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ENABLING FUTURE SCIENCE AND HUMAN EXPLORATION WITH NASA'S NEXT GENERATION NEAR EARTH AND DEEP SPACE COMMUNICATIONS AND NAVIGATION ARCHITECTURE

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Abstract

The National Aeronautics and Space Administration (NASA) is studying alternatives for the United States space architecture through the 2040 timeframe to provide communication, and position, navigation, and timing (PNT) services to both human exploration and science missions throughout the solar system. Several of NASA's key space assets are approaching their end of design life, major systems are in need of replacement, and new science and exploration opportunities are on the horizon. An opportunity to introduce major new capabilities in the ground and relay satellite architecture around Earth, Moon, and Mars occur roughly once each generation; hence, this is referred to as NASA's next generation (Next Gen) space communications architecture.

NASA's Next Gen architecture will benefit from technology and services developed over recent years. These innovations will provide missions with new operations concepts, increased performance, and new business and operating models. Advancements in optical communications will enable high-speed data channels to support the use of new and more complex science instruments. Modern multiple beam/multiple access technologies such as those employed on commercial high throughput satellites will enable enhanced capabilities for on-demand service, and, with new protocols, will help provide Internet-like connectivity for cooperative spacecraft to improve data return and coordinate joint mission objectives. On-board processing with autonomous and cognitive networking will play larger roles to help manage system complexity. Spacecraft and ground systems will coordinate among themselves to establish communications, negotiate link connectivity, and learn to share spectrum to optimize resource allocations. Spacecraft will autonomously navigate, plan trajectories, and handle off-nominal events.

NASA intends to leverage the ever-expanding capabilities of the satellite communications industry and foster its continued growth. NASA's technology development will complement and extend commercial capabilities to meet unique space environment requirements and to provide capabilities that are beyond the commercial marketplace. The progress of the communications industry, including the emerging global space Internet segment and its planned constellations of 100s of satellites offer additional opportunities for new capability and mission concepts.

The opportunities for and challenges of a future space architecture require an optimal solution encompassing a global perspective. The concepts and technologies incorporated into the architecture apply not only to NASA, but to other U.S. government agencies, international space and government agencies, and domestic and international commercial partners to advance the openness, interoperability, flexibility, and affordability of space communications. Cooperation among the world's space-faring organizations, their capabilities, standards, operations, and interoperability are key to advancing humankind's understanding of the universe and extending human presence into the solar system.

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1. Mission and Agency Needs: The Next Generation Architecture Motivation

The NASA space communications and navigation (SCaN) architecture consists of a network of ground stations and relays satellites that bring data from mission spacecraft from anywhere in the solar system back to investigators on Earth. For decades, NASA's Space Network (SN) with its Tracking and Data Relay Satellite System (TDRSS), the ground-based Near Earth Network (NEN) and the Deep Space Network (DSN) have provided a wide variety of communications and navigation services to meet not just NASA's needs but those of other government agencies, and international partner space agencies. The SCaN Networks provide overlapping coverage: SN/TDRSS provides nearly complete Earth coverage serving missions from Earth's surface to Medium Earth Orbit (MEO); NEN provides services to mission spacecraft from the Low Earth Orbit (LEO) to 2 million kilometers (Mkm) (including polar, cis-lunar and Sun-Earth L1/L2 orbits); and DSN provides coverage from approximately Geosynchronous Earth Orbit (GEO) to the far reaches of the solar system.

The Next Gen architecture timeframe is broadly defined over the next 20^{+} years, out to 2040 and more specifically defined over the next 10 years to the 2025 time frame when recent technology investments transition into development leading to operational capabilities. In this timeframe, major changes in surface, orbital, and planetary missions that use SCaN Network services will occur.

The future mission concepts range from planetary science missions, human exploration, and fleets of mission spacecraft performing coordinated science investigations. Increases in commercial satellite use and operation is also expected for imaging, agricultural, and other surveillance applications. Table 1 summarizes the mission concepts driving the requirements of the Next Gen architecture.

To enable these missions, the SCaN Network must transition and become part of an end-to-end "system of systems" which includes many elements from research spacecraft, mission control and science processing centers, network infrastructure, partner agencies both domestic and foreign, and commercially provided services and partnerships. The SCaN Network will therefore evolve in a fully coordinated way with different "systems": mission concepts and plans, ground and flight systems, and the commercial industry to develop and sustain NASA's infrastructure and future capabilities within a level, inflationary adjusted, budget and thereby avoid the budget challenges associated with a major funding increase for development of key sustaining systems, such as Earth or Mars relay spacecraft.

