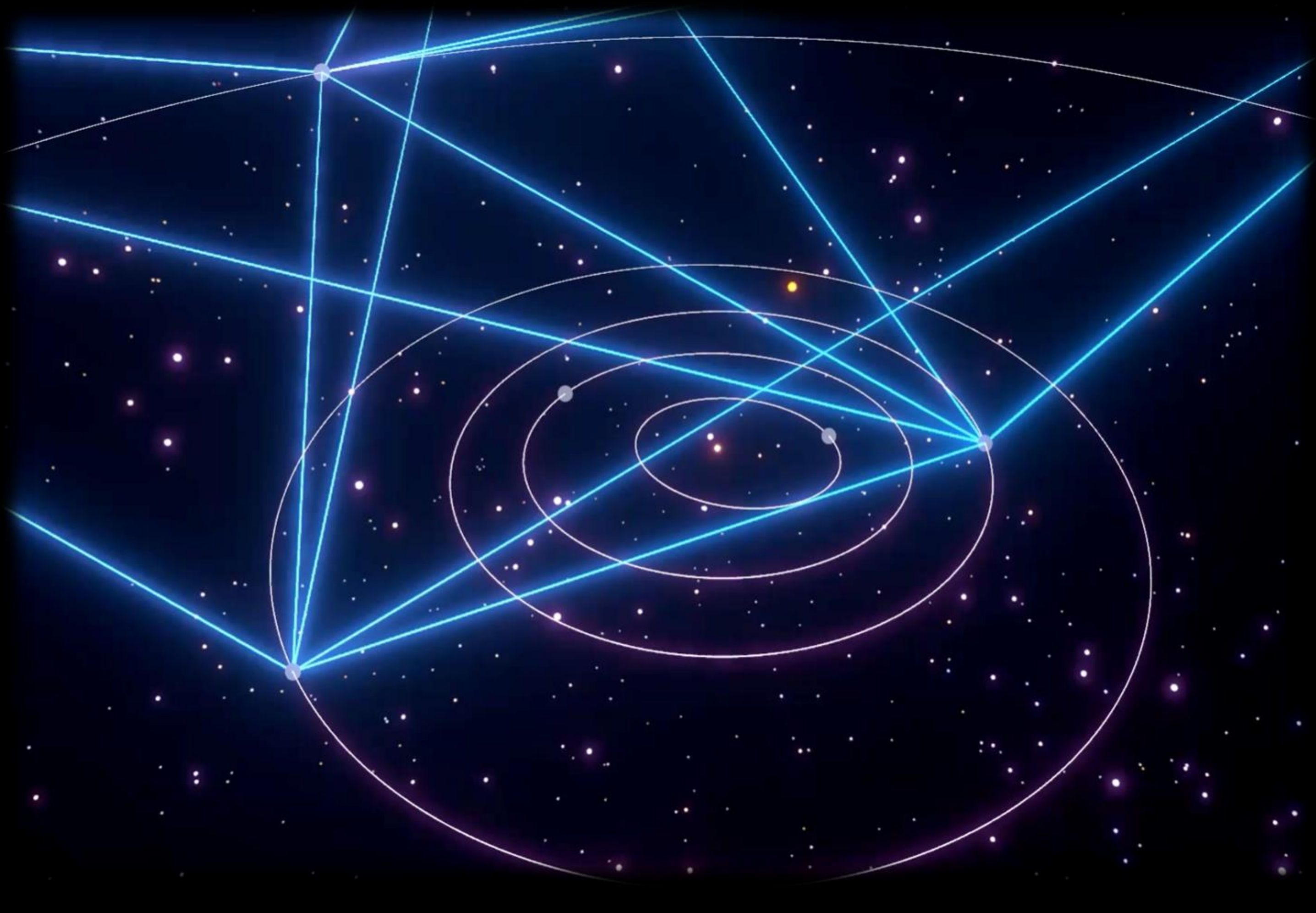
Internet Society
Interplanetary
Chapter

IPNSIG

Solar System Internet
Architecture and Governance



- from the Moon to Mars and beyond -

September, 2023

Executive Summary

Humanity landed on the lunar surface more than half a century ago, and we are entering a new era in space exploration. With momentum growing across the globe, many actors are striving to reach the Moon - Nation states drawn by its national pride, inspiration, scientific potential and private sectors enticed by its economic potential. Unlike the historical approaches that were heavily managed by nation states and space agencies, humanity is on its way to the Moon through commercial and international partnerships.

