT    Metric Ton
MTRAP Magnetic Transition Region Probe
Nano  Nanotechnology
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<th>Acronym</th>
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<tr>
<td>NAS</td>
<td>National Airspace System</td>
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<td>NavCom</td>
<td>Navigation and Communications</td>
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<td>NEO</td>
<td>Near-Earth Object</td>
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<td>NEP</td>
<td>Nuclear Electric Propulsion</td>
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<td>NEPA</td>
<td>National Environmental Policy Act</td>
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<td>NO</td>
<td>Neptune Orbiter</td>
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<td>NPOESS</td>
<td>National Polar-Orbiting Environmental Satellite System</td>
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<td>NSF</td>
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<td>National Science and Technology Council</td>
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<td>Operational Evolution Plan</td>
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<td>Operational Land Imager</td>
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<td>OSTM</td>
<td>Ocean Surface Topography Mission</td>
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<td>OSTP</td>
<td>White House Office of Science and Technology Policy</td>
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<td>R&amp;A</td>
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<td>R&amp;D</td>
<td>Research and Development</td>
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<td>RIA</td>
<td>Runway Independent Aircraft</td>
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<td>RPS</td>
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<td>Solar Probe</td>
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<td>SPAB</td>
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<td>Sun-Earth Coupling by Energetic Particles</td>
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<td>Strategic Roadmap</td>
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<td>SWB</td>
<td>Solar Wind Buoys</td>
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<td>Time History of Events and Macroscale Interactions during Substorms</td>
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<td>TPF</td>
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<td>Terrestrial Planet Finder-Interferometer</td>
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<td>Technology Readiness Levels</td>
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<td>Thermal Protection System</td>
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<td>UAV</td>
<td>Unmanned Aerial Vehicle</td>
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<td>VAP</td>
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<td>VIIRS</td>
<td>Visible/Infrared Imager/Radiometer Suite</td>
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<td>Wilkinson Microwave Anisotropy Probe</td>
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<td>World Summit on Sustainable Development</td>
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<td>Wx</td>
<td>Weather</td>
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<td>XMM</td>
<td>X-Ray Multi-Mirror</td>
</tr>
</tbody>
</table>
Contact List

Please contact the following individuals for more information:

**Strategic Roadmap Committees**

Dr. Marc Allen, Team Lead  
(202) 358-0733  
marc.allen@nasa.gov

<table>
<thead>
<tr>
<th>Committee</th>
<th>Designated Federal Official</th>
<th>Phone</th>
<th>Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robotic and Human Lunar Exploration</td>
<td>Scott Wilson</td>
<td>(202) 358-3924</td>
<td><a href="mailto:Scott.wilson-1@nasa.gov">Scott.wilson-1@nasa.gov</a></td>
</tr>
<tr>
<td>Robotic and Human Exploration of Mars</td>
<td>Dr. Michael Meyer</td>
<td>(202) 358-0307</td>
<td><a href="mailto:Michael.a.meyer@nasa.gov">Michael.a.meyer@nasa.gov</a></td>
</tr>
<tr>
<td>Solar System Exploration</td>
<td>Dr. Carl Pilcher</td>
<td>(202) 358-0291</td>
<td><a href="mailto:Carl.b.pilcher@nasa.gov">Carl.b.pilcher@nasa.gov</a></td>
</tr>
<tr>
<td>Search for Earth-like Planets</td>
<td>Dr. Eric P. Smith</td>
<td>(202) 358-2439</td>
<td><a href="mailto:Eric.p.smith@nasa.gov">Eric.p.smith@nasa.gov</a></td>
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<tr>
<td>Exploration Transportation</td>
<td>Dana Gould</td>
<td>(757) 864-7747</td>
<td><a href="mailto:Dana.c.gould@nasa.gov">Dana.c.gould@nasa.gov</a></td>
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<tr>
<td>Universe Exploration</td>
<td>Dr. Michael Salamon</td>
<td>(202) 358-0441</td>
<td><a href="mailto:Michael.h.salamon@nasa.gov">Michael.h.salamon@nasa.gov</a></td>
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<tr>
<td>Earth Science and Applications from Space</td>
<td>Dr. Gordon Johnston</td>
<td>(202) 358-4685</td>
<td><a href="mailto:Gordon.johnston@nasa.gov">Gordon.johnston@nasa.gov</a></td>
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<tr>
<td>Sun-Solar System Connection</td>
<td>Dr. Barbara Giles</td>
<td>(202) 358-1762</td>
<td><a href="mailto:Barbara.giles@nasa.gov">Barbara.giles@nasa.gov</a></td>
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<tr>
<td>Aeronautical Technologies</td>
<td>Yuri Gawdiak</td>
<td>(202) 358-1853</td>
<td><a href="mailto:Yuri.o.gawdiak@nasa.gov">Yuri.o.gawdiak@nasa.gov</a></td>
</tr>
<tr>
<td>Nuclear Systems</td>
<td>Victoria Friedensen</td>
<td>(202) 358-1916</td>
<td><a href="mailto:Victoria.p.friedensen@nasa.gov">Victoria.p.friedensen@nasa.gov</a></td>
</tr>
</tbody>
</table>
## Capabilities Roadmap Teams

