VISIONARY CHALLENGES OF
NASA STRATEGIC ENTERPRISES
FOR THE
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OFFICE OF SPACE FLIGHT VISIONARY CHALLENGES (CODE M)

The Visionary Challenge for the Space Flight Enterprise is to make possible ***the safe, affordable and effective human/robotic exploration and development of our solar system – and eventually space beyond our solar system***. In order to achieve this Visionary Challenge, we must:

1. **Create concepts, technologies, and capabilities for space transportation that enable affordable future infrastructures.**

2. **Develop innovative concepts for systems, infrastructures and missions to extend the duration and boundaries of human space flight.**

3. **Create novel aerospace concepts and technology to support future sustainable human and robotic exploration and development of space.**

Achieving these "visionary challenges" requires the development of revolutionary new concepts and technologies that satisfy the following strategic technical challenges.

<u>Nearer-Term Challenges (<2025):</u>

- **<u>Self-Sufficient Space Systems</u>**. Operation of diverse future space systems with increasing levels of self-sufficiency, including increasing autonomy vis-à-vis ground-based command and control, increasing independence vis-à-vis subsystem integration, check-out and test, and diminishing reliance on logistics provided from the Earth.
  - <u>Advanced Platform Systems</u>. Exceptionally reliable, flexible and affordable modular Platform Systems for application in a wide range of

  future systems and missions to enable ambitious human/robotic research, discovery and exploration in space.

  - Intelligent Operations. Exceptionally high levels of on-board intelligence (hardware and software) that can reduce dramatically the costs of future mission operations while improving effectiveness and reliability.
  - In Situ Manufacturing. Affordable and flexible local manufacture of robust, high-value components, systems elements, and systems (e.g., structural elements, tankage, solar arrays, spare parts for systems, etc.) in lunar and planetary venues using 'imported' and local materials.
  - Surface Construction. Affordable and flexible construction of robust local structures (e.g., radiation shielding, habitats, transportation infrastructures, etc.) in lunar and planetary venues using local (or 'imported') materials.
  - In Situ Resource Extraction and Processing. Affordable, reliable and effective local production, using local materials of key mission/systems resources (including life support system consumables, propellants, etc.).
  - Consumable and Volatiles Distribution. Affordable, reliable and effective local management, handling, transport and storage of key consumables and volatiles.

- **Space Utilities and Power**. Increasing dramatically the levels of affordable energy and/or power in space for a wide range of systems and mission applications and within diverse relevant environments—including power generation and transmission and energy storage.
  - Solar Power Generation. Highly-efficient, affordable generation of electrical power from sunlight, from very small arrays (watts) up to exceptionally high power levels (megawatts) for use in a wide range of in space, lunar and planetary environments.
  - Nuclear Power Generation. Safe, efficient and affordable generation of heat and/or electrical power from nuclear systems (radioisotopes and reactors), from very small arrays (watts) up to exceptionally high power levels (megawatts) for use in a wide range of in space, lunar and planetary environments.
  - Wireless Power Transmission. Safe, reliable and efficient wireless transport of substantial amounts of energy, as needed, for applications ranging from internal power (e.g., board level), to local power (meters or less), to remote power (10s to 1000s of kilometers).
  - Cryogenic Propellant Depots. Long-duration, low-loss transfer, management and storage of key cryogens, including hydrogen, for use in a wide variety of gravitational and other environments.
  - Power Management and Distribution. Modular, intelligent power management and distribution (PMAD) systems capable of local integration and reconfiguration that can autonomously synthesize power

    from multiple sources and distribute it with low losses to multiple ‘users’ as needed.

  - Energy Storage. Long-duration/long-cycle life Energy Storage for space applications ranging from exceptionally small systems (watts-electric or less, and watt-hours or less) up to very large systems (kilowatts or more, and kilowatt-hours or more).
  - Thermal Materials and Management. Reliable, light-weight Thermal Materials (for high- to low- temperature components) and Management (waste heat rejection for low- to high- energy systems) for space applications ranging from exceptionally small systems (watts-thermal or less) up to very large systems (kilowatts or more, and kilowatt-hours or more) in a space environments ranging from low Earth orbit, through the Earth’s Neighborhood (including the Moon), Mars, and small bodies.
  - Structural Concepts and Materials. Robust, reliable and high strength-to-weight Structural Concepts and Materials for application within future systems—particularly involving high energy space systems—enabling ambitious future human/robotic systems and missions.
  - Space Environmental Effects. Understand the Environmental Effects to be experienced by humans and systems during future in-space mission operations—and pursue mitigation of those effects to allow safe, affordable and effective research, discovery and exploration.
- **Habitation, Bioastronautics, and EVA**. Safe, affordable and highly-effective humans-in-space systems, incorporating the concept of ambitious human/robotic team operations in a diverse range of appropriate environments, including low Earth orbit, the Earth’s Neighborhood, and beyond.
  - Extravehicular Activity Systems. Safe, highly-effective and locally-maintainable Extravehicular Activity (EVA) systems for application in the context of capable human-robotic teams—in venues ranging from low Earth orbit to planetary surfaces.
  - Habitats, Habitability, and Human Factors. Safe and affordable provision of substantial habitable volume across a wide range of environments for human/robotic team operations in low Earth orbit, the Earth’s Neighborhood and venues beyond (including the neighborhood and surface of Mars).
  - Life Support, Environmental Monitoring and Control. Low mass, highly efficient and reliable Life Support, Environmental Monitoring and Control technologies to enable safe and affordable human presence and activities in low Earth orbit, the Earth’s Neighborhood (including the Moon) and venues beyond(including the neighborhood and surface of Mars).
  - Space Medicine & Health Care Systems. Safe, affordable and affective delivery of advanced, increasingly autonomous Space Medicine and Health Care systems.

