Architecting the Communication and Navigation Networks for NASA's Space Exploration Systems

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Abstract *NASA is planning a series of short and long duration human and robotic missions to explore the Moon and then Mars. A key objective of the missions is to grow, through a series of launches, a system of systems communication, navigation, and timing infrastructure at minimum cost while providing a network-centric infrastructure that maximizes the exploration capabilities and science return. There is a strong need to use architecting processes in the mission pre-formulation stage to describe the systems, interfaces, and interoperability needed to implement multiple space communication systems that are deployed over time, yet support interoperability with each deployment phase and with 20 years of legacy systems. In this paper we present a process for defining the architecture of the communications, navigation, and networks needed to support future space explorers with the best adaptable and evolable network-centric space exploration infrastructure. The process steps presented are: 1) Architecture decomposition, 2) Defining mission systems and their interfaces, 3) Developing the communication, navigation, networking architecture, and 4) Integrating systems, operational and technical views and viewpoints. We demonstrate the process through the architecture development of the communication network for upcoming NASA space exploration missions.*

Keywords: system architecting, architecting process, communication, navigation, tracking, space exploration, space network, ground network, space systems

1 Introduction

1.1 Background to NASA Methodologies

NASA has a long history of aggressively using the system engineering processes described in the NASA System Engineering Process Handbook SP-610S on mission developments. As space exploration is, by its nature, a complex system of systems (SoS), effective use of SoS engineering processes and methodologies is being pursued by the NASA Space Communication and Navigation (SCaN) program throughout each phase of exploration architecture development. This process addresses large-scale inter-disciplinary problems with multiple, heterogenous, distributed systems that involve networks at multiple levels and multiple domains.

NASA's near term exploration plans [1] call for human and robotic missions to the Moon [2, 3] and require development of architecture in the mission formulation stage. Existing resources and legacy systems, such as International Space Station (ISS) and the existing space-based and ground-based network assets, will be integrated with new systems developed and deployed at different exploration phases; yet they will work as an integrated system of systems for supporting future space exploration missions. Communication systems which must interoperate include the crew exploration vehicle (CEV), Earth relay satellites, lunar relay satellites [4], lunar surface communication infrastructures [5], Mars relay satellites, etc. Yet all of the existing and future assets have to interoperate to realize the high capacity, high performance SoS attributes needed to provide superior communication, navigation, timing, and information services. These capabilities, driven by emerging exploration requirements, [6, 7] will enable future astronauts to conduct space exploration, communicate with Earth-based scientists and excite future generations of explorers with high definition video and in-presence exploration, and return safely to earth at the end of the mission.

The process for describing the needed communications, navigation, and networking entities as a SoS construct is being accomplished by using standard system engineering methods for defining and gathering capability requirements, and identifying a generalized initial architecture. Additional steps include decomposing the architecture and using the Department of Defense Architecture Framework (DoDAF) operational, system, and technical view diagrams, and then refining the architecture as actual functional requirements are identified during the architecture development process.

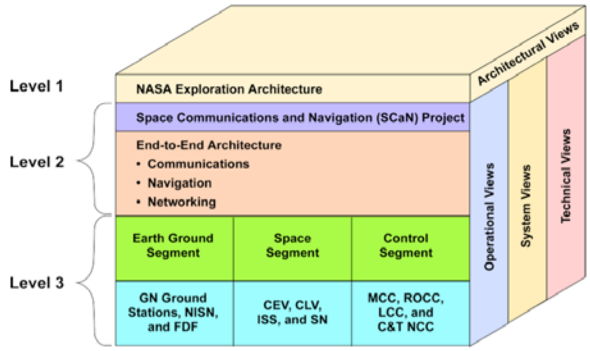

Figure 1. Architecture Decomposition

2 Architecture Decomposition Process

The SCaN Network will interface with all exploration missions from pre-launch testing through crew recovery at the end of each mission. SCaN and its resources will support each mission at launch, in low earth orbit (LEO), in early docking with ISS, in transit to and orbit around the Moon or Mars, during lunar or Mars landing, on the lunar or Mars surface, and during the trip back to Earth. SCaN will be compatible with space exploration customers to provide seamless communication, tracking, and timing services.

