NASA/TM—2015-218823

Operational Concepts for a Generic Space Exploration Communication Network Architecture

William D. Ivancic, Karl R. Vaden, Robert E. Jones, and Anthony M. Roberts
Glenn Research Center, Cleveland, Ohio

June 2015

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Technical Report Server—Registered (NTRS Reg) and NASA Technical Report Server—Public (NTRS) thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers, but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., "quick-release" reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Fax your question to the NASA STI Information Desk at 757-864-6500

- Telephone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Program
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM—2015-218823

Operational Concepts for a Generic Space Exploration Communication Network Architecture

William D. Ivancic, Karl R. Vaden, Robert E. Jones, and Anthony M. Roberts
Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

June 2015

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703-605-6000

This report is available in electronic form at http://www.sti.nasa.gov/ and http://ntrs.nasa.gov/

Operational Concepts for a Generic Space Exploration Communication Network Architecture

William D. Ivancic, Karl R. Vaden, Robert E. Jones, and Anthony M. Roberts
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

This document is one of three. It describes the Operational Concept (OpsCon) for a generic space exploration communication architecture. The purpose of this particular document is to identify communication flows and data types. Two other documents accompany this document, a security policy profile and a communication architecture document. The operational concepts should be read first followed by the security policy profile and then the architecture document.

The overall goal is to design a generic space exploration communication network architecture that is affordable, deployable, maintainable, securable, evolvable, reliable, and adaptable. The architecture should also require limited reconfiguration throughout system development and deployment. System deployment includes: subsystem development in a factory setting, system integration in a laboratory setting, launch preparation, launch, and deployment and operation in space.

Keywords:
Communication Architecture, Communication Networks, Protocols, Telemetry, Security

---

Contents

*Corresponding author

1. Goals

This document was produced as part of an effort to create a Generic Space Exploration Communication Network Architecture. The overall goal of this effort is to design a communication network for manned space exportation that is:

1) Affordable, 2) Deployable, 3) Maintainable, 4) Securable, 5) Evolvable, and 6) Reliable (Robust). Failure to meet items 3 and beyond will result in a system with significant hidden costs that only materialize after full deployment.

A secondary goal is to design the network such that it requires limited reconfiguration throughout system development and deployment. System deployment includes: subsystem development in a factory setting, system integration in a laboratory setting, launch preparation, launch, and deployment and operation in space – cradle-to-grave (end-of-mission).

2. Introduction

This document is one of three. It describes the concepts of operation for a generic space exploration communication architecture. The purpose of this particular document is to articulate the problem space and identify communication flows and data types. Two other documents accompany this document, a security policy profile [1] and a communication architecture document. The operational concepts should be read first followed by the security policy profile and then the architecture document. One intent of these three documents is to provide sufficient detail to enable development of queryable System Modeling Language (SysML) models.

This document defines the Operational Concept (OpsCon) for a generic space communication network for human space exploration beyond low Earth orbit. The document also applies to robotics space exploration, since robotic space exploration is considered a subset of human space exploration. Operational Concepts identify key capabilities and assumptions. They are used to define necessary functionality and performance expectations used to formulate requirements. For our purposes, OpsCon needs to be at sufficient detail to identify communications flows, data types, quality-of-service requirements and security requirements. The document also includes a generic Design Reference Mission (DRM). This document is patterned after NASA's Constellation Design Reference Missions and Operational Concepts Document [2] but tailored for communications network design.

3. Terminology

In order to ensure understanding, a common vocabulary must be established. The following sections attempt to define a common vocabulary relative to communication networking and data security.

Data vs. Information In this document, when discussing communication network security, we mean securing data and networks not securing information. Why? Because information is all encompassing and securing information quickly becomes an unbounded problem. Thus, it is important to understand the difference between data and information. Data is information in its purest form. Information can be more than just data.

Information is knowledge gained through study, communication, research, instruction, etcetera. Information can also be factual data. Information is unbounded because information can be inferred. Information can be inferred from voice inflections or body language. If data is encrypted, one might infer that that particular data is of more importance to someone than unencrypted data. Using data-mining one can combine collections of data to enable one to infer information. Examples include inferring medical conditions from prescription data or that a military action may be taking place from a sudden increase in pizza deliveries to the pentagon.

Data is factual *(not inferred)* information used as a basis for reasoning, discussion, or calculation. When considering network communications, data is information *in numerical form* that can be digitally transmitted or processed.

Phases of Mission For the purpose of common terminology the aviation community[1] developed a common terminology for various phases of flight [3]. The list of phases provides guidance for classification of when (what phase in flight) an aviation occurrence has happened and aids in reporting. These phases include: 1) Standing,

[1] The International Civil Aviation Organization (ICAO) and the Commercial Aviation Safety Team (CAST), which includes Government officials and aviation industry leaders, jointly chartered the CAST/ICAO Common Taxonomy Team (CICTT) with developing common taxonomies and definitions for aviation accident and incident reporting systems.

2) Pushback, 3) Taxi, 4) Take Off, 5) Initial Climb, 6) En Route, 7) Maneuvering, 8) Approach, 9) Landing, 10) Emergency Descent, 11) Uncontrolled Descent, 12) Post Impact, and 13) Unknown. The FAA also defined terms for phases of flight [4]. These include: 1) Preflight, 2) Terminal, 3) En Route, and 4) Oceanic. The following is an attempt to develop similar terminology for the Space community relative to communications requirements at various stages of a mission. As the goal of the communication architecture is cradle-to-grave (end-of-mission), we use the term "mission phase" instead of "phases of flight". Each of these mission phases has different communication requirements, data flows and, in particular, different communication link capabilities.

Subsystem and System Integration is the phase of the mission were systems and subsystems are being developed at the factory and/or being brought together at a facility for integration and testing. Since there is a desire to have limited reconfiguration from cradle-to-grave it is imperative to not ignore this phase of development.

Prelaunch is when the payload has been integrated with the launch vehicle and the combined system is on the launchpad.

Launch is the point at which the vehicle leaves the ground and is transitioning to its final destination. By final destination we mean the stage at which the payload is deployed, any antenna systems are deployed, and it has reached a stable flight dynamic. In order to combine payload systems into a larger entity prior to En Route operations in many cases the initial "destination" may be a Low-Earth Orbit (LEO).

LEO Rendezvous may be the final destination. Or, it may be a staging area were large subsystems are combined into a major system prior to En Route operations.

En Route is the phase of the mission were the system has been stabilized and is on its way to its final destination or returning from its final destination.

Destination Rendezvous is the staging area around a planet or asteroid or some other entity prior to descent and surface operations. Destination rendezvous may be the final destination as in the case, for example, of a Mars relay satellite.

Planetary Descent is the phrase from orbit around an entity to landing on that entity.

Surface Operations is the phase of the mission where surface operations occur. For example, for a Mars exploration rover, this is the phase where the rover is being operated and science missions are being accomplished.

Planetary Departure Is the point at which the vehicle leaves the planet and reaches a stable flight dynamics.

Earth Reentry is the period from when the space vehicle enters into the Earth's atmosphere through touchdown (or splashdown).

Region When discussing communications and networking, distance matters. Distance correlates to propagation delays (time) as the speed of light is finite. Distance also correlates to bandwidth as received radiated power is inversely proportional to the square of the distance. Thus, when discussing networking, communication links and protocols, it is important that we identify the "Region" for which the analysis is taking place. For a generic space exploration communication architecture, we arbitrarily and purposefully define three regions:

Local is anything internal to a structure, or within a few hundred meters of a structure. Thus time delay is insignificant and bandwidth is fairly large (10s of Mbps or more).

Neighborhood is anything beyond "local" and within a 500 msec Round Trip Time (RTT) [2]. In general, Neighborhood will likely be between a surface system and something orbiting that planetary body. General, unmodified Internet protocols are likely to work reasonable well at these minimal propagation delays.

[2] 500 msec RTT corresponds to a satellite in a circular geosynchronous orbit in the plane of the Earth's equator with a radius of approximately 42,164 km (26,199 mi) measured from the center of the Earth (a.k.a Geostationary Orbit (GEO).

Afar is communication between entities that are great distances apart. Afar would be interplanetary communications or even lunar-earth distances. Internet Protocol (IP) packets can be used at these distances and some Internet Protocols can work at these distances. However, care must be taken to ensure proper operation given the long propagation delays.

Telemetry - System and subsystem configuration and/or health and status data. The word is derived from Greek roots: tele = remote, and metron = measure.

4. Data

When designing a communication network one needs to understand what type of data is flowing through the network and what the characteristics of that data are. Data becomes quite complicated as will be shown in the following subsections on data. There are many types of data. There are multiple characteristics regarding security as well as multiple characteristics regarding Quality-of-Service (QOS). After analysis of the various data we designated there to be five types of data, three types of security sensitivity levels, three types of security objectives and three levels of impact relative to security. In addition, when considering quality of service, we identified three priority levels and six service sensitivity levels. From this we conclude there are 2430 combinations of data classification. Take notice: it is really more complicated than that because each piece of data gets classified relative to the application that is creating that data. Thus we need to find a way to distill this down. Perhaps looking at communication system from the applications running on various elements rather than the data may prove to be a better approach in the end.

4.1. Data Sources

Data comes from many sources. Understanding those sources helps with understanding what the service requirements of that data may be. Sources include:

- Human-to-human communications
- Health and status monitoring sensors
- Video cameras
- Still image cameras
- Science payloads and sensors which produce large reams of data
- Mission control and science operations control
- Machine-to-machine communications for applications such as routing protocols, close-loop control systems, and caution-and-warning.

4.2. Data Types

There are numerous data types corresponding to different applications and having a variety of QOS requirements. The following data types correspond to the vast majority of the applications applicable to space communication network architecture: voice, video, telemetry, command-and-control and files. Voice and video can be interactive or stored in files and transmitted as data for later use. Telemetry includes system health status and system configurations as well as human health status. Telemetry is generally non-interactive. Caution-and-warning data, by our definition, is telemetry data; however, caution-and-warning data may be interactive and may be part of machine-to-machine communications. Telemetry is generally low-volume, low-rate data from monitoring sensors. Science data from science payloads and science sensors is generally high-volume, high-rate data. Examples of such data include radar and hyperspectral imagery. Data may also exist as files. Such data may include manuals, personal medical data, documents, maps, entertainment, etc. Command-and-control data may be generated locally or originate from one of the operation centers. Furthermore, command-and-control data may be for closed loop control or non-real-time control – sent over long propagation delays and/or via store and forward mechanisms.

4.3. Data Classification

Data can and should be classified over a number of criteria such as sensitivity level [5], security requirements [6] and QOS where QOS includes priority, time sensitivity and reliability.

4.3.1. Sensitivity Level

Data classification, in the context of information security, is the classification of data based on its level of sensitivity and the impact to the organization should that data be disclosed, altered or destroyed without authorization. The classification of data helps determine what baseline security controls are appropriate for safeguarding that data.

All institutional data should be classified into one of three sensitivity levels, or classifications:

Restricted Data Data should be classified as Restricted when the unauthorized disclosure, alteration or destruction of that data could cause a significant level of risk to the organization or its affiliates. The highest level of security controls should be applied to Restricted data.

Private Data Data should be classified as Private when the unauthorized disclosure, alteration or destruction of that data could result in a moderate level of risk to the organization or its affiliates. A reasonable level of security controls should be applied to Private data.

Public Data Data should be classified as Public when the unauthorized disclosure, alteration or destruction of that data would results in little or no risk to the organization and its affiliates. While little or no controls are required to protect the confidentiality of Public data, some level of control may be required to prevent unauthorized modification or destruction of Public data.