  - Adaptation and Countermeasures (Microgravity). Understanding of the mechanisms of Adaptation to the microgravity environment, as well as potential countermeasures.
  - Biological Risk Prediction / Mitigation (Radiation). Understanding of the mechanisms of Biological Risk due to the radiation environment in, as well as candidate mitigation approaches.
- **Space Assembly, Maintenance, and Servicing**. Enable the machine side of safe, affordable and effective human/robotic team operations in a diverse range of appropriate environments, including low Earth orbit, the Earth's Neighborhood, and beyond..
  - Robotic/Telerobotic Advanced Concepts. Timely identification, investigation and assessment of novel, high-value Robotic and Telerobotic Advanced Concepts of very high potential value to ambitious operations for future human/robotic research, discovery and exploration in space – including analytical and experimental validation.
  - In-Space Assembly and Construction. Affordable and flexible In-Space Assembly and Construction of robust local structural systems (e.g., large arrays, observatories, habitats, transportation infrastructures, etc.) at various in-space venues using local (or 'imported') materials.
  - In-Space System Deployment. Fault-tolerant, reliable and affordable deployment of diverse future in-space systems, over a wide range of sizes and levels of complexity for future human/robotic missions and operations.
  - Self-Assembling Systems. Exceptionally flexible "systems of systems" capable of robust, reliable, affordable and largely autonomous Self-Assembly, Repair and Reconfiguration within increasingly-capable future systems and architectures for human and robotic research, exploration and discovery in space.
  - Inspection & Diagnostics. Safe, affordable and informative Inspection and Diagnostics of the full suite of potential future systems (including instruments and observatories, platforms and habitats, transportation systems in supporting infrastructure, etc.) for a diverse suite of future human/robotic system and mission operations in venues ranging for low Earth orbit, throughout the Earth's Neighborhood (including the Moon) and to destinations beyond (including the neighborhood and surface of Mars).
  - Servicing, Maintenance & Repair. Reliable, affordable, timely and effective Servicing, Maintenance & Repair of a broad range of future space systems, involving both human and robotic teams (in mixtures as appropriate to the challenge), and in venues including Earth orbit, the Earth Neighborhood (including the Moon), and beyond.
  - "Design for SAMS" (Architectures, Standards and Infrastructures). Timely availability of novel design Architectures and Standards to enable

  the cost-effective development and validation of novel Infrastructures for Space Assembly, Maintenance and Servicing to support a range of ambitious future human/robotic system and mission operations in venues ranging for low Earth orbit, throughout the Earth's Neighborhood (including the Moon) and to destinations beyond (including the neighborhood and surface of Mars).

- **Surface Exploration and Expeditions**. Safe, affordable and effective research, discovery and exploration operations at a range of surface environments, including the Moon, Mars, and other relevant targets of interest (e.g., Near-Earth Objects).
  - Mobile Surface Systems. Highly robust, intelligent and long-range Mobile Systems to enable safe/reliable, affordable and effective human and robotic research, discovery and exploration in lunar, planetary and other venues.
  - Sub-surface Access and Knowledge. Highly effective and affordable systems to enable increasingly valuable Sub-surface Access (e.g., deep drilling) and Knowledge (e.g., seismic sounding and tomographic imaging) to be obtained by future human/robotic missions in lunar, planetary and other venues.
  - Surface Laboratory Systems. Safe, affordable and effective Surface Laboratory Systems to enable increasingly valuable in situ research and discovery to be achieved by future human/robotic missions in lunar, planetary and other venues.
  - Flying and Swimming Systems. Highly effective and affordable Flying and Swimming systems to enable ambitious scientific (e.g., remotely operated sub-surface 'swimmers') and operational (e.g., regional over-flight) goals to be realized by future human/robotic missions in lunar, planetary and other venues.
  - Virtual Exploration. Acquisition (and 'fusion') of exceptionally large, multi-sensor data sets from localities—such as the Moon, Mars, or other destinations—and the creation of high fidelity "immersive" virtual reality to enable diverse operational, scientific and outreach goals to be accomplished affordably and effectively.
  - Surface Environmental Effects. Understand the environmental effects to be experienced by humans and systems during future lunar, planetary or other target missions—and pursue mitigation of those effects to allow safe, affordable and effective research, discovery and exploration.
  - Sustained Surface Exploration & Expeditions Campaign Architectures. Novel and robust architectures that best enable Sustained Surface Expeditions and Exploration Campaigns to be undertaken to enable ambitious goals for future human/robotic research, discovery and exploration.

- **Space Transportation**. Safe/reliable, affordable and effective transportation of equipment, logistics and crews for future missions in pursuit of high value future human/robotic research, discovery and exploration.
    - ETO Propulsion (On-Board). Safe/reliable, affordable and effective primary Earth-to-Orbit (ETO) Propulsion systems to enable low-cost, highly reliable transport of systems, logistics and crews to low Earth orbit for future human/robotic space research, discovery and exploration.
    - Vehicle Airframe and Structures. Robust, reliable and high strength-to-weight Vehicle Airframe and Structures concepts and materials for application in diverse future vehicles supporting future human/robotic systems and missions.
    - Atmospheric Maneuver & Precision Landing. Global, highly reliable, exceptionally safe (where humans are involved) and increasingly affordable Atmospheric Maneuver & Precision Landing for future human/robotic vehicles and missions—including robots, cargoes and crews—for missions in the Earth's Neighborhood and throughout the inner Solar System.
    - Vehicle Subsystems. Exceptionally reliable, flexible and affordable modular Vehicle Subsystems Systems for application in a wide range of future vehicles and missions to enable ambitious human/robotic research, discovery and exploration in space.
    - In-Space Propulsion (Chemical/Thermal). Highly reliable, safe (where humans are involved) and affordable Chemical/Thermal propulsion systems for future human/robotic vehicles and missions—including both primary and secondary (e.g., maneuvering) propulsion needs—for missions in Earth orbit, the Earth's Neighborhood, and throughout the inner Solar System.
    - In-Space Propulsion (Electric/Electromagnetic). Highly reliable, safe (where humans are involved) and affordable Electric and Electromagnetic propulsion systems for future human/robotic vehicles and missions—including both primary and secondary (e.g., station-keeping) propulsion needs—for missions in Earth orbit, the Earth's Neighborhood, and throughout the inner Solar System.
    - In-Space Propulsion (Nuclear). Exceptionally safe, reliable, and affordable Nuclear Propulsion Systems for future human/robotic vehicles and missions—for primary propulsion needs—for missions beyond the Earth's Neighborhood.
    - In-Space "Propellantless" Transfer Systems. Highly reliable, safe (where humans are involved) and affordable "Propellantless" propulsion systems for future human/robotic vehicles and missions—including both primary and secondary (e.g., station-keeping) propulsion needs—for missions in Earth orbit, the Earth's Neighborhood, and throughout the inner Solar System.