Notably, the origins of the Internet and of space exploration share a similar trajectory. The first packets were sent over Arpanet the same year humans landed on the moon. Today, the Internet has evolved into a terrestrial societal ecosystem, permeating every facet of human life. Its next horizon likely extends to space as humanity reaches deeper into that realm.

In the not too distant future, different communication networks provided by different actors will likely join together in space - the age of "networks of networks in Space."

This raises fundamental questions - "Can humanity construct a common infrastructure, similar to the Internet, in space, and what are the properties that must be satisfied to attain that goal? How could a collection of space-based networks work as a whole? What governance mechanisms are needed to promote this multi-party effort?"

This paper examines the governance properties and structures necessary to form a common and shared space network, along with the key technologies that will drive this endeavor. We suggest the adoption of the Bundle Protocol (BP) suite, built on Delay and Disruption Tolerant Networking (DTN) architecture concepts, as an enabling communication technology to promote interplanetary networking, in addition to the use of IPv6-based internets on other celestial bodies. We recommend adoption of a "Multistakeholder" governance approach, inherited from the Internet ecosystem, to attain a sustainable and resilient space-oriented network infrastructure.

This paper uses the term Solar System Internet (SSI), as a new manifestation of the Internet, carrying the DNA of the terrestrial Internet while adapting to new conditions. It also addresses the key principles necessary for a common SSI, reflecting on the lessons from the Internet, such as the development of standards that ensures interoperability among the various networks and fair and consistent resource allocation of numbering identifiers and spectrum. Additionally, it explores how the existing Earth-based governance organizations or their functions could be used, as well as suggesting new organizations that might be needed for the governance of the SSI.

The Interplanetary Networking Special Interest Group (IPNSIG) functioning as the Interplanetary Chapter of the Internet Society has focused largely on the "Network" deployment and operation in space, but it is expected that the views provided herein may assist in assessing multi-party governance practices for other operational use cases in space.

Internet Society Interplanetary Chapter

Table of Contents

1. Introduction

The Internet has evolved dramatically from its inception – from the tongue-in-cheek 1962 Galactic Network concept by J.C.R Licklider[1] and the very real Arpanet project[2], to the birth of packet switching and TCP/IP, the rise of the World Wide Web, web browsers, and social media. Today, the Internet permeates almost every aspect of human life, becoming an integral and still evolving part of our society.

As the newest era in space exploration begins, the Internet's future now extends into outer space. Today, we are on the cusp of an exciting re-entry into human and robotic space exploration driven by great momentum across the globe. This new era integrally involves commercial and international partners, marking a considerable departure from historic space exploration where nation states and space agencies were the primary actors, such as the Apollo program. Change in the global landscape is being propelled mainly by commercial innovation, significantly reduced launch costs, and more opportunities for non-space faring nations, private sector and academia to have access to space.

Momentum Toward a Shared Space Communication Architecture

Several initiatives now underway are part of the global momentum toward space exploration and communication. NASA, in an effort to promote the Artemis program[3] is planning to deploy the LunaNet [4] (Lunar Internet), a collaborative architecture and framework to provide communication, positioning and navigation services in cislunar space. ESA has also initiated the Moonlight program [5] and JAXA, through the Stardust program [6], aims to deploy essential communication and navigation capabilities to support lunar surface activities. NASA is also pursuing the Commercial Lunar Payload Services (CLPS) [7] initiative, aiming to acquire lunar delivery services from U.S. commercial providers.

Significant interest is emerging from the private sector to join these programs. In addition, several private programs plan to deploy communication capabilities on the lunar surface. These efforts include major telecommunications companies outside of the space agency framework, foreseeing the business potential of the lunar domain. The development of an interplanetary networking ecosystem is already emerging.