Table 1 – Mission Concepts Driving Next Generation SCaN Architecture

Key Changes in Mission Concepts	Impact to Next Gen Architecture
Human explorers return to cis-lunar space and eventually reach Mars with steadily increasing surface capabilities	• Lunar and Mars networks and services resemble Earth Network and services • Provide sufficient deep space communications and tracking capacity for human and robotic missions
Planetary missions with robotic sample return to Earth – followed by human exploration and return	• Added complexity in mission definition and navigation; planetary orbit and position determination needs accuracy beyond Global Positioning System (GPS)
Increasingly capable compact spacecraft that lead to missions consisting of larger clusters and fleets with distributed capabilities	• Increasing quantity of spacecraft simultaneously needing service and more autonomous operations • Services to disadvantaged and compact spacecraft impose high burden on networks
Missions continuing to increase their need for temporal, spatial and spectral resolution in science measurements and reduce data delivery latency	• Increasing near Earth capacity (10-100x) and deep space capacity (100-1000x) • Balanced capacity between lower cost ground stations and higher cost space relays driven by mission latency
Continued focus on mission affordability through collaboration with external partners	• Increasing need for secure cross-support with domestic and international partners that is interoperable and easy to arrange
New space entrepreneurs establishing new markets in space increasing demand for non-government communication and navigation services.	• Industry drives needs for increasing capacity and interoperability with reduced cost of services
Increasing sophistication and diversity of mission design and operations concepts as mission complexity and goals increase.	• Need for faster, less labor-intensive network support for service negotiation and mission design • Increasing need for service flexibility and rapid response to mission requests during operations • More agile operations and development process

2. Vision to Meet Mission and Agency Need

NASA continues to expand the world's horizons through missions to understand the universe and extend human presence into the solar system. Science missions constantly seek improvements in spectral, temporal, and spatial resolution (i.e., gather more frequencies more often at smaller feature sizes) to enhance their modeling and analysis of physical behavior. Improvements in any of those dimensions lead to increases in the volume of data transmitted. Human exploration seeks to go beyond Low Earth Orbit (LEO) and eventually to Mars. These increasingly challenging and complex missions drive corresponding improvements in communication capabilities to control the spacecraft and harvest their data, and navigation capabilities to plan their trajectories, provide time and metric tracking, and determine orbit position. While supporting these new mission needs, NASA is also pursuing other mandates such as lowering overall costs, promoting the growth of commercial space industries and maintaining global leadership in space technologies and capabilities. The vision for future communications and navigation services is based on the following overarching elements:

1. "Shrink" the solar system by connecting the principal investigator more closely to the instrument, the mission controller to the spacecraft, and the astronaut to the public;
2. Improve the user's experience and reduce user burden, i.e., reduce the effort and cost required to design and operate spacecraft to receive services from the SCaN Network;
3. Reduce network burden, i.e., reduce the effort and cost required to design, operate, and sustain the SCaN Network as it provides services to user missions with the collateral benefit of increasing related technology funding;
4. Apply new and enhanced capabilities of commercial telecommunications and navigation to space leveraging other organizations' investments;
5. Enable growth of the domestic commercial space market to provide – and NASA to use – commercial services currently dominated by government capabilities;
6. Enable greater international collaboration by establishing an open architecture with interoperable services that foster commercial competition and can be adopted by international agencies as well as NASA.

"Shrink" the solar system: Tomorrow's communication network will provide a variety of connectivity and advanced capability for mission spacecraft to return data back to Earth. High speed data channels will transport more data and imagery (from new and more complex science instruments) and interconnected space networks will enable Internet-like connectivity for cooperative spacecraft and planetary networks to improve data return , better connecting investigators on Earth with the science, and the public to the wonders of the world. With the Human Exploration theme of becoming "Earth Independent" to enable multi-year human expeditions to Mars, navigation autonomy and cognitive networking will play larger roles to help manage system complexity and reduce costs. Spacecraft and ground systems will coordinate among themselves to establish communications and ensure optimal resource allocation. Spacecraft will autonomously navigate, plan trajectories, execute maneuvers, and handle off-nominal events without immediate support from a control center on Earth. Spacecraft and ground nodes will negotiate data rate and connectivity for optimal throughput, while learning from their own performance to mitigate interference and share spectrum. The network will provide several options for Quality of Service (QoS) including the ability to ensure delivery of data.