  - Launch Assist/Direct Launch Systems. Highly- efficient and reliable ground-based Launch Assist and Direct Launch Systems capable of enabling exceptionally low cost access to space for a wide variety of vehicle and payload types.
  - Launch Infrastructure and Operations. Affordable, safe, efficient and reliable Launch Infrastructure and Operations capable of supporting the full range of launch vehicles and payload processing in support of ambitious future human/robotic missions.
  - Test Requirements and Instrumentation. Establish robust, high-confidence Test Requirements and Instrumentation for the validation of advanced space transportation technologies in order to assure readiness to begin systems developments; and for novel space transportation systems to assure readiness for deployment and operations..
- **In-Space Instruments and Sensors**. Robust and affordable new concepts for In-Space Instruments and Sensors that can best exploit the new opportunities made possible by the novel space systems that enable ambitious, affordable and effective human/robotic research, discovery exploration.
  - Detectors and Sensing Systems. Novel Detectors and Sensing Systems that can best exploit new systems concepts involved in future ambitious, affordable and effective for human/robotic space infrastructures and operations.
  - Microwave Sensing Systems. Novel Microwave Sensing Systems that can best exploit new systems concepts involved in future ambitious, affordable and effective for human/robotic space infrastructures and operations.
  - Submillimeter-wave Sensing Systems. Novel Submillimeter-wave Sensing Systems that can best exploit new systems concepts involved in future ambitious, affordable and effective for human/robotic space infrastructures and operations.
  - Laser Sensing Systems. Novel Laser Sensing Systems that can best exploit new systems concepts involved in future ambitious, affordable and effective for human/robotic space infrastructures and operations.
  - X-Ray and High-Energy Sensing. Novel X-Ray and High-Energy Sensing systems that can best exploit new systems concepts involved in future ambitious, affordable and effective for human/robotic space infrastructures and operations.
  - Telescope Systems. Novel Telescope Systems that can best exploit new systems concepts involved in future ambitious, affordable and effective for human/robotic space infrastructures and operations..
  - In-Space Laboratory Research Systems. Affordable, largely self-sufficient In-Space Laboratory Research Systems to enable “terrestrial field laboratory” class (or better) research in diverse venues in space, on the Moon, at Mars and elsewhere.

  - Instrument and Sensor Data Management. Affordable, highly-capable and largely self-sufficient Instrument and Sensor Data Management concepts and systems to enable "terrestrial field laboratory" class (or better) research in diverse venues in space, on the Moon, at Mars and elsewhere.

- **Information and Communications**. Affordable, exceptionally reliable and highly capable Information and Communications systems to establish "terrestrial field laboratory" class (or better) computing and to deliver consistent high-bandwidth local, regional and remote communications services—in support of ambitious future human/robotic space systems and missions.

  - Radio Frequency Telecommunications Systems. Very high-data rate Radio Frequency Telecommunications Systems to enable transmission of operational, scientific and outreach data to-and-from, and among future human/robotic mission systems and crews.

  - Laser Telecommunications Systems. Exceptionally high-data rate Laser Frequency Telecommunications Systems to enable transmission of operational, scientific and outreach data to-and-from, and among future human/robotic mission systems and crews.

  - Data Acquisition and End-to-End Management. Architectures, standards, devices and software to enable timely and cost-effective Data Acquisition and End-to-End Data Management for a diverse suite of future human/robotic system and mission operations in venues ranging for low Earth orbit, throughout the Earth's Neighborhood (including the Moon) and to destinations beyond (including the neighborhood and surface of Mars).

  - Deep Space Navigation. Highly accurate navigation in deep space, including on-board techniques, integrated with Earth-to-space and space-to-space techniques for Deep Space Navigation technology.

  - Command and Control Systems. Architectures, standards, systems and software to enable robust, timely, cost-effective and exceptionally high reliability Command and Control for a future human/robotic system and mission operations in venues ranging for low Earth orbit, throughout the Earth's Neighborhood (including the Moon) and to destinations beyond (including the neighborhood and surface of Mars).

  - Mission Control Center Intelligence. Highly "intelligent" computing and software systems, including human-machine interfaces and displays to enable increasingly safe, affordable and effective Mission Control Center operations in support of future human/robotic systems and missions.

  - Interplanetary and Planetary Networks. Architectures, standards, devices and software to enable cost-effective deployment and operation of robust, reconfigurable and largely self-reliant Interplanetary and Planetary Networks for a diverse suite of future human/robotic system and mission operations in venues ranging for low Earth orbit, throughout the Earth's

Neighborhood (including the Moon) and to destinations beyond (including the neighborhood and surface of Mars).