4.3.2. Security Objective

Within the US Government, the Federal Information Security Management Act (FISMA) defines three security objectives for information and information systems and their potential impact on Organizations and Individuals. The following is summarized from FIPS Publication 199, "Standards for Security Categorization of Federal Information and Information Systems:"

Confidentiality is preserving authorized restrictions on information access and disclosure, including means for protecting personal privacy and proprietary information. A loss of confidentiality is the unauthorized disclosure of information. Confidentiality is extremely important for data such as personal medical data due to the Health Insurance Portability and Accountability Act (HIPAA)[7].·[8]

Integrity is guarding against improper information modification or destruction, and includes ensuring information non-repudiation and authenticity. A loss of integrity is the unauthorized modification or destruction of information. Integrity is extremely important for data such as command-and-control messages, scientific data, and telemetry used for operational decision making.

Availability is ensuring timely and reliable access to and use of information. Relative to this Operational Concept (OpsCon), availability will not be addressed. Relative to security, availability has more to do with Denial of Service (DOS). Another area that affects availability is system reliability.

Relative to space exploration network architecture, we will assume data availability is a non-issue by design. We are more concerned with confidentiality and integrity.

4.3.3. Potential Impact

Low The loss of confidentiality, integrity, or availability could be expected to have a limited or no adverse effect on organizational operations, organizational assets, or individuals.

Moderate The loss of confidentiality, integrity, or availability could be expected to have a serious adverse effect on organizational operations, organizational assets, or individuals such as causing a significant degradation in mission capability to an extent and duration that the organization is able to perform its primary functions, but the effectiveness of the functions is significantly reduced.

High The loss of confidentiality, integrity, or availability could be expected to have a severe or catastrophic adverse effect on organizational operations, organizational assets, or individuals including causing a severe degradation in or loss of mission capability to an extent and duration that the organization is not able to perform one or more of its primary functions or resulting in severe or catastrophic harm to individuals involving loss of life or serious life threatening injuries.

4.3.4. Security Category

The generalized format for expressing the security category, SC, of an information type is: **SC** information type = {(**confidentiality – C**, impact), (**integrity – I**, impact), (**availability – A**, impact)}, where the acceptable values for potential impact are LOW (**L**), MODERATE (**M**), HIGH (**H**), or NOT APPLICABLE (**NA**).

4.3.5. Quality-of-Service (QOS)

The two general QOS categories are priority and service sensitivity.

Priority is a queue management mechanism. An element with high priority is served before an element with low priority. If two elements have the same priority, they are served according to their order in the queue.

Service Sensitivity is a characteristic of the application. An application often has multiple sensitivity characteristics. For example applications that require Real-Time Interaction include: interactive gaming applications that use Real-Time Protocol (RTP)/UDP streams for game control commands, and video conferencing applications that do not have the ability to change encoding rates, require low jitter and loss and very low delay.

Relative to a Space Exploration Communication Network we shall categorize Quality-of-Service (QOS) based on data (i.e., digitized information). Data can be stored for long periods of time prior to forwarding and portions of the network may have long periods of discontinuity. The difference here from, for example, the Internet, is that applications running over the Internet generally assume a connected network and minimal delay[3] In the Internet, each router manages internal packet queues and associated QOS based on the packet priority field, the Type of Service (TOS) field in IPv4 and Traffic Class field in IPv6.

The initial IPv4 priority mapped to the 1970 US military National Communications System (NCS) Voice Precedence System and used three bits to indicate the following:[10]

111 - Network Control
110 - Internetwork Control
101 - CRITIC/ECP (Critical and Emergency Call Processing)
100 - Flash Override (President, Secretary of Defense, Joint Chief of Staff)
011 - Flash (Information essential to national survival)
010 - Immediate (Pertaining to situations that gravely affect the security of national and Allied forces)
001 - Priority (Reserved for communications requiring expeditious action.)
000 - Routine

In the circuit switched voice systems of the 1970s, high precedence levels preempted lower level communications whereas in the Internet, higher priority packets get preferential treatment, but lower priority packets may still get transmitted if network resources are available.

In today's Internet, Differentiated Services (DiffServ), 6 bits in the TOS or Traffic Class field are used to specify a simple, scalable mechanism for classifying and managing network traffic and providing quality of service QOS. DiffServ is used to provide low-latency to critical network traffic such as voice or streaming media while providing best-effort service to non-critical services such as web traffic or file transfers.

Request for Comment (RFC) 4594, "Configuration Guidelines for DiffServ Service Classes[11]" provides a very good categorization of Service Classes. The Service Classes are divided into two groupings, network control and user/subscriber traffic. To provide service differentiation, different service classes are defined in each grouping. The network control traffic group is further divided into two service classes: "Network Control" for routing and network control function and "OAM" (Operations, Administration, and Management) for network configuration and management functions. The user/subscriber traffic group is broken down into ten service classes to provide service differentiation for all the different types of applications/services. Many of these service types are directly applicable to our Space Exploration Communication Network Architecture.

[3]This is not to imply the Internet Protocols cannot be used in Space Networks, just that for our space network architecture QOS has some additional parameters to consider. In fact, Internet Protocols have been demonstrated to work quite well in space networks [9].

The Telecommunication Standardization Sector of the International Telecommunications Union (ITU) has a document, ITU-T G.1010, “Series G: Transmission Systems and Media, Digital Systems and Networks: Quality of service and performance [12],” that defines a model for multimedia Quality of Service (QoS) categories from an end-user viewpoint. By considering user expectations for a range of multimedia applications, eight distinct categories are identified, based on tolerance to information loss and delay. Key parameters that impact the user are: Delay, Delay Variation (a.k.a. jitter), and Information loss. Three major applications are identified: Audio, Video and Data. Similar to RFC 4594, each application area is further divided into service classes. Audio includes: Conversational Voice, Voice Messaging and Streaming Audio. Video includes Videophone or video for real-time operational visibility to support operational decisions (interactive) and one-way video (non-interactive) such as video messages or documentary or science video with high definition and integrity. Data includes: interactive applications like Web browsing, gaming and E-commerce, Bulk Data, Command-and-control, and Instant Messaging.

For the ”local” and ”proximity” regions, the QOS parameters and mechanism identified in RFC 4594 and ITU-T G.1010 map quite well. For the ”Afar” region, propagation delay must be considered. ”Neighborhood” and ”Afar” regions also will have various degrees of disconnection and disruption due to wireless systems moving in and out of range, scheduling of assets, and orbital dynamics.

For the Space Exploration Communication Network the following QOS parameters are of interest. We have slightly rmodified the definitions for space-base networking:

Priorities:

Immediate Data is sent out as quickly as possible. Jumps all other queues. Used for services such as time-sensitive command-and-control.

Priority Data in a priority queue is generally transmitted before routine traffic, or, at least in sufficient time to fulfill the requiring expeditious action.

Routine Best effort traffic. Queues are managed base on service sensitivity.

Service Sensitivity:

Time-Sensitive Applications that require precise time delivery. For example, for space applications, this may be a command to fire a thruster. Generally a ”local” application and probably communication over a deterministic bus. Certainly not an ”afar” application.

Delay-Sensitive Applications or protocols that require some form of real-time hand shaking. For example the Transmission Control Protocol (TCP) is delay-sensitive and therefore should not be use for ”afar” communications.

Jitter-Sensitive Real-Time Interactive applications such *“local”* control commands and video conferencing applications that do not have the ability to change encoding rates.

Disconnection Sensitive[4] Any application that requires end-to-end connectivity such as closed loop control applications and real-time interactive applications such as conversational voice.

Loss Sensitive Few applications are loss insensitive. Fortunately, packet loss is usually handle at the lower layer protocols such that any loss and retransmission taken care of outside the application. Examples of loss sensitive applications are anything that is bulk encrypted or authenticated. If one does not receive the entire bulk package, one cannot authenticate or decrypt the package.

Bandwidth Sensitive Any application requiring high volumes of data to be moved between systems in a reasonable amount of time is bandwidth sensitive as $DataRate \propto Bandwidth$. Video, in particular, high-definition video is bandwidth sensitive.

5. Communication Links

It is Important to understand the various data links we have available to us. We can categorize communications links as two physical types: (1) those that are physically connected via wire or fiber and (2) wireless.

Physically connected links tend to be symmetrical, that is, they have equal bandwidth capability in both the transmit and receive directions. The links can be either full duplex or half duplex. These physical connections tend to be point-to-point. However, in the past, Ethernet daisy-chaining was used. The wiring may be multi-connector – often with twisted pairs. Examples of wire connections are RS-232 (160 kbits/s - can be up to 1.0 Mbit/s), MIL-STD-1553 (1.0 Mbps), RS-442 (10 Mbps), Universal Serial Bus (USB) ($\approx$ 720 Mbps for 3.0) and spacewire ($\leq$ 400 Mbps). Coaxial lines are often used for telecommunication equipment. Examples include T1/E1 (1.544/2.048 Mbps) and T3/E3 (45/34 Mbps) links. Today most local area connections such as in building connections or, in our case within a vehicle or habitat, are either Ethernet or fiber optics with connections distributed via a switch configured in a hub/spoke architecture.

The wireless radio links include broadcast, point-to-multipoint, mesh radio (which is really a point to multipoint radio with some type of spanning tree protocol) and point-to-point. A broadcast radio is a radio system where anybody can listen and receive. Point-to-multipoint radios really broadcast [5] however, there is usually some type of access restriction such that "not just anybody can receive and reply to messages". Point-to-multipoint radio systems include technologies such as Wi-Fi (802.11xx) and WiMAX (802.16xx). Wi-Fi radios have symmetric bandwidth capabilities. WiMAX is a high-bandwidth system but designed to be asymmetric. The transmission is generally at a lower rate from the subscriber station to the base station (a.k.a. uplink). Whereas, transmission is at a much higher rate from the base station to all subscriber stations (a.k.a. downlink). Point-to-point radio links for space-based systems – particularly systems operating in the afar region – are often highly asymmetric. The downlink is often orders of magnitude larger than the uplink. This is mainly due to the communication needs (where the information is generated). For example, for missions such as Earth observation, the vast amount of data is generated on the spacecraft and transmitted to the ground. The NASA Space Network User's Guide (SNUG) [13] provides a number of examples of the types of point-to-point links that are available and the NASA Space Network. The NASA space network is the Tracking and Data Relay Satellite System (TDRSS).

6. Element Overview

The network communication architecture for human space exploration beyond low Earth orbit consists of four architectural systems [Figure 1]. These four architectural systems are: the flight systems, the launch vehicle systems, the ground systems, and the planetary surface systems. Although the launch vehicle systems could be considered flight systems, they are separated out as they are short lived systems. Each of those architectural systems consists of multiple elements. The flight systems has six major elements. These elements are the Crew Vehicle (CV), the Extravehicular Mobile Unit (EMU), the Surface Access Module (SAM), the Cargo Vehicle (CaV), the Space Habitat (SpH), and Space Robot (SpR). Launch vehicle systems include the Crew Launch Vehicle (CLV) and a Cargo Launch Vehicle (CaLV). The ground systems have four major elements: the factories, integration facilities, ground systems, and mission systems. The planetary surface systems consist of the following elements: the Surface Habitat (SuH), Surface Robots (SuRs), and Surface Mobile Systems (SuMSs).

6.1. Flight Systems

Crew Vehicle (CV) is used to transport the crew to and from the Space Habitat (SpH). Where the SpH may be a Mars transfer vehicle of some nature. It will dock with the SpH. It will interface with the Crew Launch Vehicle (CLV). The CV is not designed to accommodate astronauts for extended duration missions. Rather, that is the function of a SpH.

The Crew Vehicle (CV) will communicate with ground systems, mission systems, EMUs, the SpH, and SpRs and may communicate with the SAM.). It may remain parked in orbit above an exploration objective.

Extravehicular Mobile Unit (EMU) a.k.a. spacesuit is the self-contained life-support system used by astronauts during Extravehicular Activities (EVAs). The EMU communicates with the CV the SAM, the space and surface habitats and all robotic systems. Data generated by the EMU consists of the space suit telemetry, caution-and-warning messages, astronaut health status, video, and files containing scientific data, intercom-quality audio, video and pictures [14].