Improve the user's experience and reduce user burden*:* The ideal situation for mission projects that develop, launch, and operate spacecraft, is for the SCaN Network to provide all desired services at the desired level of performance for the duration of the mission while imposing no constraints on the mission – unlimited capacity, on demand, at no cost. While this is impossible to achieve in the literal sense, the SCaN Network goal is to appear this way to users. Mission planning will be streamlined with a uniform, partially automated, online process, common across all networks. Data delivery and tracking services will be standardized on both NASA's and outside networks to simplify the design of the mission project's communication subsystem and mission operations. Coordination with commercial vendors will provide improved sources of standardized, off-the-shelf hardware and software. Operations in both near Earth or in deep space will have similar interfaces and network functions, providing consistent and efficient services to the missions.

Reduce network burden: Many enhancements that improve the user experience will also benefit the SCaN Network. Streamlining mission planning will reduce the network effort needed to work with users to define their service requirements and assess mission feasibility. Standardizing services across networks will reduce the amount of unique equipment and software needed as well as simplifying testing and integration. Working with commercial vendors will establish an industrial base of qualified components certified to be compliant with standard network interfaces. Potential savings from reducing network burden have been identified in pre-flight, flight, and flight support functions complementary to approaches that will reduce user burden.

Apply aspects of terrestrial communications: Connectivity between and among user spacecraft, relay satellites, surface networks, and ground stations will evolve. Similar to the Internet, whose connectivity depends on a well-coordinated collection of voluntarily interconnected networks, tomorrow's space architecture network will not only depend upon NASA's own systems, but may also leverage assets from other national space agencies, commercial entities, academic and other organizations, connected through the adoption of open, commercial, and international standards. This new connectivity will enable data exchange among spacecraft enabling new science opportunities, improving reliability and availability, and providing more ubiquitous coverage for space assets. Internetworked connectivity will be used where it reduces cost, complexity or returns greater science.

Promote domestic commercial market and international participation: With the growth of commercial space services for both terrestrial and airborne users, there is considerable activity and potential for commercially provided services to users in low Earth orbit and the possibility of commercial services in Mars and/or Lunar vicinity. Using open, commercial, and international standards will enable the use of commercial services by specifying required performance and interfaces without specifying provider-specific capabilities. Commercial entities will compete based on price, quality, timeliness, support and other factors that maintain a competitive environment. NASA's costs will be managed through reduction in provider-specific solutions, competition in an open market, and the ability to match capacity with demand, providing upward and downward scalability (including surge capability) as well as affordability.

In addition, as countries around the world venture to the Moon and Mars, there is growing potential to leverage international assets and infrastructure to advance exploration for all space participants. Current international collaboration on space communications and navigation extends to the major international space agencies and includes future services, future architectures, and development of international standards. Currently, cross support - the ability of one agency to provide services to another agency's mission - requires formal government-to-government agreements that are executed on a mission-by-mission basis. The Next Gen architecture includes the use of commercial and international participation when and where it provides a technical and/or cost advantage

In the future, a market-like mechanism is envisioned for standardizing exchange of communication and navigation services that includes automated accounting for services used by the participating partners. To avoid the exchange of direct funds between governments, a "bartering" arrangement will enable partners to periodically settle the differences in value exchanged in asset or resources (e.g. station or relay use time, science data) shared.

3. Providing the Next Generation Architecture Services

Future network capabilities and services are based on a Service Oriented Architecture, emphasizing network and mission goals, interoperability, common services, flexibility, and network evolution. The Next Gen architecture offers a range of advanced standardized network services. Standard services are self-contained functions with standard, well-defined interfaces. Providing standardized services reduces the need for costly unique mission capabilities allowing missions to share the costs of critical space infrastructure, thus providing a cost effective, national resource for space exploration.

Throughout the transition period, existing missions can continue to operate using existing services and perform routine planning and analysis, relying on the SCaN Network for standard link layer data transmission and radiometric tracking data. In the future framework, missions using one or more networks will receive common services across near Earth and deep space domains, eliminating the need for network-specific radios and protocols. New missions will take advantage of new internetworking, broadcast messaging and optimetric tracking services. Low cost missions can take advantage of new services that assist missions in planning and operations by performing functions previously done by larger missions.

The signaling interfaces (e.g. modulations, coding, and spectrum) and protocols used will be common across all networks to the fullest extent practical, taking into account the physics, mission constraints, and operational differences between near Earth and deep space missions. Reconfigurable software defined radios [1] provide the ability for mission spacecraft to adapt while in orbit to the residual differences in services provided by NASA and partner providers. A summary of the services of the future architecture include:

a) Communications
b) Navigation
c) Space Internetworking
d) Broadcast/Messaging
e) Radio Metric
f) Application Layer

<u>Communication</u>: Communication services move mission data through and among SCaN infrastructure elements. Communication services cover a wide range of functions and capabilities depending upon the mission need and include on-demand or pre-coordinated RF and future optical communications at a variety on data rates and latency both to and from mission spacecraft.