Farther-Term Challenges (>2020):

- **Earth-to-Orbit Transportation.** The challenge is to achieve Routine, reliable and increasingly low cost transport of people, systems and consumables from Earth to orbit (and back). Meeting this challenge entails achieving the following objectives:

    - Continuing reductions in cost
        - Initially, less than $2000 per kilogram average recurring cost for transportation to low Earth orbit (LEO)
        - Later, less than $200 per kilogram average recurring cost for transportation to LEO
    - Increasing reliability in transport of people and major systems
        - Initially, > 0.999 probability of nominal launch
        - Later, > 0.99999 probability of nominal launch
    - The capacity to launch more than 1000t per year, average
    - ETO transport of payloads of at least
        - Initially, > 40t per launch
        - Later, > 40-80t per launch

- **In-Space Transportation.** The challenge is to achieve Affordable, reliable and timely transport of people, machines and consumables across near-Earth and interplanetary space. Meeting this challenge depends upon achieving the following objectives:

    - Lower costs
        - Less than $500 per kilogram recurring cost from LEO to geostationary Earth orbit (GEO)
        - Less than $1000 per kilogram recurring cost from LEO to in-space destinations throughout the inner solar system
    - Increasing reliability in transport of people and major systems
        - Initially, > 0.995 probability of nominal transfer
        - Later, > 0.99995 probability of nominal transfer
    - With the capability of "fast" transits where needed (e.g., less than 4-6 months for transfer between the near-Earth space and near-Mars space)
    - Including the capacity to transport system "payloads" of at least 40-80t per "launch"
    - Including the capacity to transport more than 1000t per year, average

- **Excursion Transportation.** The challenge is to achieve *Routine, flexible and affordable "excursions" of machines and people – locally in space and to planetary surfaces (and back to space).* Meeting this challenge involves achieving the following objectives:

- Lower costs
    - Less than $200 per kilogram recurring cost to local in space "targets"
    - Less than $2000 per kilogram recurring cost to destinations on Mars, the Moon or small body surfaces
- Increasing reliability in transport of people and major systems
    - Initially, > 0.995 probability of nominal excursion
    - Later, > 0.99995 probability of nominal excursion
- Including systems of at least 10-20t per "excursion"
- Including the capacity to transport more than 100t per year, average

- **Power and Utilities.** The challenge is to achieve Affordable and abundant "on-demand" power for local and remote use in space throughout the inner solar system and in planetary venues. Meeting this challenge entails achieving the following objectives:

    - Affordable electrical power, including
        - Initially, < $200 per Watt installed cost for electrical power
        - Later, < $50 per Watt installed cost for electrical power
    - Increasing levels of power for surface applications, including
        - Initially, more than 10 kW for robotic stationary and/or human-carrying mobile planetary surface applications
        - Later, more than 100 kW for stationary planetary surface applications
    - Increasing levels of power for space applications, including
        - Initially, more than 1 MW for in space vehicle applications
        - Later, more than 10-1000 MW for in-space central power station applications (including wireless power transmission)
    - Lightweight systems for thermal management and heat rejection from transportation, infrastructure and mobile systems in space and on accessible planetary surfaces (including the Moon and Mars)

- **Human Habitats.** The challenge is to achieve Increasingly self-contained human habitats (e.g., "miniature biospheres") at various scales (and over increasing time frames) in space and on planetary surfaces. Meeting this challenge depends upon achieving the following objectives:

    - Lower costs per cubic meter of habitable volume beyond low Earth orbit
        - Initially, less than $200,000 per cubic meter
        - Later, less than $40,000 per cubic meter
    - Larger total habitable volumes beyond low Earth orbit
        - Initially, habitable volumes of more than 100 cubic meters
        - Later, habitable volumes of more than 2,500 cubic meters
    - "Near complete" recycling of "waste products" – including gases, fluids and solids – using systems that are lower cost, and/or lower mass, and/or use less energy per kilogram of waste products processed
    - Detection and elimination of chemical and/or biological contaminants

    - Integrated systems including energy sources, thermal management systems, physical-chemical and bio-regenerative processors, living things (including floral and fauna), and integrated environmental monitoring and control

- **Low Gravity.** The challenge is to achieve Micrograwity – and partial gravity – effects prevention, predictive modeling, monitoring and countermeasures on humans (and other living things necessary to achieve "miniature biosphere" goals). Meeting this challenge involves achieving the following objectives:

  - Safe and healthy "Earth-equivalent" human activities in space, over increasing periods of time:
    - Initially, for periods of up to 12-18 months
    - Later, for more than 36 months (and up to indefinite periods of time)
  - Safe and healthy "Earth-equivalent" human activities on the Moon and/or Mars, over increasing periods of time:
    - Initially, for periods of up to 6-12 months
    - Later, for more than 36 months (and up to indefinite periods of time)

- **Radiation.** The challenge is to achieve Space radiation environment monitoring and predictive modeling; and protection, predictive modeling and countermeasures associated with preventing – or mitigating adequately – the effects of space radiation on machines and humans (and other living things necessary to achieve "miniature biosphere" goals). Meeting this challenge entails achieving the following objectives:

  - Safe and healthy "as low as reasonably achievable (ALARA)" human activities in the radiation environment of space (including nominal solar particle events (SPEs), solar flares, and galactic cosmic rays (GCRs) over increasing periods of time:
    - Initially, for periods of up to 12-18 months
    - Later, for more than 36 months (and up to indefinite periods of time)
  - Safe and healthy "as low as reasonably achievable (ALARA)" human activities in the radiation environment on the Moon and/or Mars (including nominal solar particle events (SPEs), solar flares, and galactic cosmic rays (GCRs), over increasing periods of time:
    - Initially, for periods of up to 12-18 months
    - Later, for more than 36 months (and up to indefinite periods of time)