---

[1] https://en.wikipedia.org/wiki/Intergalactic_Computer_Network
[2] https://en.wikipedia.org/wiki/ARPANET
[3] The Artemis Program, https://www.nasa.gov/specials/artemis/
[4] NASA's LunaNet, https://esc.gsfc.nasa.gov/projects/TEMPO?tab=lunanet
[5] ESA's Moonlight, https://www.esa.int/Applications/Connectivity_and_Secure_Communications/Moonlight
[6] JAXA's Stardust program, https://www8.cao.go.jp/space/comittee/02-jissyou/jissyou-dai10/siryou1.pdf
[7] NASA's CLPS, https://www.nasa.gov/commercial-lunar-payload-services

Now is the moment of opportunity to envision and architect how these heterogeneous networks provided by different actors can join together in space. The terrestrial Internet is a network of networks. So too should there be an interoperable network of networks in space. Standards and collaborative governance structures are critical precursors for these various networks to work as a whole for the good of humanity.

The aspirational vision for the Solar System Internet, or SSI, is to interconnect these various types of networks in space. The Internet has been through many chapters and has transformed significantly over time. The Solar System Internet is a critical and evolutionary manifestation of the Internet, carrying the DNA of the Internet while also adapting to the unique conditions and challenges of space. The Federal Networking Council Resolution[8] defines the Internet as a global information system encompassing the "Transmission Control Protocol/Internet Protocol (TCP/IP) suite **or its subsequent extensions/follow-ons, and/or other IP-compatible protocols**". (emphasis added)

As such, interoperability in the Solar System Internet necessitates evolutionary TCP/IP successor protocols such as the Bundle Protocol (BP) and Licklider Transmission Protocol (LTP) for use in environments where TCP/IP is not practical (Refer to section 4.1 for more details).

Learning from History of the Internet

What we are about to witness in space is analogous to one of the historical events in Internet history. In 1983, three disparate networks, namely the Arpanet, SATNET and PRNET all joined together to form a single network using TCP/IP, giving birth to the operational Internet[9]. Establishing a shared and interoperable network in space will follow a similar trajectory in which different networks will interconnect by adopting common protocol standards.

Many governance issues followed the inception of the Internet. Some would describe this early environment as *"Technology first, and Governance later"*. But design and coordination requirements in that era began to coalesce a multistakeholder structure of Internet governance that included the administration and distribution of critical resources such as IP addresses and domain names, the incorporation of early cybersecurity structures around authentication by public key cryptography, and efforts to address harmful behavior online from unlawful content to harassment. These types of governance issues have dominated many international discussions. The development of the Solar System Internet will also have concomitant governance questions, and it is critical to anticipate these as the technology develops and to learn from the history of the terrestrial Internet.

[8] FNC Resolution: Definition of "Internet" 10/24/95, https://www.nitrd.gov/historical/fnc/internet_res.pdf
[9] https://www.internetsociety.org/internet/history-internet/brief-history-internet/

A Moment of Opportunity for Design and Governance of the Solar System Internet

Developments in space are progressing at a remarkable pace. Unlike the early days of the Internet, which began as a research project initiated by government and universities, the Solar System Internet will advance with private sector involvement from its earliest stages. Establishing shared architectures and governance from its inception is of paramount importance.

This paper focuses on architecture and governance of the Solar System Internet, proceeding in two parts.

1) Architectural perspective - assessing the key technical drivers and challenges.
2) Governance perspective - identifying key items requiring coordination and administration, offering governance approaches and practices.

Our work has focused largely on the "Network" deployment in space, but our perspectives and recommendations herein might also help inform multi-party governance practices for other operational use cases in space.

2. Vision for a Common Solar System Internet

Space exploration has been one of humanity's ultimate challenges for more than half a century. Humanity has long sought to expand its boundaries terrestrially and now farther into our solar system driven by a desire to understand the origins of life, acquire scientific knowledge, and to expand our social and economic ecosystem. None of this is feasible without a secure and resilient system of space communication.