The SCaN system development, including CEV-ISS mission phase (phase 1) and follow-on lunar phases, will take place over multiple phases, each spanning multiple years during which the political, management, and contractual arrangement can change. Further complexity is added by the sheer fact that the post phase 1 system has to provide communication and tracking services to space and planetary surface assets based on multi-layered architectural information systems.

During the CEV-ISS mission phase, which this paper addresses, SCaN will provide the communications and tracking services to support CEV-ISS missions. However, the SCaN architecture will be designed in a manner that will fully support later lunar and planetary mission upgrades as well.

The architecture views will convey the SCaN architecture to all the stakeholders (customers, system engineers, implementers, etc.) to assist them in verifying that the SoS will address their concerns. The depiction of the CEV-ISS mission phase SCaN architecture in this paper has been developed using the Department of Defense Architecture Framework (DoDAF) views as a starting point. The SCaN Network requires the integration of architectural practices across multiple disciplines. Such practices are based on the views of disparate stakeholders in the architecture; model-based analyses of elements of the architecture by subject-matter experts; and collaboration among the stakeholders, the architect, and the experts during the evolution of the architecture (as captured by view development) to final consensus.

A hierarchical document structure is used to present the complex CEV-ISS mission phase SCaN Network architecture in an efficient manner to a variety of users with differing needs. Thus, the amount of detail presented increases with each successive level as shown in **Figure 1**. The SCaN Network architecture is described in terms of its operational, system, and technical attributes so that the user can gain insight into how it fulfills its mission objectives. The SCaN Network architecture is decomposed into segments and elements. In order to relate the parts of the CEV-ISS mission phase SCaN Network architecture to its whole, the descriptions for each level are intended to show how segments and elements support the operational, system, and technical aspects of the architecture.

3 Defining NASA Mission Systems and Their Interfaces

A number of NASA exploration architecture teams and study groups have defined the systems to be deployed during the exploration missions. CEV is one of the critical systems which will carry the astronauts to Earth orbit and beyond. Several additional systems come into play to carry CEV into space and then to the Moon. A lunar outpost to be developed on the surface of the Moon will require another set of systems to support the lunar exploration missions which follow. In **Figure 2**, the notional communication and navigation systems shown provide the interfaces among the explorations systems on the Earth surface, in Earth orbit, in trans-lunar space, in lunar orbit and on the lunar surface. Many of the systems are dynamic in nature, which adds to the complexity to be addressed during the development of the architecture.

4 End-to-End Communication Architecting Process

The SCaN Network architecture will pursue an aggressive adoption of common communications links and protocols, drawing from standards-based IP network technology and effective use of layering to isolate functions and to aggregate common functions to maximize interoperability.