[5] Anyone can 'listen' but may not be able to interpret the message due to datelink encryption and will not be able to reply if not registered.

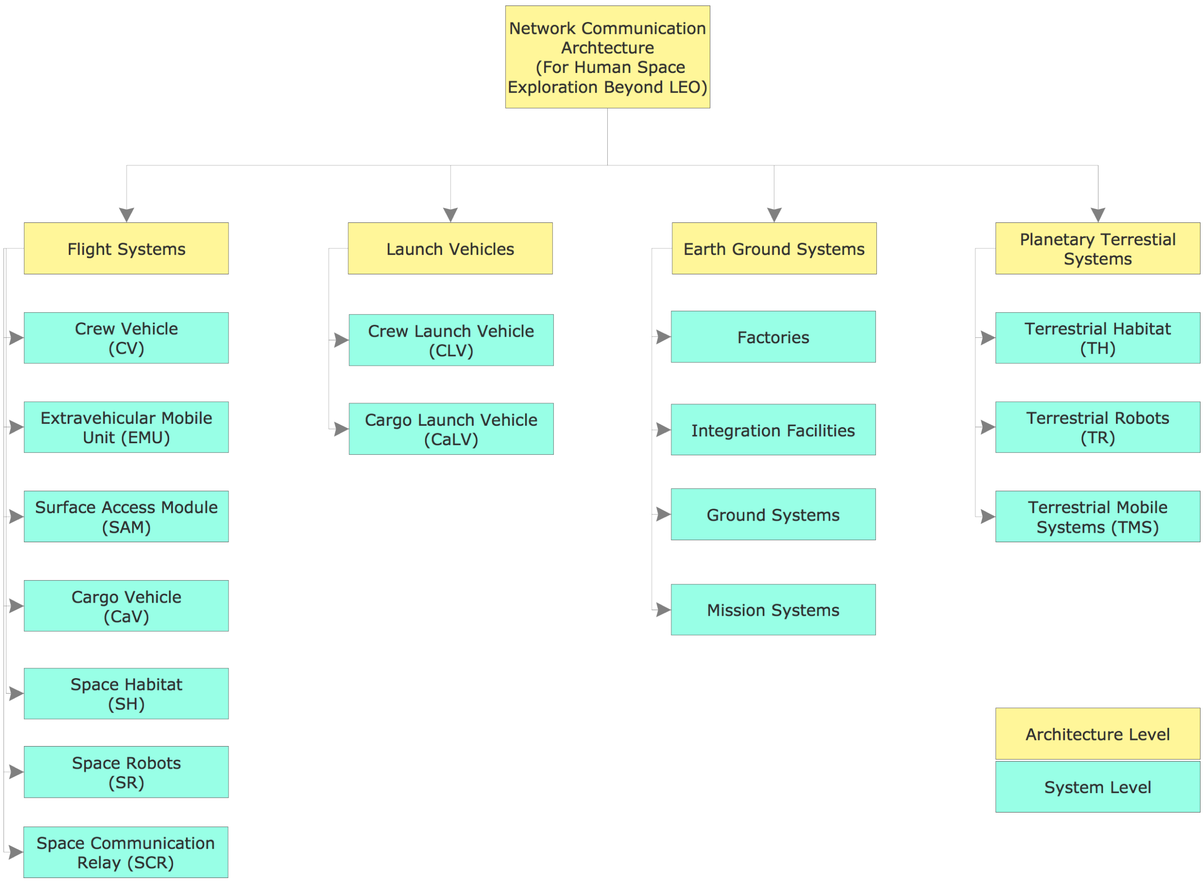

Figure 1: Network Communications Architecture Hierarchy

Surface Access Module (SAM) is the vehicle that provides transportation from the SpH to the planetary surface. The SAM communicates with both the SpH and the surface habitat and may communicate with EMUs, the CV and space robots.

Cargo Vehicle (CaV) provides supplies to the SpH. This vehicle also may return waste products and other items no longer needed from the SpH back to Earth.

Space Habitat (SpH) is the living and working module for the mission crew. It may consist of multiple small modules integrated together to form one living and working habitat. The SpH may exist in many forms depending on the mission. For discussion purposes, the International Space Station (ISS) can be considered a SpH. For new exploration missions, the habitat may be a lunar orbiting habitat or shelter at Lagrange Point 2 (L2) or even a vehicle transitioning between Earth and Mars and then orbiting around Mars.

Space Robot (SpR) systems are envisioned to be robots used to assist in monitoring and repair of space vehicles and/or assisting in space science such as an asteroid capture and retrieval mission.

Space Communication Relays (SCRs) are space systems with the primary purpose of providing high-quality, high-rate communication links over long distances. These relays may or may not be processing relays. A regenerative relay is a system that performs demodulation and re-modulation the communication signals. A processing relay is a regenerative system that also performs protocol processing. Two examples of spaced communication relays are the current Tracking and Data Relay Satellite System (TDRSS) and the Mars relay satellites. Tracking and Data Relay Satellite (TDRS) is a bent-pipe system whereas the Mars relay satellites demodulate, Store, Carry and Forward (SCF) and re-modulate communication data.

6.2. Launch Vehicles

Crew Launch Vehicle (CLV) is the heavy lift launch vehicle upon which the CV resides. As such, the CLV is designed for human rated space flight.

Cargo Launch Vehicle (CaLV)) is the heavy lift launch vehicle upon which the cargo vehicle resides. There may be multiple CaLVs of varying sizes depending on the cargo types and destinations. Regardless, the CaLV has less stringent launch requirements is not intended to launch humans and therefore does not have to meet human spaceflight launch criteria.

6.3. Earth Ground Systems

Factories are where subsystems are developed. The factories are included here because there may be a need for subsystems developed at various factories to communicate with each other prior to transport to the integration facilities. In addition, subsystems must communicate with test and validation equipment within the factory itself.

Integration Facilities are where subsystems are brought together for integration and testing prior to launch. It may be desirable to have integrated systems communicating with mission systems for early operational check out.

Ground Systems consist of the following: launch site, tracking sites, and communication ground stations. All of these sites can communicate via terrestrial means using Internet communications systems and products. The ground stations are likely owned and operated by multiple third parties and various international partners. Appropriate communication and information security policies must be in place to allow for such communications.

Mission Systems include human spaceflight mission centers, various science mission centers, and potentially payload specific mission centers. These mission centers are most likely distributed in various geographical locations.

6.4. Planetary Surface Systems

Surface Habitat (SuH) is the living and working module for the mission crew. It may consist of multiple small modules integrated together to form one living and working habitat.

SuRs are envisioned to be robots used to assist in monitoring and repair of planetary surface systems and/or assisting in science missions. There may be numerous surface robots. These robots may act together to perform functions and operate in swarms.

SuMSs are vehicles used to move astronauts and/or cargo on the planetary surface. These vehicles may or may not have self-contained life-support similar to a habitat but for much shorter duration.

7. Generic Reference Mission

Figure 2 depicts a generic design reference Mission [6]. The purpose is to show a cradle-to-grave (end-of-mission) example that includes build, test, integration, launch, planetary mission, science return, and return of the crew and mission – end-of-mission. The design reference mission only needs to be at sufficient detail to identify communications flows and interoperability requirements, data types, quality-of-service requirements and security requirements.

The generic exploration design reference Mission shows a timeline of events. It is an attempt to show which major modules have to be available at what time sequence. For example we start with the launch of the surface habitat and surface robotics. These elements have to be in place at the destination planet prior to manned missions. Also it is assumed that major modules will first be launched to Low-Earth Orbit (LEO) where they can meet up with another vehicle that can carry it to the destination orbit around the destination planet. From there, the modules will descend and land on the planet and be maintained until the manned-mission can occur. While in this state, some communication with these modules will be required just to monitor health and status.

[6] Destination may be a Planet or Object e.g. asteroids

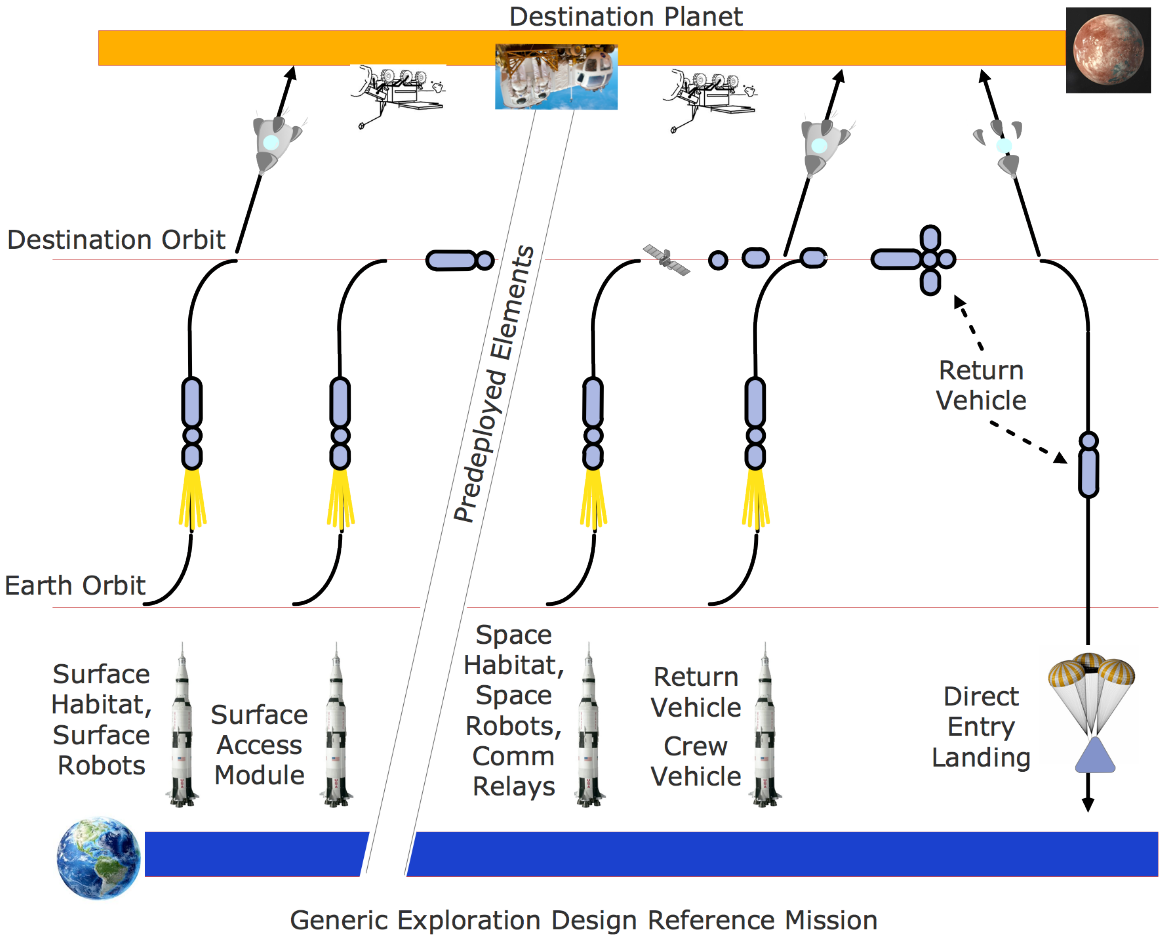

Figure 2: Generic Design Reference Mission

The second major initiative will be the launch and deployment of a Surface Access Module (SAM). This module will allow humans to land and return from the surface. These are the pre-deployment elements.

Prior to launching the crew the necessary major components must be in place to carry the crew from low Earth orbit to the destination planet. These modules include the SpH, space robotics and communication relays. The SpH is the living and working facility for the crew on its way to and on the return from the destination planet.

Once the SpH is in place we can then launch the crew and the return vehicle. The CV will meet rendezvous and dock with the SpH. The crew will then transfer from the CV to the SpH for its journey to and from the destination planet (E.G., Mars). The return vehicle will provide the power and propulsion for the SpH to and from the destination planet.