Traditional link layer services will be enhanced by using common link protocols on all space links (direct from/to Earth and space-to-space links) to support increased data rates, increased number of space vehicles, and reduce latency.

New services will also include Digital Video Broadcast (DVB) (currently DVB-S2 for satellites [11]) for broadcast quality High Definition TV with Variable and Adaptive Coding and Modulation (VCM, ACM) consistent with interactive Internetworking services.

Navigation: Navigation services will provide improved availability and accuracy by expanding and enhancing the services available today. Metric tracking data will be provided on any microwave or optical carrier that transmits data. Observations will be formed on space-to-space, space-to-ground, and ground-to-space physical links and then delivered to consumers of metric tracking data. Optimetrics will provide order of magnitude improvements in ranging, Doppler, and pointing (angular) observation accuracy. Non-coherent observation types, specifically one-way forward ranging (new service provided by SCaN) and Doppler, will facilitate autonomous navigation on-board the mission platform. In areas of high mission concentration, a navigation beacon may be provided as the basis of a stand-alone service. Navigation observables will be tied to a common time scale compatible with Global Navigation Satellite Systems (GNSS) in the near Earth domain and the network will provide atomic clock accuracy to missions in deep space. When complete, the Next Gen architecture will offer new services for orbit determination, trajectory and maneuver planning, and surface vehicle position determination to enhance space system autonomy.

Space Internetworking: Network layer services provide reliable data delivery over unreliable physical links eliminating the need for applications to store and retransmit mission data. SCaN is currently introducing Internet Protocol (IP)-based networking within its individual networks. Future network layer service will expand to full establishment of IP-based and Delay/Disruption Tolerant Networking (DTN)-based interoperability among space and terrestrial networks. Internet Protocol v6 (IPv6) service relies on IP Security (IPSec) while DTN relies on Bundle Protocol Security (BPSec) [2].

Broadcast/Messaging: Broadcast services are a new category of service to support the communication, navigation, and network capabilities of the Next Gen networks. A beacon from the relay satellite to the user spacecraft carrying low data rate traffic will synchronize the network and missions by providing regular updates of the network's state, including time, service availability, relay maneuvers, relay ephemeris, and other information simultaneously to all missions without the need for individual missions to schedule service. The beacon will provide the forward link component of the two-way channel necessary for User Initiated Services, where spacecraft autonomously request services. Giving missions access to a broadcast service's forward data volume capacity will reduce the need for scheduled forward service, improving the network's overall efficiency and simplifying mission control operations.

Radio Metrics: Time transfer services will enhance operations, complement navigation services, and enable new science. Precise time synchronization of the network and missions allows for the application of new multiple access techniques, thereby increasing the number of simultaneous missions supported by the network. Transition to one-way range and Doppler tracking also requires synchronization but will allow for new processing/routing relay satellite designs in place of bent pipe relays. Timing error reduction is necessary to translate the accuracy of optimetric observations to accuracy in orbit determination. Radio and optical science applications will benefit from an increased time and frequency precision of the network and the mission.

Application Layer Services: With IP and DTN networking services, the entire realm of off-the-shelf 'apps' or application layer services becomes available to any space system. Basic services envisioned include end-to-end file transfer, messaging, and email to Mars. QoS levels similar to those offered on terrestrial networks will be possible (subject to speed of light limitations).

Missions will receive common application layer services from the network across near Earth and deep space. The interfaces and protocols used will be common across all networks to the fullest extent practical, taking into account the physics, mission constraint, and operational differences between near Earth and deep space missions.

4. Next Generation Architecture Characteristics

The Next Generation Architecture can be viewed as distributed across planetary networks, corresponding to the planetary bodies currently under study by NASA and other space partner agencies: the Earth, Mars, and the Moon. Each individual planetary network contains similar capabilities or elements such as science orbiters, relay satellites, surface elements, and ground stations. These common elements lead to common space interfaces for proximity and trunk links, with connectivity between local or proximity elements and the trunk links back to Earth, respectively, as illustrated in Figure 1. Within the Mars system, for example, communications between any two elements will only require proximity links, e.g., between relay(s) in aerosynchronous orbit, spacecraft in low Mars orbit, and surface systems, thus, limiting trunk links (Mars relay to DSN) to Earth which involve long delays. Proximity links require less power than trunk links, less stringent pointing and tracking, and have higher link availability.

A planetary network such as the Earth Network includes both space-based relay satellite and ground-based ground station capacity. In the NextGen architecture, the current SN/TDRSS, NEN and DSN evolve into the Earth Network. Aggregate mission needs determine the mixture of capacity between the space and ground segments.