The Interplanetary Networking Special Interest Group (IPNSIG)[10] has long envisioned a common Solar System Internet, a shared infrastructure that benefits humanity. Conceptually like the terrestrial Internet, a common communication infrastructure in space would enable sustainable and resilient human and robotic activity, enhance commercial opportunities and growth, augment scientific achievements and incubate innovation that would bring benefit to all[11].

What are the necessary architectural and governance mechanisms to construct a foundational Solar System Internet for human communication and innovation? This is the core question that we address in this paper.

---

[10] https://www.ipnsig.org/

[11] Strategy toward a Solar System Internet for Humanity, IPNSIG (2021) https://www.ipnsig.org/_files/ugd/d716c2_953b0e8d294e4315bb1b094d798c7c25.pdf

3. Anticipated Evolution of the Solar System Internet

The Solar System Internet architecture, analogous to the terrestrial Internet, will evolve over time. As the architecture and its users change, governance must adapt accordingly. Figure-1 illustrates the anticipated transition in architecture and governance. This future projection was used to assess the governance needs which are discussed in Section 7.

The evolution

Today - Space Agency-led, point-to-point

- The Space agencies sustain the space communication backbone, which is characterized by point-to-point communication systems. End users are mostly government or space agencies who conduct narrowly targeted space missions.
- Inter-agency support through bartering or agreements amongst the space agencies are frequently applied to effectively accomplish a given mission.
- Some commercial entities may develop their own networks, but are still limited to those with sufficient capital.
- In the near-term it is anticipated that networking capabilities will be introduced into the NASA DSN (Deep Space Network) and NSN (Near Space Network) systems in support of international missions, for example.

Transitional phase - Emergence of Commercial networks and expansion

- Space agencies start funding commercial entities, toward the goal of procuring commercial services for its infrastructure. Public-private partnership models emerge (e.g., "LunaNet" as being defined by the Interagency Operations Advisory Group (IOAG) and Consultative Committee for Space Data Systems (CCSDS) with initial implementation by NASA, JAXA and ESA. LunaNet may well consist of multiple networks, which will become part of the Solar System Internet).
- For LunaNet, commercial access provider services are initially procured by space agencies.
- Some commercial backbones may gradually emerge in the lunar region connecting with space agency backbones. Some space agency backbones may also start interconnecting with each other (cooperating space agencies will provide cross-support to each other using their commercial service providers).
- Some assets like NASA's DSN could still be self-sponsored.

Future- Commercialization of Space Networks

- Commercial entities provide networking services for end users using their own funds.
- End users could be governments, space agencies and also the commercial sector and academia. Yet unknown, but someday, the general public may have access to the network.
- It is anticipated that multiple stakeholders will engage in the Solar System Internet.
- Each commercial network will have the capability to interconnect with others based on private-private partnerships or agreements, similar to the peering concept in today's Internet environment.
- There could still be exclusive, government or space agency sponsored networks independently operating, to serve national security missions for example.