- **Medical Care.** The challenge is to achieve Increasingly comprehensive *in situ* routine and emergency medical care for humans in space and on planetary surfaces (and other living things necessary to achieve miniature "Biosphere" goals). Meeting this challenge entails achieving the following objectives:

  - Illness
    - Detection, diagnosis and treatment of "moderate" illness (e.g., appendicitis) in the mid-term

  - Near-“Earth equivalent” detection, diagnosis and treatment of “major” illness (e.g., cancer) in the far-term
- Injury
  - Diagnosis and treatment associated with “minor” physical trauma (e.g., broken limb injury) in the mid-term
  - Diagnosis and treatment associated with “major” physical trauma (e.g., major burn injury) in the far-term

- **Resources Development.** The challenge is to achieve <u>Flexible and affordable, physical and chemical translation, transformation and utilization of material solar system resources.</u> Meeting this challenge involves achieving the following objectives:

  - *In situ* production of propellants, life support and other consumables from local materials (including gases, ices, and mineral solids)
  - Manufacture of end items (including components and eventually systems) for use in local and remote operations
  - Increasingly complex self-replicating machines

- **Human and Machine Operations.** The challenge is to achieve <u>Effective, affordable and adaptive machine and human operations in the vacuum and accessible planetary environments.</u> Meeting this challenge depends upon achieving the following objectives:

  - Increasingly capable robotic assembly, maintenance and repair of systems in near-Earth space
  - Safe and robust “shirt-sleeve” class human extravehicular activity (EVA) operations in the far-term
  - Including EVA systems capable of 100’s of uses with only local servicing, maintenance and repair

- **Human / Machine Communities.** The challenge is to achieve <u>Sustained, evolvable and increasingly autonomous and self-sufficient machine and human operations in space and on planetary surfaces – leading to self-reliant “communities”.</u> Meeting this strategic technical challenge entails achieving the following objectives:

  - Initially, the capacity for ~10-100 distinct systems to inter-operate without intervention from Earth-based controllers
  - Later, the capacity for ~100-1000 distinct systems to inter-operate without intervention from Earth-based controllers
  - Bio-mimetic systems and architectures capable of collective learning and adaptive behaviors

- **Surface Mobility and Access.** The challenge is to achieve <u>Timely local, regional and global mobility in accessible planetary venues, with access at various</u>

depths below – and altitudes above – planetary surfaces. Meeting this challenge involves achieving the following objectives:

- Mobility at increasing range across the surface of the Moon or Mars
  - Initially, at distances of > 100 km
  - Later, at distances from 1000 km up to circumnavigation of the body
- Acquisition of samples that preserve physical, chemical and ”location” information from below planetary and small body surfaces
  - Initially, at depths of 10-100 meters
  - Later, at depths of 100-1000 meters
- Acquisition of samples from the Mars (and later other) atmosphere at various altitudes that preserve chemical and “location” information
- Appropriate forward- and back- contamination features – sufficient to meet both scientific requirements and key public concerns

- **Research Facilities.** The challenge is to achieve Affordable and adaptive “world-class” basic and applied research instruments and laboratories in space and on planetary surfaces. Meeting this challenge depends upon achieving the following objectives:

  - High-quality (high resolution and multi-spectral) imaging, ranging from the microscopic to long distance
  - High-quality (“mapping” capable) spectroscopy and other instrumentation
  - Geological and/or geophysics instruments and laboratories capable of investigation of nano-scale structures
  - Safe and self-sufficient organic / biochemical and/or biological sciences laboratories
  - Safe and semi-autonomous life sciences laboratories, including the capability for both flora and fauna (over multiple generations)
  - Near terrestrial class “clean room” operations
  - Effective indigenous planetary sample curation – locally and for transportation back to terrestrial laboratories (for further study)

- **Networks & Communications.** The challenge is to achieve On-demand broadband computing and network communications locally and over interplanetary distances. Meeting this strategic technical challenge involves achieving the following objectives:

  - Open architectures for real-time and asynchronous communications
  - Increasing local data capacity
    - Initially, with local data capacity of 10-100 Mbps, with
      - 99.9% availability
      - Total daily capacity > 10 Tb
    - Later, with local capacity of greater than 100-1000 Mbps, with
      - 99.99% availability
      - Total daily capacity > 10 Tb

- Increasing interplanetary data transfer capacity
  - Initially, interplanetary data rates greater than 1-10 Mbps, with
    - ➢ 99 % availability
    - ➢ Total daily capacity > 1 Tb
  - Later, interplanetary data rates greater than 10-100 Mbps, with
    - ➢ 99.9 % availability
    - ➢ 10 Tb total daily capacity

- **Virtual Exploration.** The challenge is to achieve <u>High quality and evolutionary human virtual presence, exploration and operations in space and on planetary surfaces</u>. Meeting this challenge entails achieving the following objectives:

  - High-quality “exploration” through virtual means of large data sets, including both scientific analysis and public engagement requirements
  - High-quality physical modeling of natural and human-made systems to simulate exploration situations and activities
    - Near-real-time involvement (e.g., oversight) of exploration activities through near-natural human-machine interfaces, including operational, scientific and public engagement requirements

OFFICE OF SPACE SCIENCE VISIONARY CHALLENGES (CODE S)

In the continuing quest for discovery, we seek clues from the past that can help us in the future and lessons from distant bodies that can teach us about our home planet. The future holds the promise of understanding the universe as a system of interacting matter and energy, radiation and particles, minerals and water. Imagine understanding completely how the Sun varies and how it interacts with Earth. Imagine deploying the most powerful exploration craft ever to uncover the mysteries of the outer planets. And imagine looking from the Sun to the comets —and beyond— for those markers that signify the presence of life. Beyond our own small community of planets and our familiar star, imagine finding the remnant ripples in gravity from the Big Bang, uncovering the secrets of the dark energy that pervades the universe, and taking pictures of a black hole. Imagine finally reading the whole story of how galaxies, stars, and planets came to be. The future of space science really consists of understanding the past. With ever greater capabilities, we seek to connect with the elements, planets, and universe that brought us into being. How and when did the amazing events in the chain leading to our existence take place? Could they have happened elsewhere? Will they happen again? In seeking answers to these questions, humankind can reflect on its place and its destiny in the universe. These questions in the space sciences will be addressed by pursuing the following Visionary challenges:

Understand the Earth system and apply Earth system science to improve the prediction of climate, weather, and natural hazards.