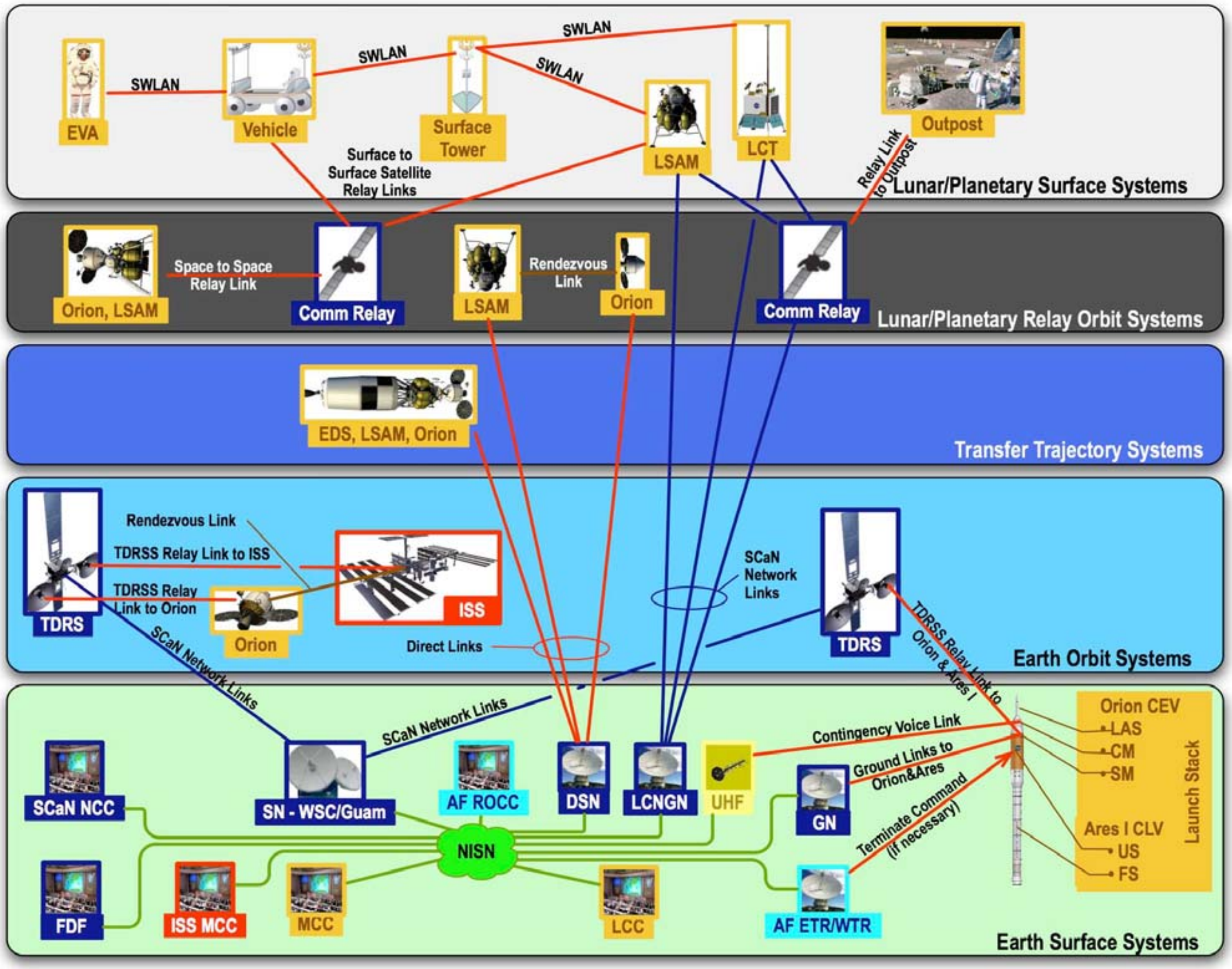

Figure 2. Notional System Communication Navigational Functions and Interfaces

NASA's space communication system must be flexible and evolvable enough to adapt to changing technology, changing missions, and user needs that will inevitably occur over the next 20 years. With the short Earth-based Internet generational life cycles and communication-rich appli-cation training of future astronauts, the space-based command, control, communication, and information (C3I) capabilities will need to be raised to meet the expectations of future users.

4.1 Communications Architecture

The SCaN Network architecture for CEV-ISS missions will include the NASA Ground Network (GN), Space Network (SN), NASA Integrated Services Network (NISN), Flight Dynamics Facility (FDF), and new SCaN Network Control Center (NCC), which are depicted in **Figure 2**. The SCaN Network communication architecture will provide end-to-end S-band services to the CEV, end-to-end Ka-band services to the CEV, and end-to-end S-band services to the CLV during all CEV-ISS mission phases. The SCaN network end-to-end S-band and Ka-band services will support communications, radiometric tracking, and timing synchronization activities. For CEV-ISS missions, the end-to-end services will be based upon the Internet Protocol (IP) as requested by the exploration missions; therefore, the SCaN Network will support the end-to-end transfer of IP packets between the CEV/CLV and ground-based mission elements like the MCC, as depicted in **Figure 3**.