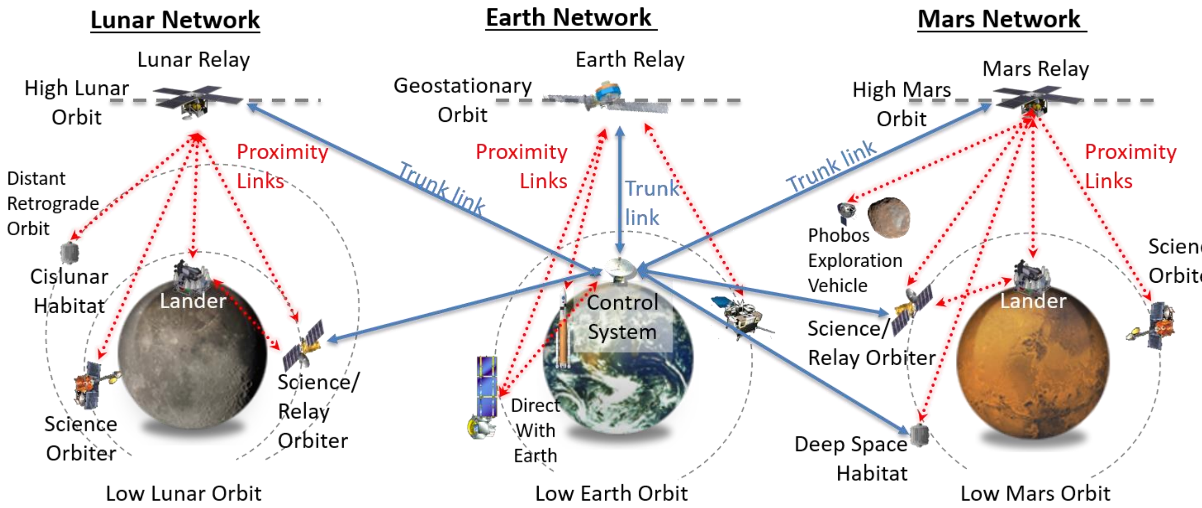

Figure 1– Initial Planetary Network Architecture

A Lunar Network may have orbiting Lunar relays, Lunar positioning capability (functionally similar to GPS), and surface Lunar communication terminals that may be provided by NASA, commercial and/or international partners [10]. The Lunar Network may emerge in the mid-to-late 2020's to provide service to science and robotic exploration missions especially to polar and far-side locations that are not serviced or partially serviced by trunk (directly to and from Earth) links.

Today, the Mars Network includes three NASA science spacecraft with relay capabilities and ESA's Mars Express and Trace Gas Orbiter. Over time, NASA will evolve its Mars capability from relay packages embedded in science spacecraft towards dedicated Mars Relay satellites to meet increasing science needs in the 2020's and new Human Exploration needs in the 2030's.

Near Earth Relay Satellite Architecture: Figure 2 depicts an early deployment concept of the Earth relay satellite architecture (a subset of the Earth network). The architecture is comprised of NASA and commercial service satellite nodes and ground station. For terrestrial through GEO coverage, NASA requires 24x7 network access for mission spacecraft, provided through GEO or MEO orbits with varying field-of-view; with additional nodes providing overlapping coverage areas, increased network bandwidth, and increased network availability. A combination of optical and RF relay and direct-to-ground links are envisioned for mission users along with optical cross links to route data to continental U.S. based ground stations