Explore the solar system and the universe beyond, understand the origin and evolution of life, and search for evidence of life elsewhere.

The following specific space science strategic goals are directly related to addressing these Visionary challenges.

<u>Understand the origins and societal impacts of variability in the Sun-Earth connection.</u>

- Develop the capability to predict solar activity and the evolution of solar disturbances as they propagate in the heliosphere and affect Earth.

- Specify and enable prediction of changes to Earth's radiation environment, ionosphere, and upper atmosphere.

- Understand the role of solar variability in driving space climate and global change in Earth's atmosphere.

Catalog and understand potential impact hazards to Earth from space.

- Determine the inventory and dynamics of bodies that may pose an impact hazard to Earth.

- Determine the physical characteristics of comets and asteroids relevant to any threat they may pose to Earth.

Learn how the solar system originated and evolved to its current diverse state.

- Understand the initial stages of planet and satellite formation.

- Study the processes that determine the characteristics of bodies in our solar system and how these processes operate and interact.

- Understand why the terrestrial planets are so different from one another.

- Learn what our solar system can tell us about extrasolar planetary systems.

Understand how life begins and evolves and determine the characteristics of the solar system that led to the origin of life.

- Determine the nature, history, and distribution of volatile and organic the characteristics of the solar system that led to the compounds in the solar system.

- Identify the habitable zones in the solar system.

- Identify the sources of simple chemicals that contribute to prebiotic evolution and the emergence of life.

- Study Earth's geologic and biologic records to determine the historical relationship between Earth and its biosphere.

Understand the current state and evolution of the atmosphere, surface, and interior of Mars.

- Characterize the present climate of Mars and determine how it has evolved over time.

- Investigate the history and behavior of water and other volatiles on Mars.

- Study the chemistry, mineralogy, and chronology of martian materials.

- Determine the characteristics and dynamics of the interior of Mars.

Determine if life exists or has ever existed on Mars.

- Investigate the character and extent of prebiotic chemistry on Mars.

- Search for chemical and biological signatures of past and present life on Mars.

Develop an understanding of Mars in support of possible future human exploration.

- Identify and study the hazards that the martian environment will present to human explorers.

- Inventory and characterize martian resources of potential benefit to human exploration of Mars.

Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.

- Understand the structure and dynamics of the Sun and solar wind and the origins of magnetic variability.

- Determine the evolution of the heliosphere and its interaction with the galaxy.

- Understand the response of magnetospheres and atmospheres to external and internal drivers.

Understand the fundamental physical processes of space plasma systems.

- Discover how magnetic fields are created and evolve and how charged particles are accelerated.

- Understand coupling across multiple scale lengths and its generality in plasma systems.

Learn how galaxies, stars, and planetary systems form and evolve.

- Learn how the cosmic web of matter organized into the first stars and galaxies and how these evolved into the stars and galaxies we see today.

- Understand how different galactic ecosystems of stars and gas formed and which ones might support the existence of planets and life.

- Learn how gas and dust become stars and planets.

- Observe planetary systems around other stars and compare their architectures and evolution with our own.

Understand the diversity of worlds beyond our solar system and search for those that might harbor life.

- Characterize the giant planets orbiting other stars

- Find out how common Earth-like planets are and see if any might be habitable.

- Trace the chemical pathways by which simple molecules and dust evolve into the organic molecules important for life.

- Develop the tools and techniques to search for life on planets beyond our solar system.

Discover what powered the Big Bang and the nature of the mysterious dark energy that is pulling the universe apart.

- Search for gravitational waves from the earliest moments of the Big Bang.

- Determine the size, shape, and matter-energy content of the universe.

- Measure the cosmic evolution of the dark energy, which controls the destiny of the universe.

Learn what happens to space, time, and matter at the edge of a black hole.

- Determine how black holes are formed, where they are, and how they evolve.

- Test Einstein's theory of gravity and map space-time near event horizons of black holes.

- Observe stars and other material plunging into black holes.

Understand the development of structure and the cycles of matter and energy in the evolving universe.

- Determine how, where, and when the chemical elements were made, and trace the flows of energy and magnetic fields that exchange them between stars, dust, and gas.

- Explore the behavior of matter in extreme astrophysical environments, including disks, cosmic jets, and the sources of gamma-ray bursts and cosmic rays.

- Discover how the interplay of baryons, dark matter, and gravity shapes galaxies and systems of galaxies.

OFFICE OF BIOLOGICAL AND PHYSICAL RESEARCH VISIONARY CHALLENGES
(CODE U)

Five organizing questions are the basis for the Biological and Physical Research Enterprise Strategy: (1) How can we assure the survival of humans traveling far from Earth? (2) How does life respond to gravity and space environments? (3) What new opportunities can research bring to expand understanding of the laws of nature and enrich lives on Earth? (4) What technology must we create to enable the next explorers to go beyond where we have been? (5) How can we educate and inspire the next generation to take the journey? The answers to these questions determine our research strategy, the platforms or programs to execute the science, applications for the research, and the metrics to measure progress. As we fulfill our Enterprise strategy, we contribute in an integral way to realizing the NASA Vision: to improve life here, to extend life to there, and to find life beyond. In doing so, the Enterprise helps not only our scientific, educational, and industrial partners, but also citizens around the globe.