4.2 IP Compliant Networking Architecture

The SCaN Network consists of numerous new and legacy system elements included in the Ground Network (GN), Space Network (SN), Deep Space Network (DSN), NASA Integrated Services Network (NISN), and network elements that will be added as space exploration extends to the Moon and Mars. Some system elements, such as the Deep Space Network (DSN) and Johnson Space Center (JSC), have over 20 years of legacy hardware, software, and policies. These networks are administered by different control center software systems and operational policies. To put together an IP compliant end-to-end management system with human rated real-time responsiveness requires stitching numerous different administrative systems and domains with different policies, priorities, and management

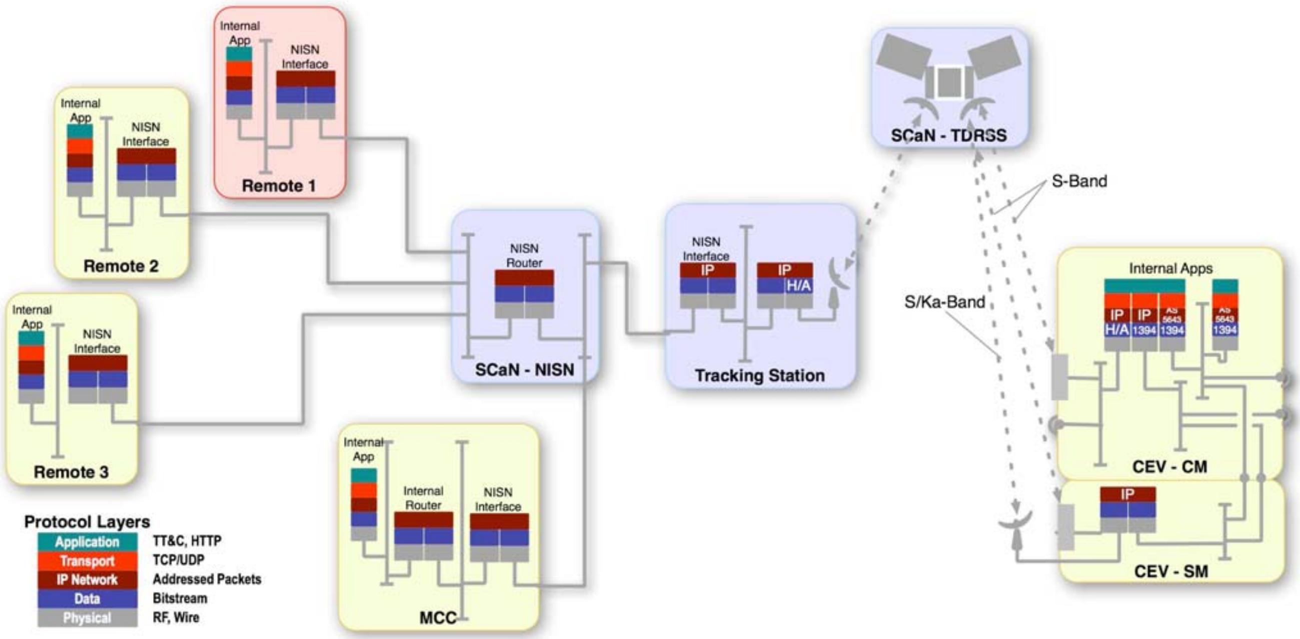

Figure 3. Layered IP Network Links Ground and Space Together

systems into an integrated system that can plan, allocate, control, deploy, coordinate and monitor the resources of the network to support space exploration. Many of the legacy systems supporting existing space missions also have to evolve into the future architecture to meet the space exploration mission requirements. Currently, GN, SN and DSN do not provide a network interface to missions; we need to extend network layer capabilities to space. Quality of Service (QoS) over different domains poses another challenge in mapping and preservation of QoS integrity over multiple domains. With human lives at stake on Mars or the Moon, automation, automatic error recovery, and local distributed control will have to be pervasive in the architecture.

4.3 Propagating Navigation Architecture to Space

As the SCaN Network is deployed in space from Earth-based to lunar and Mars network support, a system of coarse and fine-grain navigation references will be integrated with the SCaN Network to enable future space explorers and applications to access navigation and position services.