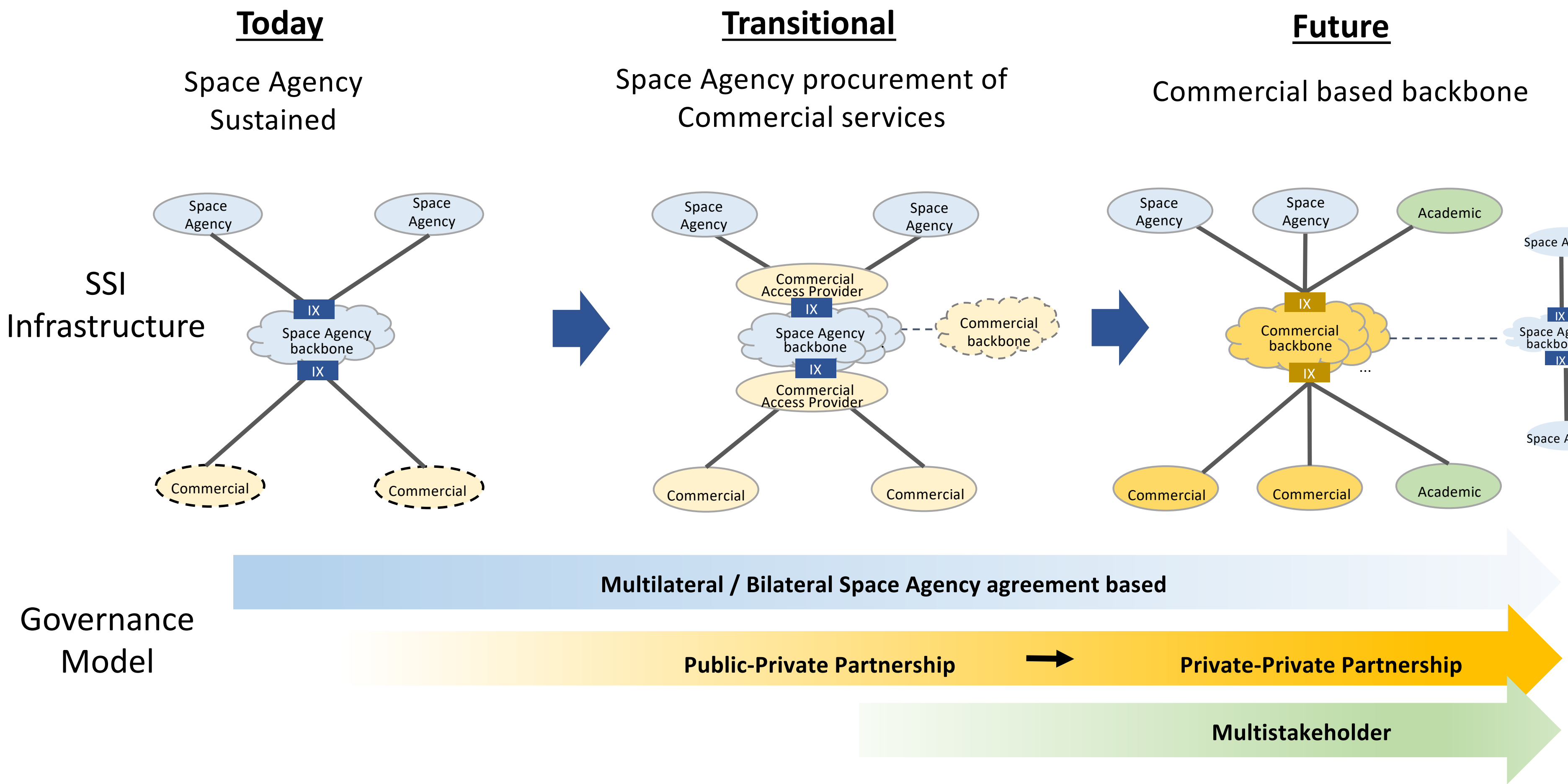


Figure-1 The Solar System Internet Architecture and Governance Evolution

4. Key Technology and Future challenges

Several key technologies will enable interplanetary networking in the challenging environment of space. In space, communication can be easily disrupted by planetary motion – as a spacecraft will lose connectivity with ground stations when it orbits behind planets. Communication at astronomical distances is subject to significant signal attenuation and propagation delays. Network infrastructure can be damaged by space debris, comets, solar flares, and radiation, requiring networks with greater resiliency, autonomy, and recovery mechanisms. These characteristics contrast with our terrestrial environment and have to be addressed at early design and governance stages.

Space internetworking is a necessary next step in the evolution of space communications. Traditional point-to-point methods can only be scaled up so far, and the near-term future of space exploration has reached a point requiring new networking techniques specifically designed for space. The following are some of the key technologies to address these unique challenges, which take on paramount importance for interplanetary communication.

4.1 Delay and Disruption Tolerant Networking

Terrestrial Internet protocols[12] are designed for continuously-connected low-latency networks, and while they have their place on well-connected surface networks via on or off-Earth relays, a technology is needed to handle communications where frequent link outages due to orbital motions, highly variable delays due to speed of light limitations and unreliable radio links are the driving design factors.