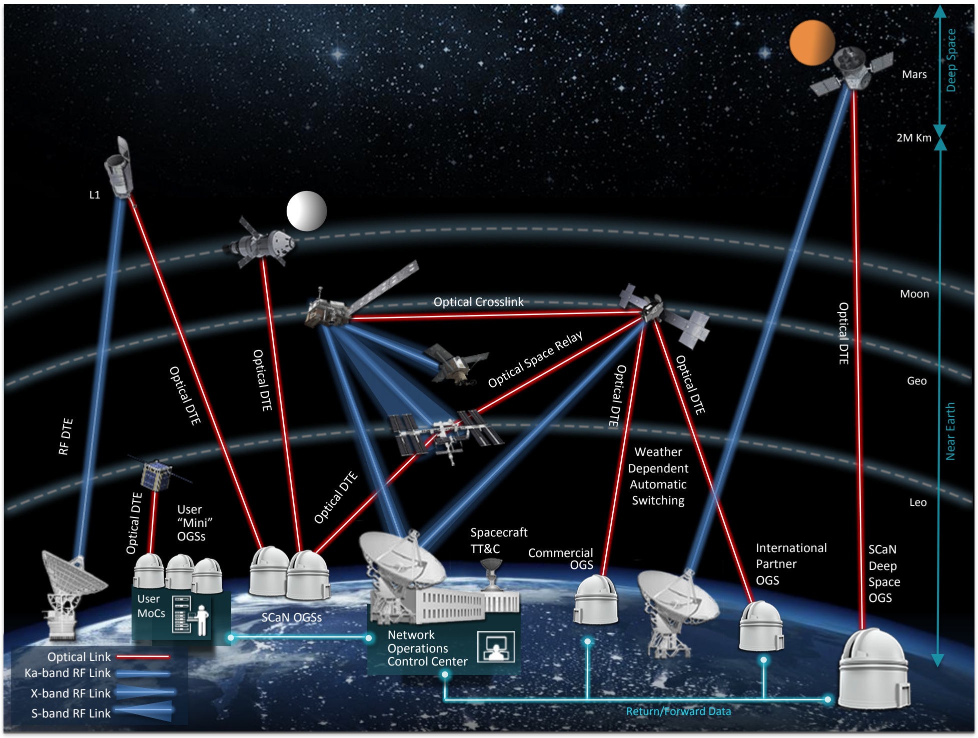

Figure 2 – Initial near Earth Communications and Navigation Architecture Concept

New services to missions in low Earth orbit (LEO) and beyond include: high rate optical communications with up to 10 Gbps user links and up to 100 Gbps cross and space-to-ground links, IP and DTN internetworking, and broadcast and on-demand signaling for asynchronous messaging and autonomous network scheduling services. Other capability includes high rate Ka-band data link to the ground, on-board data processing, routing, and storage, and secure and resilient spacecraft command and control. Some legacy architecture assets such as ground antennas and elements of the existing TDRSS fleet are expected to remain operational until the 2040 timeframe and will continue to provide current data delivery services to existing user spacecraft such as: multiple access over S-band, high rate single access Ku- and Ka-band, and moderate to low rate single access S-band, while new services are added.

Finally, NASA's initiative to introduce automation, cognition, and networking features to improve the efficiency and performance of the service and provisioning operations enhances the replenishment of the relay satellite network. New features include enhanced service management including autonomous scheduling and operation, demand access service, service provision and monitoring, and service accounting; adaptive rate communications to increase throughput, broadcast and message facilities with network state information to support navigation and communication services as well as network operations; and use of open commercial and international standards for interoperability among commercial and partner assets (e.g. relays, ground stations, control centers).

Additional relay satellites will provide the Next Gen space-based Earth network capacity. A combination of business approaches may be used to provide flexibility in the way capacity scales to meet mission needs and manage costs. NASA may retain ownership of essential core capacity to mitigate risks of using commercial services and ensure the ability to meet government continuity of operations requirements. Commercial services and international partner agencies cross-support could provide additional capacity. Strategies for evaluating various business approaches intended to minimize cost and manage risk are underway.

NASA continues to work with commercial industry and international partners to formulate architecture approaches and concepts. Several companies recently conducted architecture studies for near Earth and deep space under contract to NASA. The output of those studies are available in References 3,4,5,6. The concepts presented in this paper consider and in some cases incorporate portions of those studies.

<u>Deep Space Mars Relay Satellite Architecture</u>: The Mars Network of the future includes two to three dedicated relay orbiters in areostationary/areosynchronous orbit and a full relay payload on each of NASA's science orbiters. The network provides continuous coverage to human exploration activities on and around Mars as illustrated in Figure 3. In addition, during the early phase of Mars exploration, the relay will be capable of supporting moons Phobos and Deimos as potential targets of exploration in the Mars vicinity. Dedicated Mars relays will also provide near-continuous trunk link availability to Earth, thus minimizing end-to-end

forward/return data latency. Trunk lines to Earth will operate using RF (Ka- and X-band) up to 125 Mbps and with optical links up to 300 Mbps with forward links operating at 50 Mbps.

Each relay orbiter communicates with the mission orbiters (science or exploration spacecraft) and surface vehicles (e.g., habitats, communications stations, landers, and rovers) via proximity links. The maximum data rate of these local links for each mission is nominally 50 Mbps (considering either Ka-band or optical). Each relay orbiter, functioning as a DTN node, provides full network-layer services, plus on-demand, simultaneous/concurrent access by surface vehicles via proximity links and to mission orbiters via crosslinks.