> From "A Message from the Associate Administrator for Biological and Physical Research" contained in the Biological and Physical Research Enterprise Strategy.

Opportunities through the NIAC in exploring innovative answers to the first four organizing questions would be most welcome. In particular, questions 1 and 4 specifically address research needs for human exploration beyond low Earth orbit. For example, a significant risk associated with space exploration is how humans adapt to microgravity on extended missions and what if any countermeasures are needed to minimize this risk (Question 1a). Artificial gravity has been proposed as a countermeasure for consideration, yet we do not understand the physiological adaptation of artificial gravity for humans. We do not know if artificial gravity would be required on a continuous basis or if periodic exposure would be sufficient. This topic is a high priority on our critical path to ensure safety as we prepare to explore.

Organizing Question 1. – How can we assure the survival of humans traveling far from Earth?

1a. **How does the human body adapt to space flight and what are the most effective and efficient ways to counteract those adaptive effects when hazardous?** – focuses on understanding, characterizing, and counteracting the whole body's adaptations to microgravity, enabling healthy astronauts to accomplish missions objectives and return to normal life following a mission.

1b. **How can we limit the risk of harmful health effects associated with exposure of human space explorers to the space radiation environments?** – defines the research strategy necessary to understand the effects of space radiation environments on humans and protect crews from those effects.

1c. **How can we provide an optimal environment to support the behavioral health and human performance of the crew before, during, and after space flight?** – focuses on the research strategy required to maintain the psychosocial and psychophysiological functions (e.g., sleep and circulation functioning) of the crew for missions of increasing duration and distance.

1d. **How can we enable autonomous medical care in space? –** addresses the development of medical care systems and tools required to diagnose and treat medical events arising during flight, with an emphasis on increasingly autonomous operations.

Organizing Question 2. – How does life respond to gravity and space environments?

2a. **How do space environments affect life at molecular and cellular levels? –** focuses on the effects of microgravity, radiation, and other unique aspects of space environments on gene expressions and other cellular responses, offering tantalizing clues about the effects of microgravity on life at its most fundamental levels.

2b. **How do space environments affect organisms throughout their lives? –** addresses the developmental, physiological, and maturation processes of life at many levels, including tissues, organs, systems, and whole organisms, providing insight into potential mechanisms to allow humans to successfully adapt to long-duration space exposure.

2c. **How do space environments influence interactions between organisms? –** examines the ecosystems within our own bodies and on spacecraft, as well as their optimization to support us on long journeys from Earth.

2d. **Can life be sustained and thrive in space across generations? –** studies living systems over multiple generations as they move beyond Earth for increasingly long periods and evolve, adapting to new niches and novel environments.

Organizing Question 3. – What new opportunities can research bring to expand understanding of the laws of nature and enrich lives on Earth?

3a. **How do space environments change physical, chemical, and biophysical processes, the essential building blocks of many critical technologies? –** uses microgravity to better understand these processes and their application on Earth, leading to better design tools in energy, materials, and communication technologies.

3b. **How do structure and complexity arise in nature? –** examines the origins of order in nature in a variety of settings, including grain coarsening in metals, evolution of structure in solidifying alloys, order-disorder transitions in colloidal systems, and heat transport in superfluid helium.

3c. **Where can our research advance our knowledge of the fundamental laws governing time and matter? –** describes the forces present in the universe and their effects on matter, achieving greater clarity and accuracy through experiments planned for the ISS and free-flying satellites, exploring concepts like the quantum properties of matter, the limits of Einstein's theory of gravitation, the properties of the electron, and other outstanding questions.

3d. **What biophysical mechanisms control the cellular and physiological behavior observed in the space environment? –** applies interdisciplinary research and experimental methodologies and technologies in physical and biological sciences, such as the use of fluid dynamics and transport analysis to quantify the effects of gravity on living tissues; applies biological principles to new technologies in areas such as biomimetic materials.

3e. **How can research partnerships – both market-driven and interagency – support national goals, such as contributing to economic growth and sustaining human capital in science and technology?** – fosters the use of the environments of space to advance agribusiness, materials science, biotechnology, communications, and other economic opportunities for the private sector and to assure the development of a workforce capable of meeting the aerospace challenges of the future.

Organizing Question 4. – What technology must we create to enable the next explorers to go beyond where we have been?

4a. **How can we enable the next generation of autonomous, reliable spacecraft human support subsystems? –** discusses the research strategy for life-support systems necessary to sustain crews for extended periods.

4b. **What new reduced-gravity engineering systems and advanced materials are required to enable efficient and safe deep-space travel? –** identifies technology options to provide solutions for a range of challenges, such as in-space fabrications utilizing in situ resources and recycled materials.

4c. **How can we enable optimum human performance and productivity during extended isolation from Earth? –** presents the research strategy to enable crews in habitable environments far from Earth to be self-supporting, autonomous, and productive.

4d. **What automated sensing and control systems must we create to ensure that the crew is living in a safe and healthy environment? –** discusses the research strategy to provide future spacecraft and space habitats with improved, miniaturized networks of integrated sensors for environmental monitoring and control.

OFFICE OF EARTH SCIENCE VISIONARY CHALLENGES:
“Our Place in the Universe”
(CODE Y)

NASA’s Earth Science Enterprise (ESE) endeavors to use our vantage from space to fulfill NASA’s mission to understand and protect our home planet. Thus, ESE seeks to answer the question: *“How is Earth changing, and what are the consequences for life on Earth?”*

In addressing this overarching question, ESE uses the global view from space to provide accurate and objective scientific knowledge on the present and future state of the Earth system and to make this knowledge available for policy decisions and practical applications here on Earth, and use the knowledge of Earth’s planetary system in exploring our galaxy and those beyond to search for life. ESE scientific and technological efforts focus on understanding the Earth system by:

- ☐ Characterizing the Earth as a planetary system,
- ☐ Understanding the forces at work on the Earth system and the responses of the Earth system to these forces, and
- ☐ Predicting the future evolution of the Earth system and its relationship to natural phenomena and human activity, and validating this predictive capability.