This space networking protocol architecture is known as Delay and Disruption-Tolerant Networking (DTN)[13] [14]. By far the most common implementation of DTN is the Bundle Protocol (BP) suite, which uses the Bundle Protocol[15] [16] as its networking layer.

Under development for more than two decades, the BP suite accommodates networking in lunar and deep space environments where one-way light transmission times prohibit the use of highly interactive IP protocols, and the lack of continuous end-to-end paths requires storage in the

---

[12] We include Earth orbiting satellites in the definition of "terrestrial."

[13] V. Cerf, S. Burleigh, L.Torgerson, et al, "Delay-Tolerant Networking Architecture", Request for Comments: RFC 4838, April 2007. [Online]. Available: https://datatracker.ietf.org/doc/html/rfc4838

[14] Consultative Committee for Space Data Systems, "Solar system internetwork (SSI) architecture," Informational Report CCSDS 730.1-G-1, July 2014. [Online]. Available: https://public.ccsds.org/Pubs/730x1g1.pdf

[15] K. Scott and S. Burleigh, "Bundle Protocol Specification," Request for Comments: RFC 5050, Nov. 2007. [Online]. Available: https://www.rfc-editor.org/info/rfc5050

[16] S. Burleigh, K. Fall, and E. Birrane III, "Bundle Protocol Version 7," Request for Comments: RFC 9171, Jan. 2022. [Online]. Available: https://www.rfc-editor.org/info/rfc9171

network. A BP data unit (bundle) carries the content of messages that are to be transmitted to other BP suite nodes. BP suite nodes incorporate storage, so when a relay node does not have a link to another spacecraft or lander, the bundles are stored at the intermediate relay node until the next link is available.

Space links are often plagued with noise or disconnected altogether due to orbital mechanics or antenna pointing issues. While modern techniques of forward error correction coding may do an excellent job of providing noise immunity, coding is not designed to handle total link outages. The BP suite uses a robust Automatic Repeat Request (ARQ) system which is implemented in the Licklider Transmission Protocol (LTP)[17] [18] above the RF link layers and below the BP network layer. LTP automatically detects and tracks data loss and when the link is back up, LTP recovers missing data without labor-intensive ground operator intervention, as is required in today's space missions.

In addition to providing a network data transport and delivery system for deep space, the BP suite accommodates file transfer using the CCSDS (Consultative Committee for Space Data Systems) File Delivery Protocol (CFDP)[19], data confidentiality and cryptographic integrity checking via the Bundle Protocol Security (BPSec)[20] provisions, and has a network monitoring and control system[21] built in that allows network operators to be informed of BP suite node status and to easily command configuration changes as needed.

DTN was designed as an overlay network, and may use an underlying terrestrial Internet for transport, any internal spacecraft bus systems, or directly use space links (RF or optical). DTN and the BP suite also provide for the use of IP networks on other celestial bodies, with the BP suite providing a long-haul reliable backbone service.

The BP suite of protocols that are required to begin establishing space networking has been standardized by both the IETF and CCSDS, with the CCSDS organization making specific recommendations on how to implement the IETF standards in space systems. Core BP suite protocols have been space-qualified on several spacecraft, and is flying at the moon today on the Korea Pathfinder Lunar Orbiter (KPLO)[22] as a Development Test Objective (DTO), and is used on

---

[17] Consultative Committee for Space Data Systems, "Licklider transmission protocol (LTP)," Recommended Standard CCSDS 734.1-B-1, May 2015. Available: https://public.ccsds.org/Pubs/734x1b1.pdf

[18] M. Ramadas, S. Burleigh, and S. Farrell, "Licklider Transmission Protocol - Specification," RFC 5326, September 2008. Available: https://www.rfc-editor.org/info/rfc5326. DOI: 10.17487/RFC5326.