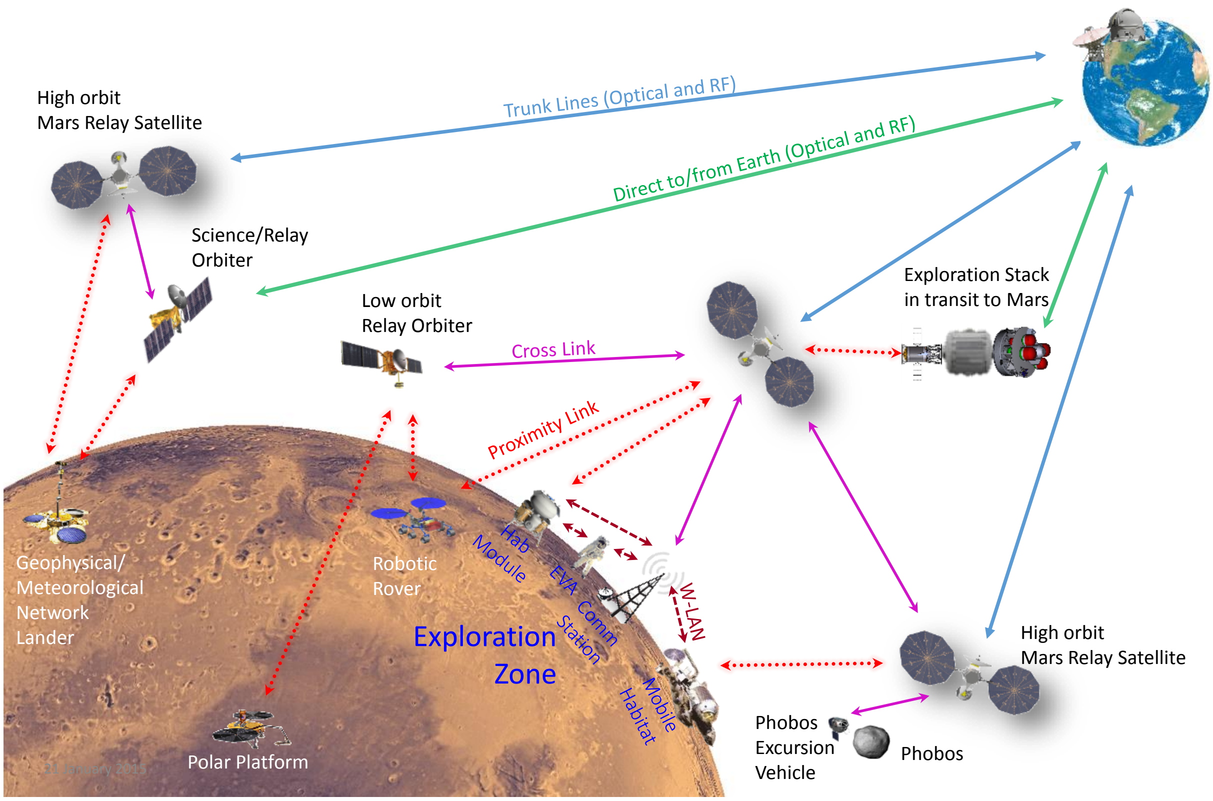

Figure 3 – Deep Space Mars Communications and Navigation Architecture Concept

4. Commercial Communication Services

NASA intends to leverage the expanding capabilities of the U.S. satellite communications (SatCom) industry and foster its continued growth for both government and commercial users. The Telecommunications Industry Association (TIA) estimated the global telecommunications market at *$5.6 trillion* in revenue in 2015 and predicted the U.S. market to reach $1.85 trillion in 2020 [7]. The Satellite Industries Association (SIA) estimates that the satellite market in 2016 was $241B and has doubled in the last 10 years [8]. Of this total, satellite services accounts for $127B including telecommunications, Earth observation, science, and national security. NASA will monitor the progress of the industry including the emerging global space internet segment and its planned constellations of 100s of satellites for potential applicability of new capabilities and services. The technology investments made by the telecommunications industry vastly exceed those made by NASA. NASA's technology development will thus complement and extend commercial telecommunications capabilities selectively to meet unique space environment requirements and to provide capabilities that are beyond the commercial marketplace.

SatCom industry capabilities available for NASA use include payload development, spacecraft integration, launch vehicle integration and launch services, spacecraft and network operations, hosted payload services, and commercial space and terrestrial telecommunications services. NASA's Next Gen architecture will use a combination of: (1) commercially owned and operated capabilities and services without NASA ownership and operational responsibilities; (2) hosted payloads with options for varying combinations of ownership and operation (i.e. government owned payload, commercially provided spacecraft); and (3) select government owned and operated elements on dedicated free-flyers.

5. Capabilities and Technology Investment

New mission capabilities enabled by network enhancements rely on specific technology investments and advancements that are fundamental to the mission experiences desired of the Next Gen architecture. Investments in technology involve both high risk/high return technologies and focused development on nearer term capabilities.