Overall communication requirements include: communication with a number of modules while in LEO, communication with a limited number of modules to and from the destination orbit, communication with the return vehicle and SpH while it remains in the destination orbit, and communication with surface modules and the surface habitat.

In the following sections we identify the various communication needs, data types, and data flows for each phase of operations as well as identifying the security requirements of each data type during each phase of operation.

Note that in the Subsystem Integration Figure 3 and Prelaunch Integration Figure 4, no single government entity is assumed or no single government funded and owned system is assumed. Sites for various facilities are purposely shown to spread across the globe and be owned and operated by vastly different governments, organizations, or industry and academia partners. This is purposefully done to force one to address international interoperability and international security deployment considerations.

In order to address each phase of the mission in the communication requirements some sort of generic design reference mission is required. Thus, we have chosen somewhat of a “worse-case” [7] mission, a mission to land a two crewmembers on Mars for period of a few days and return them safely to Earth. The following assumptions have arbitrarily been made *as we are only concerned with a model that identifies data flows, security needs and communication requirements:*

- The mission will require a four-person crew with two crewmembers landing on the surface of Mars.
- The Surface Access Module (SAM) will also be the vehicle that will return the crewmembers to an awaiting structure spacecraft for return to Earth.
- The SpH can perform the functions of delivering crewmembers from the LEO Rendezvous to the Destination Rendezvous, orbit Mars with two crewmembers while the other two crewmembers land on the planet, and return safely to Earth.
- For this short duration of the surface, a surface habitat is not required. The SAM will suffice.
- A surface mobile system and surface robots will be deployed.
- All necessary communications can be handled by the SpH.
  - The SpH will act as the communication relay for the astronauts while on the surface.
- 24/7 Communications is not a requirement, thus autonomous operations by the crew and robots is necessary independent of mission control.
- The SpH cannot be launched as a single structure. Rather, two launches are required with the SpH assembled at the LEO Rendezvous point.

7.1. Subsystem and System Integration

The first phase of a mission that we consider is the subsystem and system integration phase. Obviously this phase has to occur at the beginning of any mission, what can occur throughout as new subsystems are being developed and integrated prior to deployment. Figure 3 illustrates the basic concept. Here, various components are being developed

[7] Hard to do rather than simply having multiple launch elements and multiple types of launch elements.

by different entities in different locations and perhaps even in different countries. Previously developed and deployed assets using legacy communication systems will exist as well, and accurate copies are required for integration of new systems with potentially obsolescent implementations. These components will be brought together eventually at a single location for subsystem integration. However, it is highly desirable to have those components communicate and interoperate and perform initial testing while still at their respective factories. It is conceivable that one will begin integration with payload operations, science operations and/or mission operations at this time to work out interface issues. Today this can be done using Internet technologies. However, one must design the components to be able to readily take advantage of such technologies. Furthermore, one would like to use Internet technologies and protocols directly while testing within the factory itself. Thus, it is highly advantageous to use commercial off-the-shelf interfaces and protocols to communicate with various components and subsystems.

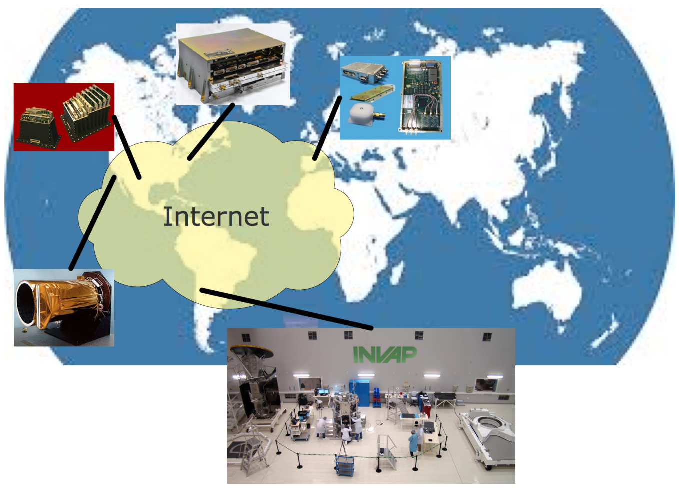

Figure 3: Subsystem Integration

A prime example of the advantage of using commercial-off-the-shelf standard interfaces and protocols is the NASA Airborne Science program's NASA Airborne Science Data And Telemetry System (NASDAT). A rugged avionics box provides both aircraft and experimenter data interfaces. Ethernet, Satellite Communications (SATCOM), and legacy connections are supported. Standardized IP protocols allow this system to serve as an abstraction layer for interfacing any instrument to any aircraft. Built on open standards and dynamically reconfigurable, the NASDAT enables any research platform to participate in the wider sensor web, such that remote experimenters can control their instruments, and display applications can receive near real time data.[15], [16]

During the subsystem and system integration phase, the test and validation data being transmitted between the component under test and a test unit includes: files, command-and-control, and telemetry. Data being transmitted between sites includes: files, command-and-control, telemetry, and perhaps voice and video depending on the component integration required. Data rates and security requirements vary greatly depending on the component or subsystem integration requirements. Data rates could vary from kilobits for simple sensors to hundreds of megabits or even gigabits for sophisticated science sensors. As a minimum between sites some type of virtual private network will have to be established.

All security mechanisms that can be, should be tested and verified during each phase of integration. As the system grows from component integration to subsystem integration to complete systems, the amount of security mechanisms will grow. It is the goal to have limited reconfiguration throughout system development and deployment including security and addressing. System deployment includes: subsystem development in a factory setting, system integration in a laboratory setting, launch preparation, launch, and deployment, operation in space.

7.2. *Prelaunch and Launch*

The prelaunch and launch phase phases are generally the most complex regarding communication. During these phases all elements have to be checked out while at the launch site and then communication must be maintained during launch through deployment. Figure 4 provides an illustration of the major ground elements and includes spacecraft integration, mission control, launch integration, and payload, science, and range operations. In Figure 4, the "location markers" represent all ground stations used for tracking during launch and for communication once in orbit or on its trajectory to the final destination. Note, the ground stations may be leased for service and owned and operated by third parties. The same applies to the launch site. Therefore, data and communication security mechanisms must be able to handle this communication mix of international, public and private subnetworks.

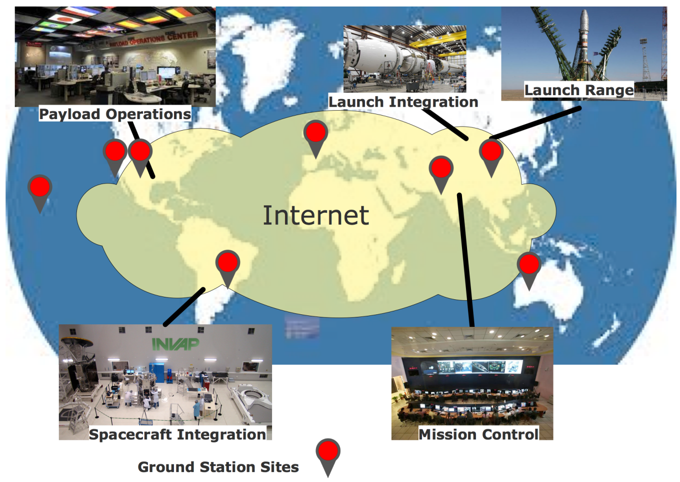

Figure 4: Prelaunch and Launch Integration

There are two major launch types: 1) unmanned launches for cargo such as habitats, robotic systems or communication relays; and, 2) manned launches to get the crew into space via the CV. The main difference for manned launches are: a) all elements have to be rated for manned flight, b) additional procedures are needed to ensure crew safety when terminating a launch while on the pad, c) there is voice communication to and from the CV, and, d) while on the pad, astronaut health status data is sent to the proper authorities at mission operations. Since manned launch is more complex and has more communication requirements than an unmanned launch, we use manned to describe the various communication paths and requirements as depicted in Figure 5.

During prelaunch the spacecraft and payload may still be at integration facilities away from the launch site. Testing and system checkout with the science payload and mission control is desirable even at this stage to ensure interoperability prior to launch integration. Eventually all the major subsystems will be integrated at the launch site. At this time, all communication interfaces need to be validated for operation. Once this is completed, the rocket and the cargo vehicle or CV and associated payload are moved to the launch pad. While on the launch pad, communication is via hardwired umbilical cord and local wireless. Furthermore the communication links to the tracking communication systems such as NASA's TDRSS need to be confirmed.

Figure 5 shows seven major elements included in and Prelaunch and Launch phases while a vehicle is on the launchpad. These elements include: the Crew Launch Vehicle (CLV) or Cargo Vehicle (CaV) and the CV or CaV, the crew or payload, range safety, launch operations, mission operations, and tracking and communications services.

Range safety is responsible for ensuring the integrity of the range, the safety of the range, and the safety of any personnel on the range or downrange. Range safety tracks the vehicle during launch and if necessary, executes proper procedures to terminate the launch or destroy the vehicle if it deviates from its expected path or poses any threat to personal or property due to deviations in the planned flight path. Range safety keeps launch operations informed of conditions on a range. Tracking of the vehicle is done via radar and the only communication with the vehicle is a secure wireless Radio Frequency (RF) communication link to issue the necessary commands to terminate the launch in whatever manner is appropriate.

The Tracking and Communications Services track the vehicle during launch and reports the positioning back to

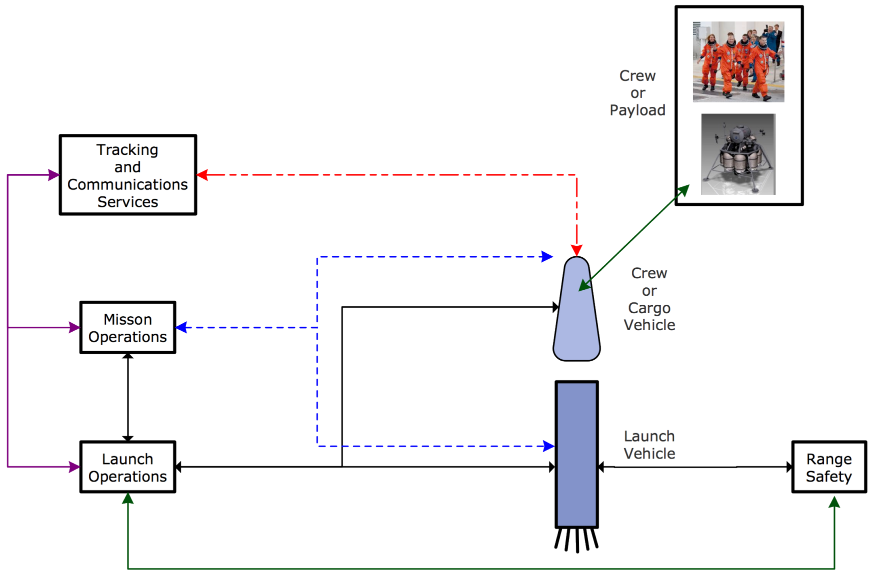

Figure 5: Launch Pad Interfaces

mission control and launch operations. Once the umbilical is removed from the launch vehicle, all communication between the crew and launch and mission operations is via the Tracking and Communications Services.

Launch operations is responsible for executing a successful launch and ensuring the safety of the crew or the payload. Launch Operations is in control of the mission from launch integration up to the point where the vehicle leaves the pad.

During manned-launch, mission operations monitors the health and status of the crew and CV to ensure nominal operations and to keep the crew informed of the current launch status. For unmanned operations, mission operations monitors the health and status of the cargo vehicle and the payload while launch operations is concerned with the CaLV and getting the system off the pad. Once the vehicle clears the pad, mission operations takes over all aspects of operations except range safety.