Rita Willcoxon, Team Lead  
(321) 867-7771  
[rita.g.willcoxon@nasa.gov](mailto:rita.g.willcoxon@nasa.gov)

<table>
<thead>
<tr>
<th>Roadmap</th>
<th>Expert</th>
<th>Phone</th>
<th>Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Energy Power and Propulsion</td>
<td>Joe Naniger</td>
<td>216-977-7103</td>
<td><a href="mailto:joseph.j.nainiger@nasa.gov">joseph.j.nainiger@nasa.gov</a></td>
</tr>
<tr>
<td>In-Space Transportation</td>
<td>Paul McConnaughey</td>
<td>256-544-1599</td>
<td><a href="mailto:paul.k.mcconnaughey@nasa.gov">paul.k.mcconnaughey@nasa.gov</a></td>
</tr>
<tr>
<td>Advanced Telescopes and Observatories</td>
<td>Lee Feinberg</td>
<td>301-286-5923</td>
<td><a href="mailto:lee.d.feinberg@nasa.gov">lee.d.feinberg@nasa.gov</a></td>
</tr>
<tr>
<td>Communication and Navigation</td>
<td>Bob Spearing</td>
<td>202-358-4780</td>
<td><a href="mailto:bob.spearing@nasa.gov">bob.spearing@nasa.gov</a></td>
</tr>
<tr>
<td>Robotic Access to Planetary Surface</td>
<td>Mark Adler</td>
<td>818-354-6277</td>
<td><a href="mailto:mark.adler@quest.jpl.nasa.gov">mark.adler@quest.jpl.nasa.gov</a></td>
</tr>
<tr>
<td>Human Planetary Landing Systems</td>
<td>Rob Manning</td>
<td>818-393-7815</td>
<td><a href="mailto:robert.m.manning@jpl.nasa.gov">robert.m.manning@jpl.nasa.gov</a></td>
</tr>
<tr>
<td>Human Health &amp; Support Systems</td>
<td>Dennis Grounds</td>
<td>281-483-6338</td>
<td><a href="mailto:dennis.j.grounds@nasa.gov">dennis.j.grounds@nasa.gov</a></td>
</tr>
<tr>
<td>Human Exploration Systems and Mobility</td>
<td>Christopher Culbert</td>
<td>281-483-8080</td>
<td><a href="mailto:christopher.j.culbert@nasa.gov">christopher.j.culbert@nasa.gov</a></td>
</tr>
<tr>
<td>Autonomous Systems Robotics and Computing</td>
<td>James Crawford</td>
<td>650-604-1139</td>
<td><a href="mailto:jcrawford@arc.nasa.gov">jcrawford@arc.nasa.gov</a></td>
</tr>
<tr>
<td>Transformational Spaceport and Range</td>
<td>Karen Poniatowski</td>
<td>202-358-2469</td>
<td><a href="mailto:karen.s.poniatowski@nasa.gov">karen.s.poniatowski@nasa.gov</a></td>
</tr>
<tr>
<td>Scientific Instruments and Sensors</td>
<td>Richard Barney</td>
<td>301-286-9588</td>
<td><a href="mailto:richard.d.barney@nasa.gov">richard.d.barney@nasa.gov</a></td>
</tr>
<tr>
<td>In-situ Resource Utilization</td>
<td>Gerry Sanders</td>
<td>281-483-9066</td>
<td></td>
</tr>
<tr>
<td>Advanced Modeling and Simulation</td>
<td>Erik Antonsson</td>
<td>818-393-7600</td>
<td><a href="mailto:ekantons@mail.jpl.nasa.gov">ekantons@mail.jpl.nasa.gov</a></td>
</tr>
<tr>
<td>Systems Engineering Cost Risk analysis</td>
<td>Steve Cavanaugh</td>
<td>757-864-7019</td>
<td><a href="mailto:stephen.cavanaugh-1@nasa.gov">stephen.cavanaugh-1@nasa.gov</a></td>
</tr>
<tr>
<td>Nanotechnology</td>
<td>Murray Hirschbein</td>
<td>202-358-4662</td>
<td><a href="mailto:murray.s.hirschbein@nasa.gov">murray.s.hirschbein@nasa.gov</a></td>
</tr>
<tr>
<td></td>
<td>Minoo Dastoor</td>
<td>202-358-4518</td>
<td><a href="mailto:minoo.n.dastoor@nasa.gov">minoo.n.dastoor@nasa.gov</a></td>
</tr>
</tbody>
</table>