Demonstrating new capabilities with existing ground and space assets, ground-based demonstrations, or flying technology demonstration missions such as the Laser Communications Relay Demonstration mission [9] will be essential to reduce risk, smoothly transition to operations, and avoid the typical multi-year project lifecycle for mission adoption. Reducing and sharing the operational and technological risk will help motivate missions to adopt new capabilities as they are deployed operationally. SCaN and the mission community must move forward hand-in-hand to advance network and mission capability successfully in an increasingly constrained budget environment.

The future architecture will improve the mission experience through network enhancements and technology advancements shown in Table 2.

Individual technologies to enable the high data rate Ka-band and optical services include optical/laser terminals and ground stations, detectors, pointing and acquisition systems, beaconless pointing, multi-mode, reconfigurable transceivers, and Ka-band electrically steerable antennas. Additional network capacity and coverage in planetary regimes will be provided by additional Ka-band equipped NEN stations, communicating with multiple spacecraft per antenna aperture techniques, and Mars relay satellites placed in orbits optimized for communication service volumes.

Improved access, connectivity, and control will come through enhanced multiple access services (either Ka-band or optical) providing a higher number of simultaneous beams coupled with options of on-board routing (enabling mission-to-mission links without going to the ground), and space-based or ground-based beamforming. These capabilities will enable new science concepts and increase network capacity. Bidirectional multiple beams will enable a Demand Assigned Multiple Access (DAMA) type provisioning for User Initiated Service (UIS) requests; a service request messaging system to arrange on-demand forward and return high rate services.

The TDRSS Demand Access System (DAS) is a contemporary precursor to such a demand-assigned access service. In general, demand-assigned access services will trade maximum forward and return achievable data rates for greater availability, broader service volume, higher number of simultaneous missions, and lower latency. An available forward data delivery mechanism, such as a global relay-sourced beacon or broadcast beam will provide the necessary path for messages of confirmation and coordination between user spacecraft and ground resource allocation.

Smallsats represent a potentially unprecedented increase in the number of spacecraft simultaneously using the network. Traditional look-ahead scheduling, manual de-confliction, and reliance on human operators will break down under the current architecture. A transition to automated UIS requests will mitigate the coordination risk posed by a large increase in the number of missions requesting SCaN services.

Table 2. Mission Capabilities, Network Enhancements, and Advanced Technologies

Advanced Technologies	Network Enhancements	Mission Capabilities
Optical communications	Increased capacity	
Multiband, multimode Ka-band & optical user terminals	Improved multiple access service	Increased data volume return
Electrically steered Ka-band antennas	Network layer service including IP and delay/disruption tolerant networking	Assured data delivery
On-board processing and routing	Adaptive/automated link configuration, navigation, and service requests	Reduced user terminal burden (size, mass, power)
Cognitive communications		Synchronization, time, automated positioning
International standards	Enhanced security and resilience	Greater control, access, connectivity, efficiency
Ka-band and optical multiple access techniques	International & commercial cross support	

Automated dissemination of ground and relay asset locations to missions through the network-provided broadcast service will complete the capability required for antenna pointing. Future onboard autonomous navigation (autonav) will enable precise location and trajectory knowledge.

New services offered in the future architecture include assured data delivery, synchronization, more precise positioning and navigation, and enhanced data security. Assured data delivery provided by the network (as opposed to mission) will reduce mission burden and be available through a common network interface, continuing the network integration begun over the last few years. This network experience will be consistent across the SCaN Networks using a data delivery protocol such as DTN, eliminating the need for mission-managed repetition of data transmission, thereby reducing mission buffering requirements and simplifying operations. Synchronization (time transfer), positioning, and navigation will be improved services in each domain and will rely on the GPS and GNSS, where appropriate.

6. Conclusion

The Next Generation Architecture will provide unprecedented new mission capabilities:

- Increased data rates from 10's to 100's of Gbps;
- Greater mission flexibility, autonomy, and efficiency using standardized network-layer services providing assured data delivery and more accurate optimetric tracking;
- Enhanced spacecraft Ka-band and optical terminals with reduced mission burden;
- Streamlined network management at lower cost to NASA; and
- Growth of the commercial SatCom market into LEO and beyond based on an open, international standards-based architecture.

Implementing the architecture in a cost effective way will entail:

- Collaboration with international partners and commercial service providers to allow for the incremental procurement of services with short lead-time and at an affordable cost to meet unexpected growth in customer demand.
- Standardizing hardware, software, and protocols across the network (e.g. relays, ground stations, and mission terminals).

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