It is important to note that during each phase of the mission different communication links are active and different types of data flows are taking place between elements. A detailed discussion of this is provided in the Data Flows Section [8]. For example during prelaunch, while on the pad, most of the communication between the launch vehicle and launch operations or mission operations is via hardwired connections. With such conductivity, it is possible to transfer large amounts of data if necessary. Once the vehicle leaves the pad, the launch phase, all communications is via radio between the vehicle and mission operations. At this time, data rates are relatively small – in the tens to hundreds of kilobits per second. This is due to the ever-changing position of the launch vehicle relative to the tracking and data relay systems – be it ground tracking systems or GEO-based tracking systems such as TDRSS. It becomes difficult to close the RF link at high data rates prior to deployment of high-gain antennas. Antenna deployment only occurs after a stable orbit has been obtained, or some other stable configuration has been obtained "en route" to space destination [8].

Immediately following liftoff through the end-of-mission, all communications to Earth is via a ground-base communication support network as shown in Figure 6. Depending on the phase of flight and the particular mission or submission, communication may be via: multiple ground stations supporting direct spacecraft to ground communication, a GEO communication relay satellite system such as NASA's TDRSS, or distributed deep space communication network consisting of three or more ground networks with large aperture antennas capable of deep space communications. The NASA Deep Space Network (DSN) [17] is one such example. The European Space Agency (ESA) Norcia facility in western Australia and the Chinese Deep Space Network [18]are another examples.

[8]For discussion purposes, we consider Deep Space, anything beyond GEO distances.

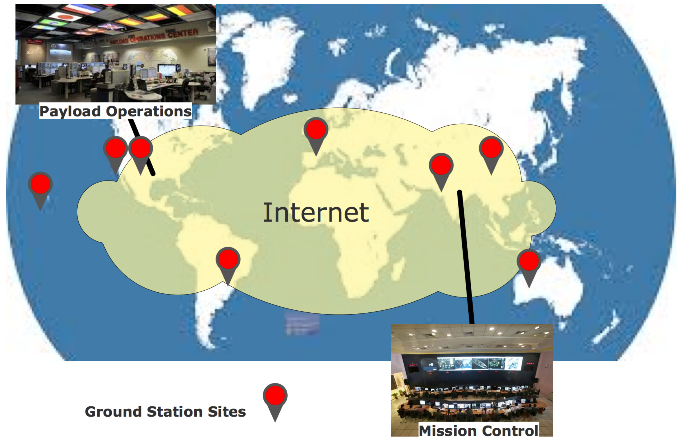

Figure 6: Post Launch

7.3. LEO Rendezvous

We provide a scenario to address the communication needs for a LEO Rendezvous. Per our reference mission, the SpH cannot be launched as a single structure. Rather, two launches are required with the SpH assembled at the LEO Rendezvous point. One the SpH is assembled, the crew will be deployed to the habitat via the CV. The CV will detach from the habitat and either remain at LEO or return to Earth and be redeployed upon return of crew from Mars. For our generic Concept of Operations (CONOPS), we will assume that the CV has been placed in a hibernation mode and will remain at LEO for use in Earth reentry.

Communication at LEO will be via a GEO relay satellite constellation in order for the operations center to oversee the assembly. We shall assume that all assembly will be performed autonomously, without the assistance of a crew.[9]

During assembly of the SpH, data transferred from LEO to ground is primarily low-rate telemetry and high-rate video. Since the operations occur autonomously, the video does not have to be real-time and could be sent as files. Critical communication is machine-to-machine between sub-elements of the SpH as they dock, thereby creating one large SpH. Here, ranging data exchange between the docking systems is critical.

The SpH submodules could be designed such that humans have to be involved in the assembly. Regardless, autonomous operations still has to be done at the Destination Rendezvous, so doing so at LEO is the first step in validating the technologies necessary to make this happen. If mission operations were involved in the real-time integration of the SpH, high-rate video, telemetry and real-time command-and-control would likely occur from LEO to ground via a system of GEO relay satellites.

With the arrival of the crew, additional voice communications would ensue.

7.4. En Route–Out (to the Destination)

En Route takes place traveling to and returning from the destination. While en route, all communication is via a Deep Space Network (DSN). Therefore communication is limited. No real-time communication can be assumed due to propagation delay as well scheduling of communication assets. All communication is via some form of file/bundle transfer. These data files will consist of video, voice messages, and telemetry. All command-and-control will be via some file-like mechanism. The only real-time radio processing will be ranging data.

For telemetry, the most useful habitat-to-Earth communications is last-in, first-out queueing.

The communication Earth-to-habitat data rates are expected to be higher for manned flight simply to provide some entertainment communications to the crew.

[9] In which case, one could rely entirely on direct LEO to ground communications.

Experiments are expected to be performed en route. The results will be transmitted back to Earth with some non-real-time interactions expected between either the Crew and the Principal Investigator (PI) or the PI and the experiment package.

7.5. Destination Rendezvous

Once the SpH reaches Mars, it will remain in orbit around Mars as the crew prepares for the next phase of the mission, landing two crewmembers on the surface of Mars for a few days and returning them back to the SpH. In order to accomplish this, the SpH rendezvous SAM. The SAM docks with the SpH and two crewmembers transfer to the SAM. SAM then separates and ascends to the planet surface.

The propagation delay from Mars to Earth is quite large, in the order of 4 to 24 minutes one-way (i.e, 8 to 48 minutes RTT) depending on the separation between Mars and Earth due to their orbits. Thus, no real-time command-and-control can take place. Instead, all local operations are designed as autonomous operations relative to mission control. *However, we will assume that all critical operations occur during periods in which there is a full communication path between Mars and Earth. This assumption holds for all phases of operations including ascent and departure.*

During critical operations, telemetry and, if sufficient bandwidth is available, video will be transmitted (streamed in real-time) from the source to Mission Control. It is assumed that much of the video data will have to be stored for later transmission over lower rate communications links over long periods of time.

7.6. Planetary Descent

Descent is a critical operation. As such, telemetry and, if sufficient bandwidth is available, video will be transmitted (streamed in real-time) from the source to Mission Control. We will assume that this occurs via some relay be it the SpH or a Space Communication Relay (SCR) around Mars. Such relays will enable higher rate communication from the SAM to Earth. Much of the data may be stored on the relay for later transmission.

7.7. Surface Operations

Once safely on the surface, the Space Robots (SpRs) and the Surface Mobile System (SuMS) will rendezvous with the SAM. The crew will perform a number of sorties that include use of the service it use of the SpRs and a SuMS. In addition they will perform Extravehicular Activities (EVAs) using Extravehicular Mobile Units (EMUs). As such there is a great amount of high-bandwidth vocal communication between systems. The EMUs will communicate with each other as well as with the robots. We will assume the surface mobile system can act as a relay to communicate back to the SAM and that the SAM can act as a relay to communicate with the satellite relay or the SpH.

We will assume that sorties can take place independent of communication with mission control and that much of the data and applications will be designed to function in a Store, Carry and Forward (SCF) communication architecture.

Data generated during these surface sorties includes: telemetry, voice, video, imagery, medical, navigation (position) and sensor data from scientific instruments. The major data received from mission operations includes maps, schedules, procedures, software updates, and personal communications for each crewmember.

7.8. Planetary Departure

The communication needs and requirements for departure are identical to those for Descent.

7.9. En Route–Back (from the Destination)

The communication needs and requirements for En Route–Back are identical to En Route–Out.

7.10. Earth Reentry

For the Earth reentry phase, we will assume that the Space Habitat (SpH) docks with the Crew Vehicle (CV). The crew will move from the SpH into the CV. At this point the SpH is put into hibernation and the CV separates. The CV will descend to the Earth's surface where the crew will be recovered by an awaiting team. Once the crew has been recovered, the mission is complete (end-of-mission).

8. Data Flows

The following subsections show a system connectivity matrix and one specific data-characteristic matrix for the space habitat. The SpH Data characteristic matrix shows the various data types and flow for each element connected to the SpH. These matrices encompass all phases of the mission. If one were to model any element one would need to create a connectivity matrix and data-characteristic matrix for each phase of the mission. That was not done for this paper as an aggregate model is sufficient to illustrate the complexity.

8.1. System Connectivity

Figure 7 shows conductivity between elements and is an aggregate of all phases of the mission. For example, during initial launch the surface access module can be considered payload and has some form of communication connection with the cargo vehicle perhaps just to send health and status telemetry. During launch the surface access module does not communicate with the space habitat. However, during destination rendezvous in preparation for dissent, the surface access module and a space habitat have a communication path in order to perform docking procedures. From the simple illustration, it is apparent that the conductivity matrix changes depending on the phase of the mission and that to be complete a connectivity matrix has to be generated for each phase of the mission.

Element	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Cargo Vehicle	x			x	x	x	x	x	x	x		x	x	x	x	x	x	x
Crew Vehicle		x	x	x	x	x			x									x
EMU			x			x						x	x	x	x	x	x	
Launch Ops	x	x		x	x	x			x									x
Launch Vehicle (Cargo or Crew)	x	x		x	x	x			x									x
Mission Ops	x	x	x	x	x	x				x	x	x	x	x	x	x	x	x
Payload							x	x										
Payload Ops	x	x					x	x										
Range Safety	x	x		x	x	x			x									
Return Vehicle	x					x				x	x	x						x
Space Communication Relay						x				x	x	x	x	x	x	x	x	x
Space Habitat	x		x			x				x	x	x	x	x	x	x		x
Space Robot	x		x			x				x	x	x	x					x
Surface Access Module	x		x			x					x	x		x	x	x		x
Surface Robots	x		x			x					x	x			x	x	x	x
Surface Habitat	x		x			x					x	x			x	x	x	x
Surface Mobile Systems	x		x			x					x				x	x	x	x
Tracking and Communications System	x	x		x	x	x				x	x	x	x	x	x	x	x	x

Figure 7: Connectivity Matrix

8.2. Data Characteristics

Figure 8 shows types of data the characteristics of the data being transferred between the SpH and other elements. This matrix is an aggregate of all phases of the mission. The characteristics for security, priority and service sensitivity are also provided as are the communication links. These data characteristics and communication links, as presented, are also aggregates over all phases of the mission and for all data types. To properly model the system communication system, one would need to generate a connectivity matrix for each phase of the mission. Each of those connectivity matrices would be multidimensional such that for each type of data the characteristics for security priority, and service sensitivity along with the communication link (or links) used would have to be identified. Furthermore, often same data-type may have differing data characteristics depending on the application. Appendix B shows the aggregate data characteristics matrix of each major element.

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Space Habitat	x		X			X				X	X	X	X	X	X	X		x
Voice			X			X					X	X		X		X		X
Video			X			X					X	X	X	X	X	X		X
Telemetry	x		X			X					X	X	X	X	X	X		X
Command and Control	x		X			X				X	X	X	X	X	X	X		X
Files			X			X					X	X	X	X	X	X		X
SL-Restricted			X			X					X	X	X	X	X	X		X
SL-Private	x		X			X				X	X	X	X	X	X	X		X
SL-Public			X								X	X		X		X		
SO-Confidentiality			X			X					X	X	X	X	X	X		X
SO-Integrity	x		X			X				X	X	X	X	X	X	X		X
SO-Availability			X			X				X	X	X	X	X	X	X		X
PI-Low	x		X			X					X	X		X		X		X
PI-Moderate			X			X				X	X	X	X	X	X	X		X
PI-High										X	X	X	X	X	X	X		X
P-Immediate						X				X	X	X	X	X	X	X		
P-Priority			X			X				X	X	X	X	X	X	X		X
P-Routine	x		X			X				X	X	X	X	X	X	X		X
Time			T			S				S	T	T	T	T	T	T		T
Delay			T			S				S	T	T	T	T	T	T		T
Jitter			T			S				S	T	T	T	T	T	T		T
Disconnection	N		T			N				N	T	T	T	T	T	T		T
Loss	N		T			N				N	T	T	T	T	T	T		T
Bandwidth	L		B			H				H	B	B	B	B	B	B		B
Serial Wired (1553, RS422, etc)	x					X				X		X						
Spacewire																		
Coaxial																		
Ethernet			X			X				X		X						
Fiberoptic			X			X				X		X						
Broadcast																		
Point-to-Multipoint			X									X	X					
Mesh Radio			X										X					
Point-to-Point						X					X		X	X	X	X		X

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure 8: Data Characteristics and Connections for the Space Habitat (SpH)

One has to analyze each application to determine: where the data is flowing, over what communication links, what security needs to be implemented and what quality of service is required. For example, consider some functions on an EMU. The EMU is performing an EVA. We may have a file that consists of health and status telemetry from a particular sensor. This file requires no security and can be sent from the EMU to mission control via some SCF mechanism by way of the Space Habitat (SpH). The file can be sent with routine priority over an Ethernet umbilical once the EMU returns to the SpH . Another file consists of *medical health and status* of a crewmember (medical data protected by HIPAA regulations). This data may require high confidentiality but routine priority. It is also sent over the umbilical link once the astronaut reaches the SpH. A third file consists of caution-and-warning data being sent from one crewmember to another – one EMU to another in close range. This is unsecured high-priority data.[10] This data is sent over the "local" mesh radio system. Thus, we have the same data-type treated multiple ways depending on the application and being sent over various links and within or between regions (in this case, telemetry is sent *afar* and caution-and-warning is sent over *local* links). The combinations are enormous.