5 Applying DoDAF Views

The use of DoDAF methodologies is not mandated for NASA systems, but selected key DoDAF views are being used to identify architecture issues and gaps. This is being done by utilizing the generation of crosscutting views of the multitude of NASA as-is legacy systems and IP network compliant decomposition views of the future network layers and network-centric architecture. The architecture diagramming methods used range from the defined DoDAF graphical views to custom diagrams that use pictorial icons to represent nodal entities.

Three views are defined within DoDAF for an architectural description, namely, operational views (OVs), system views (SVs) and technical standard views (TVs). We have adopted a subset of the OV and SV products to describe the CEV-ISS Mission phase that NASA is initiating as a precursor to future lunar and Mars exploration. Communication and navigation systems and operational activities evolve over different mission stages. For example, testing communications to crew and launch vehicles prior to launch, versus supporting communications and tracking of the crew vehicle in low-Earth orbit, involve different systems and operations. The graphical products used to capture evolving communication and navigation scenarios provide an architectural description for each stage of the mission. For the CEV/ISS mission phase, four main mission stages were used, namely, (i) pre-launch testing; (ii) launch and ascent; (iii) LEO-orbit including rendezvous and docking with the International Space Station (ISS) and (iv) de-orbit, re-entry, descent, landing and recovery. A few examples of the architectural description products are presented next. **Figure 4** shows an OV-2 diagram that describes the operational node connectivity for the mission. The colored boxes indicate the operational nodes. The connections between the nodes are considered needlines; the bubbles along the needlines display the information that must be passed from one node to another to enable each node to accomplish its operational tasks.

Figure 5 shows an example of a system interface diagram (SV-1) representing the first 350-seconds of launch. Critical Events include first-stage separation and

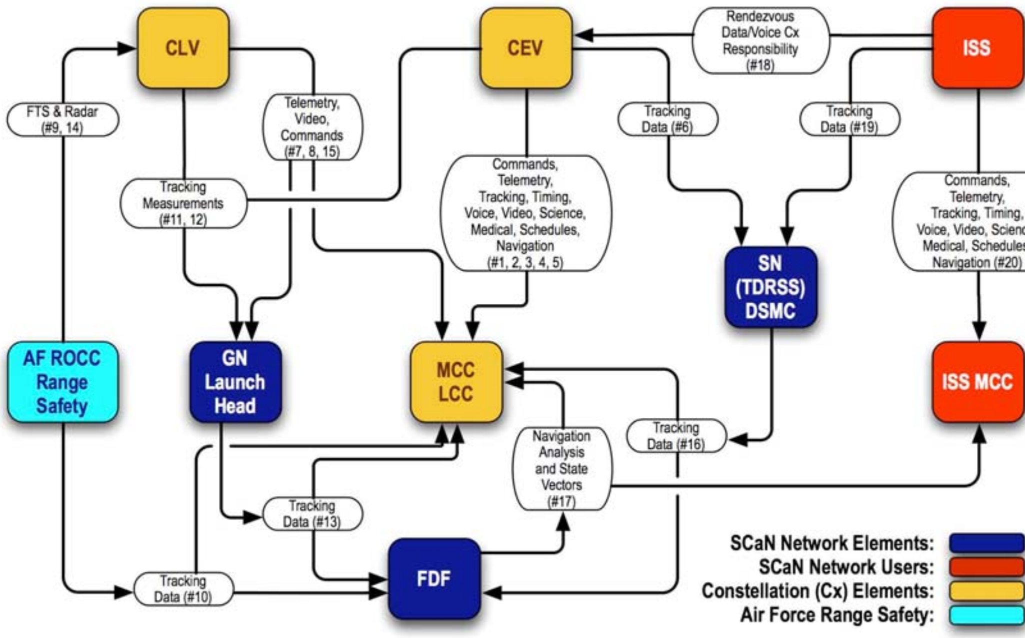

Figure 4. DoDAF OV-2 Operational Node Connectivity Description

establishing primary communications with the TDRS satellites. During the first 350 seconds, the CLV may be downlinking live imagery to the launch-head. Interfaces between US Air Force range safety and CLV in the event of required flight termination are also shown.