During the past 20 years Earth science research has focused on understanding the components of the Earth system and their interactions. New global observations and development of computer models that address specific Earth system processes have produced these accomplishments. We have made significant progress. Current observational systems include capable operational satellites operating in polar and geostationary orbits. As we look twenty years into the future, the challenge for the scientific community and NASA will be to develop-with national and international partners- an inclusive Earth system model suite integrating remote sensing and *in situ* measurements with advanced computational modeling capabilities. This model suite would enable NASA and its partners to respond in the global interest to regional and local changes, and understand such changes in their global context. To fulfill this vision, progress along a broad front of science and technology is required. Components include:

1. Improved Predictability of the Earth System (with associated estimates of uncertainty):
    - Two week accurate weather prediction
    - Decadal climate/environmental prediction
    - Decadal land cover, ecosystem, and biosphere change prediction
    - Regional prediction of air and water resource conditions
    - Timely and accurate prediction of natural hazards
    - Timely prediction of risks associated with environmental health, disease vectors, and invasive species

- Improved understanding and management of natural resources (e.g., observation and model-based ecological forecasts, with associated estimates of error, that predict the impact of land-use management or development decisions on endangered and threatened species)

2. New Scientific Understanding:
    - Revealing the Earth's structure beneath the surface to understand dynamics of the Earth's crust, mantle and core with special emphasis upon the state of stress and rheology of the crust and lithosphere, and the physics of the geomagnetic dynamo.
    - Remotely measuring characteristics of the Earth beyond current capabilities, such as monitoring: species and biodiversity across scales, three dimensional ocean phenomena (from the surface to the deep ocean floor), atmospheric composition (including surface level pollutants and aerosol composition), etc.
    - Exploring new scientific frontiers concerning the Earth's long-term history and future development.

3. Challenging concepts of potential interest:
    - Seismology from Space (e.g. the proxy measurement of ionospheric perturbations or through high resolution measurement of surface displacement),
    - Remote sensing of the seafloor to understand better the stress and strain distribution and related thermal events at plate boundaries,
    - Improved geodetic measurement techniques for high resolution Earth rotation and increased stability of the Terrestrial Reference Frame,
    - Innovative new approaches to Holistic Planetary Measurements including electric, magnetic, gravity field and particle tomography of the Earth to understand better and predict the dynamics of the Earth System
    - Architectures and implementation strategies for non-photon remote sensing including quantum gravity remote sensing
    - Measurement from space of the atmospheric pressure down to the Earth's surface (to sub-millibar accuracy)
    - Coupling landscape-level remote sensing of the environment with the molecular-scale tools of genomics and proteomics to understand the evolutionary effects of environmental changes and how these evolutionary effects feed back into changes in the biogeochemical cycling of key elements such as carbon and nitrogen

4. Global to Local Observations:
    - Develop architectures and implementation strategies for the deployment, maintenance, and seamless integration of diverse, distributed measurement and modeling capabilities into a smart, adaptable, and robust Earth science "sensor web." Such a sensor web could incorporate near space (LEO, MEO), far space (L1, L2, GEO), suborbital, and surface-based sensors. It would also have the capability to command specific orbital, suborbital and surface

platforms to investigate local to landscape level phenomena at higher spatial, spectral, or temporal resolutions.

- Apply new space-borne sensor deployment strategies including LaGrange points, Molniya orbits, high Earth orbits and non-Keplerian positioning.

5. Broad Utilization of Space-based observations
    - Techniques to enhance the integration and assimilation of ESE data into the education, planning, and operational processes of the global citizenry.
    - Techniques to deliver Earth system data and predictions in an easily digestible manner for humans and machines.

For the 2030 timeframe, ESE envisions a paradigm shift for Earth science, in which the dynamic Earth system is fully observed using an international suite of Earth observation systems, and then represented in a family of interacting models that include all major system Earth Science components: atmosphere, oceans, biosphere and solid Earth. The composite Earth Information System will provide a quantitative predictive capability of system interactions. Key attributes of the Earth Information System are that it:

- ☐ Observes the whole Earth system, such that the changes in any component system can be traced to measure the total impact;
- ☐ Models the whole Earth system and all its components, such that effects of changes in any component can be predicted;
- ☐ Evolves to define the system behavior that best describes ongoing observations;
- ☐ Yields predictions with quantitative uncertainties that are useful in the public decision making process.

In addition, many examples of activities link Earth science to NASA's mission to explore the universe and search for life:

- ☐ Comparative planetology, understanding processes on a planetary scale under a range of conditions (gravity, solar radiation, orbital inclination, atmospheric composition, etc.).
- ☐ Understanding the causes of variability of the Sun and its impact on the Earth's climate, such as studying the "solar cycle" of other Sun-like stars to increase the sample size for predicting future solar variability.
- ☐ Understanding the signatures of life on Earth, and how they may relate to planned, future observations of Earth-like planets around sun-like stars.
- ☐ Understanding if there may be records of the early Earth, such as material ejected by a major impact and preserved relatively unchanged, that may answer questions about the evolution of the Earth system and the origin of life.
- ☐ Understand the linkage between the near-space environment (such as the thermosphere, ionosphere, and mesosphere) and the Earth's environment.

The Earth Science Enterprise Strategy (pp. 69-74) identifies key prediction goals and required technologies for this time frame. This document can be accessed at:http://www.earth.nasa.gov/visions/index.html .