9. Summary

The operational concepts for a generic space communication network for human space exploration beyond low Earth orbit has been articulated. Common terminology has been defined and communication flows and data types and characteristics have been identified. A generic design reference Mission was developed in sufficient detail to identify communications flows, data types, quality-of-service requirements and security requirements from cradle to end-of-mission. A system connectivity matrix was presented showing the connectivity between all major elements aggregated over each mission phase. Data characteristics matrices were also developed for each element and are provided in appendix B. A detailed analysis of the data characteristics for the Space Habitat (SpH) was provided. *The significant item to note is that one has to analyze each application to figure out where the data is flowing, over what communication links, what security needs to be implemented and what quality of service is required.*

[10]For *local or proximity* medical data, Crewmembers must wave their privacy rights as situational awareness among all crewmembers is critical for all to survive.

Bibliography

[1] W. Ivancic, K. Vaden, R. Jones, and A. Roberts, "Security policy profile for a generic space exploration communication network architecture," NASA Glenn Research Center, Technical Memorandum NASA/TM—2015-TBD, May 2015.

[2] NASA, "Constellation design reference missions and operational concepts," *NASA CxP PUBS*, vol. REVISION B, CHANGE 003, October 2008. [Online]. Available: http://everyspec.com/NASA/NASA-CxP-PUBS/

[3] ICAO, "Phases of flight: Definiations and usage notes," ICAO, Tech. Rep., April 2013.

[4] US-GAO, "Status of nas modernization," US Government Accounting Office, Tech. Rep. GAO-06-154, October 2005.

[5] (January, 2015) Cmu data classification. [Online]. Available: http://www.cmu.edu/iso/governance/guidelines/data-classification.html#classification

[6] P. FIPS, "Fips pub 199," *Standards for Security Categorization of Federal Information and Information Systems*, pp. 2–3, 2004.

[7] A. Act, "Health insurance portability and accountability act of 1996," *Public Law*, vol. 104, p. 191, 1996.

[8] U. Congress, "42 u.s.c. 1320d-2 - standards for information transactions and data elements," *Public Law*, p. 8, 2010. [Online]. Available: http://www.gpo.gov/fdsys/pkg/USCODE-2010-title42/pdf/USCODE-2010-title42-chap7-subchapXI-partC-sec1320d-2.pdf

[9] W. Ivancic, P. Paulsen, D. Stewart, D. Shell, L. Wood, C. Jackson, D. Hodgson, J. Northam, N. Bean, E. Miller *et al.*, "Secure, network-centric operations of a space-based asset: Cisco router in low-earth orbit (cleo) and virtual mission operations center (vmoc)," *NASA Technical Memorandum*, vol. 213556, pp. 0704–0188, 2005.

[10] J. Postel, "Internet Protocol," Internet Engineering Task Force, RFC 0791, Sep. 1981. [Online]. Available: http://www.rfc-editor.org/rfc/rfc791.txt

[11] J. Babiarz, K. Chan, and F. Baker, "Configuration Guidelines for DiffServ Service Classes," Internet Engineering Task Force, RFC 4594, Aug. 2006. [Online]. Available: http://www.rfc-editor.org/rfc/rfc4594.txt

[12] S. Kwok, "Gallaway, dkk., 2001, itu-t recommendation g. 1010," 2011.

[13] S. N. U. Guide, "Revision 10, 450-snug," *NASA Goddard Space Flight Center, Greenbelt, MD*, 2012.

[14] W. Ivancic, O. S. Sands, C. J. Bakula, D. Oldham, T. Wright, M. Bradish, and J. Klebau, "Power, avionics and software communication network architecture," NASA Glenn Research Center, Technical Memorandum NASA/TM—2014-216628, February 2014.

[15] J. B. Forgione, J. R. Grose, J. S. Myers, C. E. Sorenson, and R. G. Vogler, "The eip: a standard experimenter interface panel for nasa airborne science," in *SPIE Optical Engineering+ Applications*. International Society for Optics and Photonics, 2012, pp. 85 160A–85 160A.

[16] C. Sorenson, J. Forgione, and C. Barnes, "The nasa airborne science data and telemetry system (nasdat)," in *AGU Fall Meeting Abstracts*, vol. 1, 2011, p. 1283.

[17] (February, 2015) Nasa deep space network. [Online]. Available: http://deepspace.jpl.nasa.gov/

[18] (April, 2015) Chinese deep space network. [Online]. Available: http://en.wikipedia.org/wiki/Chinese_Deep_Space_Network

A. Acronyms List

CaLV Cargo Launch Vehicle

CaV Cargo Vehicle

CLV Crew Launch Vehicle

CONOPS Concept of Operations

CV Crew Vehicle

DOS Denial of Service

DRM Design Reference Mission

DSN Deep Space Network

EMU Extravehicular Mobile Unit

ESA European Space Agency

EVA Extravehicular Activity

FISMA Federal Information Security Management Act

GEO Geostationary Orbit

HIPAA Health Insurance Portability and Accountability Act

ISS International Space Station

IP Internet Protocol

L2 Lagrange Point 2

LEO Low-Earth Orbit

NASDAT NASA Airborne Science Data And Telemetry System

OpsCon Operational Concept

PI Principal Investigator

QOS Quality-of-Service

RF Radio Frequency

RFC Request for Comment

RTP Real-Time Protocol

RTT Round Trip Time

SAM Surface Access Module

SATCOM Satellite Communications

SCF Store, Carry and Forward

SCR Space Communication Relay

SpH Space Habitat

SNUG Space Network User's Guide

SpR Space Robot

SuH Surface Habitat

SuMS Surface Mobile System

SuR Surface Robot

SysML System Modeling Language

TCP Transmission Control Protocol

TDRS Tracking and Data Relay Satellite

TDRSS Tracking and Data Relay Satellite System

TOS Type of Service

USB Universal Serial Bus

B. Data Characteristics and Connections

B.1. Cargo Vehicle (CaV)

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Cargo Vehicle	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Voice																		
Video									X									
Telemetry	x			x	x	x	x	x	X	x	x	x	x	x	x	x		x
Command and Control	x			x	x		x		X	x	x	x	x	x	x	x		
Files																		
SL-Restricted				x					X									
SL-Private					x	x	x		X	x	x	x	x	x	x	x		x
SL-Public																		
SO-Confidentiality				x					X									
SO-Integrity				x	x	x	x	x	X	x	x	x	x	x	x	x	x	x
SO-Availability				x	x	x	x	x	X									
PI-Low					x	x				x	x	x	x	x	x	x	x	x
PI-Moderate					x		x	x										
PI-High	x			x					X									
P-Immediate				x	x				X									
P-Priority						x												
P-Routine							x	x		x	x	x	x	x	x	x	x	x
Time	S			S	S				S									T
Delay	S			S	S				S									T
Jitter	S								T									T
Disconnection				S	N	S	N	N	N	N	N	N	N	N	N	N	N	S
Loss				S	N				S	N	N	N	N	N	N	N	N	T
Bandwidth				L	L	L	L	L	B	L	L	L	L	L	L	L	L	L
Serial Wired (1553, RS422, etc)	x				x		x			x	x	x	x	x	x	x	x	
Spacewire																		
Coaxial																		
Ethernet	x			x		x		x	X									
Fiberoptic	x			x		x		x	X									
Broadcast																		
Point-to-Multipoint																		
Mesh Radio																		
Point-to-Point	x			x		x		x	X									x

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure B.9: Data Characteristics and Connections for the Cargo Vehicle (CaV)

B.2. *Crew Vehicle (CV)*

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Crew Vehicle		X	X	X	X	X			x									X
Voice		X	X	X		X												X
Video		X	X	X	X	X			X									X
Telemetry		X	X	X	X	X			X									X
Command and Control		X		X	X	X			X									X
Files		X	X	X		X												X
SL-Restricted		X		X		X			X									X
SL-Private		X	X	X	X	X			X									X
SL-Public						X												X
SO-Confidentiality		X		X		X			X									X
SO-Integrity		X	X	X	X	X			X									X
SO-Availability		X	X	X	X	X			X									X
PI-Low		X	X	X	X	X												X
PI-Moderate		X		X	X	X												X
PI-High						X			X									X
P-Immediate		X			X	X			X									X
P-Priority		X		X	X	X												X
P-Routine		X	X	X	X	X												X
Time		S	T	T	S	T												T
Delay		S	T	T	S	T												T
Jitter		S	T	T	T	T												T
Disconnection		N	T	N	S	T												T
Loss		N		N	S	T												T
Bandwidth		H	B	H	B	B			B									B
Serial Wired (1553, RS422, etc)		X		X	X													
Spacewire																		
Coaxial																		
Ethernet		X		X	X	X			X									
Fiberoptic		X		X	X	X			X									
Broadcast																		
Point-to-Multipoint		X		X														
Mesh Radio																		
Point-to-Point		X		X		X			X									X

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure B.10: Data Characteristics and Connections for the Crew Vehicle (CV)

B.3. *Extravehicular Mobile Unit (EMU)*

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
EMU			X			X						X	X	X	X	X	X	
Voice			X			X						X	X	X	X	X	X	
Video			X			X						X	X	X	X	X	X	
Telemetry			X			X						X	X	X	X	X	X	
Command and Control			X			X						X	X	X	X	X	X	
Files			X			X						X	X	X	X	X	X	
SL-Restricted			X			X						X				X		
SL-Private			X			X						X	X	X	X	X	X	
SL-Public						X						X	X	X	X	X	X	
SO-Confidentiality			X			X						X				X		
SO-Integrity			X			X						X	X	X	X	X	X	
SO-Availability			X			X						X	X	X	X	X	X	
PI-Low			X			X						X	X	X	X	X	X	
PI-Moderate			X			X						X	X	X	X	X	X	
PI-High																		
P-Immediate			X															
P-Priority			X									X	X	X	X	X	X	
P-Routine			X			X						X	X	X	X	X	X	
Time			T			T						T	T	T	T	T	T	
Delay			T			T						T	T	T	T	T	T	
Jitter			T			T						T	T	T	T	T	T	
Disconnection			T			T						T	T	T	T	T	T	
Loss			T			T						T	T	T	T	T	T	
Bandwidth			B			B						B	B	B	B	B	B	
Serial Wired (1553, RS422, etc)			X															
Spacewire			X															
Coaxial																		
Ethernet			X									X		X		X	X	
Fiberoptic												X		X		X	X	
Broadcast																		
Point-to-Multipoint			X			X						X	X	X	X	X	X	
Mesh Radio			X			X						X	X	X	X	X	X	
Point-to-Point																		