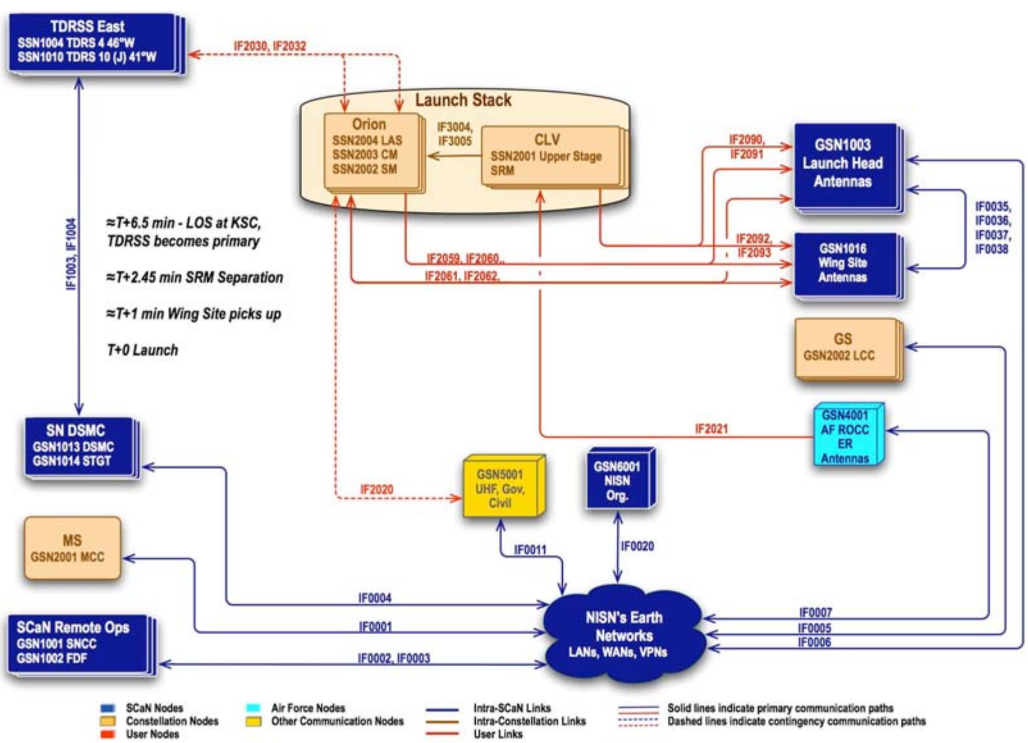

Figure 5. SV-1 for Launch and Ascent Phase of the CEV-ISS Mission , T0 to ≈T+6.5 minutes

6 Conclusions and Future Work

We have described a system engineering and system architecture process for decomposing the NASA Space Exploration system-of-system vision into the incremental upgrade components that will enable NASA's future communication, navigation, and timing architectures. As the program marches forward, future innovations in the use of architecture processes and tools are anticipated to create a world-class infrastructure to advance man's exploration in space.

The next step is to pursue an aggressive plan to develop and use a rich suite of integrated modeling and simulation processes and tools, a suite of system engineering and integration tools, and a distributed testbed network of multiple system integration laboratories.

With effective integration of the development environment and tool fidelities, the modeling and simulation tools can be useful in all phases of implementation including architecture definition, requirement decomposition, design, test definition, test validation, training, and the resulting operations.

During the architecture and requirements definition phases of the program, modeling and simulation are used to study architecture trade-offs for making key architectural decisions based on identified driving requirements, validation of requirements feasibility, comparison of trade alternatives, performance optimization, and risk reduction by simulating the operational scenarios. System engineering tools to manage requirements and architecture definition are key in automation of system engineering functions such as requirement flowdown, test planning, risk management, functional and operational flow decompositions.

During the test phase, modeling and simulation tools integrated with an emulation testbed environment can cost-effectively reduce program risk by verifying and validating operational test scenarios, identifying early integration and validation risk areas, performing metric collection, and refining details for concept of operations (CONOPS) and operational procedures.

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