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure B.11: Data Characteristics and Connections for the Extravehicular Mobile Unit (EMU)

B.4. Launch Operations

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Launch Ops	X	x		X	X	X			X									X
Voice					X	X			X									X
Video	X				X	X			X									X
Telemetry	X				X													X
Command and Control					X													X
Files						X												X
SL-Restricted					X	X												X
SL-Private	X				X	X			X									X
SL-Public																		X
SO-Confidentiality					X	X			X									X
SO-Integrity	X				X	X			X									X
SO-Availability	X				X	X			X									X
PI-Low					X	X												X
PI-Moderate	X				X	X			X									X
PI-High						X												X
P-Immediate	X				X	X			X									X
P-Priority	X				X	X			X									X
P-Routine					X	X												X
Time	S				S	T			S									T
Delay	S				S	T			S									T
Jitter	T				S	T			S									T
Disconnection	S				S	T			S									N
Loss	S				S	T			S									T
Bandwidth	B				B	B			B									N
Serial Wired (1553, RS422, etc)																		
Spacewire																		
Coaxial																		
Ethernet	X				X	X			X									X
Fiberoptic	X				X	X			X									X
Broadcast																		
Point-to-Multipoint																		
Mesh Radio																		
Point-to-Point																		

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure B.12: Data Characteristics and Connections for Launch Operations

B.5. Launch Vehicle

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Launch Vehicle (Cargo or Crew)	X	X		X	X	X			X									x
Voice																		
Video				X					X									X
Telemetry	X	X		X		X			X									X
Command and Control	X	X		X	X				X									X
Files																		
SL-Restricted				X					X									X
SL-Private	X	X		X	X	X												X
SL-Public																		
SO-Confidentiality				X		X			X									X
SO-Integrity	X	X		X	X	X			X									X
SO-Availability	X	X		X	X	X			X									X
PI-Low						X												
PI-Moderate	X	X		X	X													X
PI-High									X									X
P-Immediate	X	X		X	X				X									X
P-Priority	X	X		X	X													X
P-Routine						X												
Time	S	S		S	S	T			S									S
Delay	S	S		S	S	T			S									S
Jitter	S	S		S	S	T			S									S
Disconnection	N	N		N	N	S			S									S
Loss	N	N		S	N	S			S									S
Bandwidth	L	L		B	B	L			B									B
Serial Wired (1553, RS422, etc)	X	X			X													
Spacewire																		
Coaxial																		
Ethernet	X	X		X	X	X			X									
Fiberoptic	X	X		X	X	X			X									
Broadcast																		
Point-to-Multipoint																		
Mesh Radio																		
Point-to-Point						X			X									X

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure B.13: Data Characteristics and Connections for the Launch Vehicle

B.6. Mission Operations

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Mission Ops	x	X	X	X	X	X				X	X	X	X	X	X	X	X	X
Voice		X	X	X						X		X		X		X		
Video		X	X	X						X		X		X		X		
Telemetry	x	X	X							X	X	X	X	X	X	X	X	X
Command and Control		X	X		X					X	X	X	X	X	X	X	X	X
Files		X	X	X						X	X	X	X	X	X	X	X	X
SL-Restricted		X	X	X						X	X	X		X		X		X
SL-Private	x	X		X	X					X	X	X	X	X	X	X	X	X
SL-Public			X										X		X		X	
SO-Confidentiality		X	X	X						X	X	X	X	X	X	X	X	X
SO-Integrity	x	X	X	X	X					X	X	X	X	X	X	X	X	X
SO-Availability	x	X	X	X	X					X	X	X	X	X	X	X	X	X
PI-Low	x	X	X	X						X	X	X		X		X		
PI-Moderate		X		X	X					X	X	X	X	X	X	X	X	X
PI-High			X	X							X							X
P-Immediate		X	X	X	X					X		X		X		X		
P-Priority	x	X	X	X	X					X	X	X	X	X	X	X	X	X
P-Routine		X	T	X						X	X	X	X	X	X	X	X	X
Time		S	T	T	S					S	T	S	T	S	T	S	T	T
Delay		S	T	T	S					S	T	S	T	S	T	S	T	T
Jitter		S	T	T	S					S	T	S	T	S	T	S	T	T
Disconnection	S	N	T	T	N					N	T	N	T	N	T	N	T	T
Loss		N	B	T	N					N	T	N	T	N	T	N	T	T
Bandwidth	L	H	X	B	B					H	B	H	B	H	B	H	B	L
Serial Wired (1553, RS422, etc)		X	X		X					X		X		X		X		
Spacewire																		
Coaxial			X															
Ethernet	x	X		X	X	X				X		X	?	X	?	X	?	
Fiberoptic	x	X		X	X	X				X		X	?	X	?	X	?	
Broadcast			X															
Point-to-Multipoint		X	X							X			X	X	X	X	X	
Mesh Radio													X		X		X	
Point-to-Point	x	X								X	X	X	X	X	X	X	X	X

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure B.14: Data Characteristics and Connections for Mission Operations

B.7. Payload

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Payload							X	X										
Voice																		
Video																		
Telemetry							X	X										
Command and Control							X	X										
Files																		
SL-Restricted																		
SL-Private																		
SL-Public																		
SO-Confidentiality																		
SO-Integrity																		
SO-Availability																		
PI-Low																		
PI-Moderate																		
PI-High																		
P-Immediate							X											
P-Priority							X	X										
P-Routine								X										
Time							N	T										
Delay							N	T										
Jitter							N	T										
Disconnection							N	T										
Loss							N	T										
Bandwidth							B	L										
Serial Wired (1553, RS422, etc)							X											
Spacewire																		
Coaxial																		
Ethernet							X	X										
Fiberoptic							X	X										
Broadcast																		
Point-to-Multipoint																		
Mesh Radio																		
Point-to-Point								X										

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure B.15: Data Characteristics and Connections for the Payload

B.8. Range Safety

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Range Safey	x	x		X	X				X									
Voice				X					X									
Video	X	X		X	X				X									
Telemetry	X	X			X													
Command and Control	X	X			X													
Files																		
SL-Restricted	X	X			X				X									
SL-Private	X	X		X					X									
SL-Public																		
SO-Confidentiality	X	X		X	X				X									
SO-Integrity	X	X		X	X				X									
SO-Availability	X	X		X	X				X									
PI-Low																		
PI-Moderate				X					X									
PI-High	X	X			X				X									
P-Immediate	X	X		X	X				X									
P-Priority				X					X									
P-Routine									X									
Time	S	S		S	S				S									
Delay	S	S		S	S				S									
Jitter	T	T		S	S				S									
Disconnection	N	N		S	S				N									
Loss	S	S		S	S				S									
Bandwidth	B	B		B	B				H									
Serial Wired (1553, RS422, etc)																		
Spacewire																		
Coaxial																		
Ethernet	X	X		X	X				X									
Fiberoptic	X	X		X	X				X									
Broadcast																		
Point-to-Multipoint																		
Mesh Radio																		
Point-to-Point	X	X			X													

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure B.16: Data Characteristics and Connections for Range Safety

B.9. Return Vehicle

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Return Vehicle	X					x				X	X	X						X
Voice						X					X							X
Video						X					X							X
Telemetry	X					X					X							X
Command and Control	X					X				X	X	X						X
Files						X					X							X
SL-Restricted	X					X					X							X
SL-Private	X					X				X	X	X						X
SL-Public						X					X							X
SO-Confidentiality	X					X					X							X
SO-Integrity	X					X				X	X	X						X
SO-Availability	X					X				X	X	X						X
PI-Low						X					X							X
PI-Moderate	X					X				X	X	X						X
PI-High						X				X	X	X						X
P-Immediate	X					X				X	X	X						X
P-Priority	X					X				X	X	X						X
P-Routine						X				X	X	X						X
Time	S					T				S	T	S						T
Delay	S					T				S	T	S						T
Jitter	S					T				S	T	S						T
Disconnection	N					T				N	T	N						T
Loss	S					T				N	T	N						T
Bandwidth	L					B				H	B	H						B
Serial Wired (1553, RS422, etc)	X									X		X						
Spacewire																		
Coaxial																		
Ethernet	X					X				X		X						
Fiberoptic	X					X				X		X						
Broadcast																		
Point-to-Multipoint																		
Mesh Radio																		
Point-to-Point						X					X							X

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure B.17: Data Characteristics and Connections for the Return Vehicle

B.10. Space Communication Relay (SCR)

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Space Communications Relay						X				X	X	X	X	X	X	X	X	X
Voice						X				X		X	X	X	X	X	X	X
Video						X				X		X	X	X	X	X	X	X
Telemetry						X				X		X	X	X	X	X	X	X
Command and Control						X				X	X	X	X	X	X	X	X	X
Files						X				X		X	X	X	X	X	X	X
SL-Restricted						X				X		X	X	X	X	X	X	X
SL-Private						X				X	X	X	X	X	X	X	X	X
SL-Public										X		X	X	X	X	X	X	
SO-Confidentiality						X				X		X	X	X	X	X	X	X
SO-Integrity						X				X		X	X	X	X	X	X	X
SO-Availability						X				X		X	X	X	X	X	X	X
PI-Low						X				X		X	X	X	X	X	X	X
PI-Moderate						X				X	X	X	X	X	X	X	X	X
PI-High						X				X	X	X	X	X	X	X	X	X
P-Immediate										X	X	X	X	X	X	X	X	
P-Priority						X				X	X	X	X	X	X	X	X	X
P-Routine						X				X	X	X	X	X	X	X	X	X
Time						T				T	S	T	T	T	T	T	T	T
Delay						T				T	S	T	T	T	T	T	T	T
Jitter						T				T	S	T	T	T	T	T	T	T
Disconnection						T				T	N	T	T	T	T	T	T	T
Loss						T				T	N	T	T	T	T	T	T	T
Bandwidth						B				B	B	B	B	B	B	B	B	B
Serial Wired (1553, RS422, etc)											X							
Spacewire											X							
Coaxial																		
Ethernet											?							
Fiberoptic											?							
Broadcast																		
Point-to-Multipoint																		
Mesh Radio																		
Point-to-Point						X				X		X	X	X	X	X	X	X

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure B.18: Data Characteristics and Connections for the Space Communication Relay (SCR)

B.11. Space Habitat (SpH)

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Space Habitat	x		X			X				X	X	X	X	X	X	X		x
Voice			X			X					X	X		X		X		X
Video			X			X					X	X	X	X	X	X		X
Telemetry	x		X			X					X	X	X	X	X	X		X
Command and Control	x		X			X				X	X	X	X	X	X	X		X
Files			X			X					X	X	X	X	X	X		X
SL-Restricted			X			X					X	X	X	X	X	X		X
SL-Private	x		X			X				X	X	X	X	X	X	X		X
SL-Public			X								X	X		X		X		
SO-Confidentiality			X			X					X	X	X	X	X	X		X
SO-Integrity	x		X			X				X	X	X	X	X	X	X		X
SO-Availability			X			X				X	X	X	X	X	X	X		X
PI-Low	x		X			X					X	X		X		X		X
PI-Moderate			X			X				X	X	X	X	X	X	X		X
PI-High										X	X	X	X	X	X	X		X
P-Immediate						X				X	X	X	X	X	X	X		
P-Priority			X			X				X	X	X	X	X	X	X		X
P-Routine	x		X			X				X	X	X	X	X	X	X		X
Time			T			S				S	T	T	T	T	T	T		T
Delay			T			S				S	T	T	T	T	T	T		T
Jitter			T			S				S	T	T	T	T	T	T		T
Disconnection	N		T			N				N	T	T	T	T	T	T		T
Loss	N		T			N				N	T	T	T	T	T	T		T
Bandwidth	L		B			H				H	B	B	B	B	B	B		B
Serial Wired (1553, RS422, etc)	x					X				X		X						
Spacewire																		
Coaxial																		
Ethernet			X			X				X		X						
Fiberoptic			X			X				X		X						
Broadcast																		
Point-to-Multipoint			X									X	X					
Mesh Radio			X										X					
Point-to-Point						X					X		X	X	X	X		X

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure B.19: Data Characteristics and Connections for the Space Habitat (SpH)

B.12. *Space Robot (SpR)*

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Space Robot	x		X			X					X	X	X					X
Voice			X			X					X							
Video			X			X					X	X	X					X
Telemetry	x		X			X					X	X	X					X
Command and Control	x		X			X					X	X	X					X
Files			X			X					X	X	X					X
SL-Restricted						X					X	X	X					X
SL-Private	x		X			X					X	X	X					X
SL-Public			X								X							
SO-Confidentiality						X					X	X	X					X
SO-Integrity	x		X			X					X	X	X					X
SO-Availability			X			X					X	X	X					X
PI-Low	x		X			X					X							X
PI-Moderate			X			X					X	X	X					X
PI-High											X	X	X					X
P-Immediate						X					X	X	X					
P-Priority			X			X					X	X	X					X
P-Routine	x		X			X					X	X	X					X
Time			T			S					T	T	T					T
Delay			T			S					T	T	T					T
Jitter			T			S					T	T	T					T
Disconnection	N		T			N					T	T	T					T
Loss	N		T			N					T	T	T					T
Bandwidth	L		B			H					B	B	B					B
Serial Wired (1553, RS422, etc)	x					X												
Spacewire																		
Coaxial																		
Ethernet						X												
Fiberoptic						X												
Broadcast																		
Point-to-Multipoint			X									X	X					
Mesh Radio			X									X	X					
Point-to-Point						X					X	X	X					X

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure B.20: Data Characteristics and Connections for a Space Robot (SpR)

B.13. Surface Access Module (SAM)

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Surface Access Module	x		x			X					X	X	X	X	X	X		x
Voice			X			X					X	X				X		X
Video			X			X					X	X	X		X	X		X
Telemetry	x		X			X					X	X	X		X	X		X
Command and Control	x		X			X					X	X	X	X	X	X		X
Files			X			X					X	X	X		X	X		X
SL-Restricted						X					X	X	X		X	X		X
SL-Private	x		X			X					X	X	X	X	X	X		X
SL-Public			X								X	X				X		
SO-Confidentiality						X					X	X	X		X	X		X
SO-Integrity	x		X			X					X	X	X	X	X	X		X
SO-Availability			X			X					X	X	X	X	X	X		X
PI-Low	x		X			X					X	X				X		X
PI-Moderate			X			X					X	X	X	X	X	X		X
PI-High											X	X	X		X	X		X
P-Immediate						X					X	X	X	X	X	X		
P-Priority			X			X					X	X	X	X	X	X		X
P-Routine	x		X			X					X	X	X		X	X		X
Time			T			S					T	T	T	S	T	T		T
Delay			T			S					T	T	T	S	T	T		T
Jitter			T			S					T	T	T	S	T	T		T
Disconnection	N		T			N					T	T	T	N	T	T		T
Loss	N		T			N					T	T	T	N	T	T		T
Bandwidth	L		B			H					B	B	B	L	B	B		B
Serial Wired (1553, RS422, etc)	x					X								X				
Spacewire														X				
Coaxial																		
Ethernet						X								X				
Fiberoptic						X								X				
Broadcast																		
Point-to-Multipoint			X			X							X		X			
Mesh Radio			X										X		X			
Point-to-Point						X					X	X	X		X	X		X

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure B.21: Data Characteristics and Connections for the Surface Access Module (SAM)

B.14. *Surface Robot (SuR)*

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Surface Robot	x		X			X					X	X		X	X	X	X	X
Voice			X			X					X							
Video			X			X					X	X		X	X	X	X	X
Telemetry	x		X			X					X	X		X	X	X	X	X
Command and Control	x		X			X					X	X		X	X	X	X	X
Files			X			X					X	X		X	X	X	X	X
SL-Restricted						X					X	X		X	X	X	X	X
SL-Private	x		X			X					X	X		X	X	X	X	X
SL-Public			X								X							
SO-Confidentiality						X					X	X		X	X	X	X	X
SO-Integrity	x		X			X					X	X		X	X	X	X	X
SO-Availability			X			X					X	X		X	X	X	X	X
PI-Low	x		X			X					X							X
PI-Moderate			X			X					X	X		X	X	X	X	X
PI-High											X	X		X	X	X	X	X
P-Immediate						X					X	X		X	X	X	X	
P-Priority			X			X					X	X		X	X	X	X	X
P-Routine	x		X			X					X	X		X	X	X	X	X
Time			T			S					T	T		T	T	T	T	T
Delay			T			S					T	T		T	T	T	T	T
Jitter			T			S					T	T		T	T	T	T	T
Disconnection	N		T			N					T	T		T	T	T	T	T
Loss	N		T			N					T	T		T	T	T	T	T
Bandwidth	L		B			H					B	B		B	B	B	B	B
Serial Wired (1553, RS422, etc)	x					X												
Spacewire																		
Coaxial																		
Ethernet						X												
Fiberoptic						X												
Broadcast																		
Point-to-Multipoint			X											X	X	X	X	
Mesh Radio			X											X	X	X	X	
Point-to-Point						X					X	X		X	X	X	X	X

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure B.22: Data Characteristics and Connections for the Surface Robot (SuR)

B.15. *Surface Habitat (SuH)*

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Surface Habitat	x		X			X					X	X		X	X	X	X	X
Voice			X			X					X	X		X		X	X	X
Video	x		X			X					X	X		X	X	X	X	X
Telemetry			X			X					X	X		X	X	X	X	X
Command and Control			X			X					X	X		X	X	X	X	X
Files	x		X			X					X	X		X	X	X	X	X
SL-Restricted			X			X					X	X		X	X	X	X	X
SL-Private			X			X					X	X		X	X	X	X	X
SL-Public			X								X	X		X		X	X	X
SO-Confidentiality			X			X					X	X		X	X	X	X	X
SO-Integrity	x		X			X					X	X		X	X	X	X	X
SO-Availability	x		X			X					X	X		X	X	X	X	X
PI-Low			X			X					X	X		X		X	X	X
PI-Moderate	x		X			X					X	X		X	X	X	X	X
PI-High	x										X	X		X	X	X	X	X
P-Immediate	x					X					X	X		X	X	X	X	
P-Priority	x		X			X					X	X		X	X	X	X	X
P-Routine	x		X			X					X	X		X	X	X	X	X
Time			T			S					T	T		T	T	T	T	T
Delay			T			S					T	T		T	T	T	T	T
Jitter			T			S					T	T		T	T	T	T	T
Disconnection	N		T			N					T	T		T	T	T	T	T
Loss	N		T			N					T	T		T	T	T	T	T
Bandwidth	L		B			H					B	B		B	B	B	B	B
Serial Wired (1553, RS422, etc)	x					X										X		
Spacewire																		
Coaxial																		
Ethernet			X			X										X	?	
Fiberoptic			X			X										X	?	
Broadcast																		
Point-to-Multipoint			X			X									X	X	X	
Mesh Radio			X												X		X	
Point-to-Point						X					X	X		X	X		X	X

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS

Figure B.23: Data Characteristics and Connections for the Surface Habitat (SuH)

B.16. Surface Mobile System (SuMS)

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Surface Mobile Systems	x		X			X					X				X	X	X	x
Voice			X			X					X					X	X	X
Video	x		X			X					X				X	X	X	X
Telemetry			X			X					X				X	X	X	X
Command and Control			X			X					X				X	X	X	X
Files	x		X			X					X				X	X	X	X
SL-Restricted			X			X					X				X	X	X	X
SL-Private			X			X					X				X	X	X	X
SL-Public			X								X					X	X	X
SO-Confidentiality			X			X					X				X	X	X	X
SO-Integrity	x		X			X					X				X	X	X	X
SO-Availability	x		X			X					X				X	X	X	X
PI-Low			X			X					X					X	X	X
PI-Moderate	x		X			X					X				X	X	X	X
PI-High	x										X				X	X	X	X
P-Immediate	x					X					X				X	X	X	
P-Priority	x		X			X					X				X	X	X	X
P-Routine	x		X			X					X				X	X	X	X
Time			T			S					T				T	T	T	T
Delay			T			S					T				T	T	T	T
Jitter			T			S					T				T	T	T	T
Disconnection	N		T			N					T				T	T	T	T
Loss	N		T			N					T				T	T	T	T
Bandwidth	L		B			H					B				B	B	B	B
Serial Wired (1553, RS422, etc)	x					X												
Spacewire																		
Coaxial																		
Ethernet			X			X										?	X	
Fiberoptic			X			X										?	X	
Broadcast																		
Point-to-Multipoint			X			X									X	X	X	
Mesh Radio			X												X	X	X	
Point-to-Point						X					X				X	X	X	X

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure B.24: Data Characteristics and Connections for the Surface Mobile System (SuMS)

B.17. Tracking and Communication System

Element connected to Element -->	Cargo Vehicle	Crew Vehicle	EMU	Launch Ops	Launch Vehicle (Cargo or Crew)	Mission Ops	Payload	Payload Ops	Range Safety	Return Vehicle	Space Communication Relay	Space Habitat	Space Robot	Surface Access Module	Surface Robots	Surface Habitat	Surface Mobile Systems	Tracking and Communications System
Tracking and Communication System	x	X		X	X	X				X	X	X	X	X	X	X	X	X
Voice		X		X						X	X	X		X		X	X	X
Video		X		X	X					X	X	X	X	X	X	X	X	X
Telemetry	x	X		X	X	X				X	X	X	X	X	X	X	X	X
Command and Control		X		X	X	X				X	X	X	X	X	X	X	X	X
Files		X		X		X				X	X	X	X	X	X	X	X	X
SL-Restricted		X		X	X	X				X	X	X	X	X	X	X	X	X
SL-Private	x	X		X	X	X				X	X	X	X	X	X	X	X	X
SL-Public		X		X						X						X	X	X
SO-Confidentiality		X		X	X	X				X	X	X	X	X	X	X	X	X
SO-Integrity	x	X		X	X	X				X	X	X	X	X	X	X	X	X
SO-Availability		X		X	X	X				X	X	X	X	X	X	X	X	X
PI-Low	x	X		X						X	X	X	X	X	X	X	X	X
PI-Moderate		X		X	X	X				X	X	X	X	X	X	X	X	X
PI-High		X		X	X	X				X	X	X	X	X	X	X	X	X
P-Immediate		X		X	X					X							X	X
P-Priority		X		X	X	X				X	X	X	X	X	X	X	X	X
P-Routine	x	X		X		X				X	X	X	X	X	X	X	X	X
Time	T	T		T	S	T				T	T	T	T	T	T	T	T	T
Delay	T	T		T	S	T				T	T	T	T	T	T	T	T	T
Jitter	T	T		T	S	T				T	T	T	T	T	T	T	T	T
Disconnection	S	T		N	S	T				T	T	T	T	T	T	T	T	T
Loss	T	T		T	S	T				T	T	T	T	T	T	T	T	T
Bandwidth	L	B		N	B	L				B	B	B	B	B	B	B	B	B
Serial Wired (1553, RS422, etc)																		X
Spacewire																		X
Coaxial																		X
Ethernet				X													X	X
Fiberoptic				X													X	X
Broadcast																		
Point-to-Multipoint																	X	
Mesh Radio																	X	
Point-to-Point	x	X			X	X				X	X	X	X	X	X	X	X	X

X	Has Characteristic
S	Sensitive
T	Tolerant
L	Low Bandwidth, Low Data Rate i.e. < Mbps
H	High Bandwidth, High Data Rate i.e ≥ Mbps
B	Both High and Low Bandwidth depending on Phase of OpS
N	Not Applicable

Figure B.25: Data Characteristics and Connections for the Tracking and Communication System