[19] Consultative Committee for Space Data Systems, "CCSDS file delivery protocol (CFDP)," CCSDS Recommended Standard, CCSDS 727.0-B-5, July 2020. Available: https://public.ccsds.org/Pubs/727x0b5.pdf

[20] E. Birrane, III and K. McKeever, "Bundle Protocol Security (BPSec)," Request for Comments: RFC 9172, Jan. 2022. Available: https://www.rfc-editor.org/info/rfc9172

[21] E. J. Birrane, S. Heiner, and E. Annis, "DTN management architecture," Draft for Comments: draft-ietf-dtn-dtnma-06, IETF Datatracker, Jul. 2023. Available: https://datatracker.ietf.org/doc/html/draft-ietf-dtn-dtnma-06

[22] https://www.kari.re.kr/eng/sub03_07_01.do

dozens of payload packages on the International Space Station[23]. DTN has been recommended by the international Interagency Operations Advisory Group (IOAG), as well as CCSDS, as the preferred way to implement the Solar System Internet[24], and is baselined for LunaNet in the LunaNet Interoperability Specification[25].

The BP suite includes a number of applications, the core Bundle Protocol (BP), the deep space ARQ reliability protocol (LTP) and lower layer interfaces with various terrestrial and space link protocols. The NASA Interplanetary Overlay Network (ION) implementation[26] contains a comprehensive collection of capabilities from applications to space telemetry link capabilities. Over the years, a number of other BP implementations have been developed, including the Glenn Research Center (GRC) High Rate DTN (HDTN) BP/LTP implementation for high speed comm use, the Marshall Space Flight Center (MSFC) DTN Marshall Enterprise (DTN-ME) implementation for ground stations, a BPLIB bundle protocol library for use with the Goddard Space Flight Center (GSFC) core Flight System (cFS), a JPL BP/LTP implementation for flight software known as F-Prime, there are European implementations at ESA, a space-tested implementation by D3TN (a company in Dresden, Germany), and other new implementations being tested now in Korea and Japan.

There now exists a solid foundation for the integration of DTN into space exploration. NASA is implementing BP suites in its Near Space Network and Deep Space Network to meet the needs of several missions that want to take advantage of this capability. ESA has deployed and demonstrated BP suite capabilities in its ESTRACK network of ground stations.

Importantly, the Solar System Internet infrastructure developed within the lunar domain will serve as the scaffold for humans and robots to extend even farther. This underscores the significance of adopting the BP suite from the outset of lunar exploration promoted by the space agencies and other interested parties.

Recommendations

DTN and the BP suite should be the basis for all communications that might have to traverse paths that the IP protocol suite cannot support. This includes all paths spanning interplanetary distances as well as all paths that might experience disruptions in communications due to antenna pointing and/or scheduling constraints.

---

[23] "DTN Leads the International Space Station Payload Operation in Advanced Exploration", https://ntrs.nasa.gov/api/citations/20170001364/downloads/20170001364.pdf

[24] Space Internetworking Strategy Group, "Operations concept for a solar system internetwork (SSI)", Interagency Operations Advisory Group, IOAG.T.RC.001.V1, Oct. 2010. https://www.ioag.org/Public%20Documents/SISG%20Operations%20Concept%20for%20SSI%20-%20final%20version.pdf

[25] N. Babu, "LunaNet interoperability specification document," NASA Technical Publication, NASA/TP–20210021073/Rev.4, September 2022. https://ntrs.nasa.gov/api/citations/20220013528/downloads/NASA%20TP%2020210021073%20Rev.4.pdf

[26] https://www.nasa.gov/sites/default/files/atoms/files/1.1_lecture_-_intro_to_dtn_implentation_of_the_dtn_architecture.pdf

4.2 Routing and Forwarding

Critical to the operation of any communication network are standard procedures for forwarding data and for computing routes over which data can best be forwarded in order to reach their destination. The routing and forwarding procedures of the terrestrial Internet would not adapt well in the Solar System Internet, as topological state information could not be provided in a timely manner due to the lengthy signal propagation delays, frequent lapses of connectivity, and dynamic topology due to spacecraft orbits that characterize interplanetary communication. New technology is needed.

Considerations that must be borne in mind when developing this new technology include:

- By what delay-tolerant mechanism(s) does this technology obtain the information on which it decides which next-hop node to forward a given bundle to? Does it do so by route computation, by scoring and/or preferential ranking of neighboring nodes, or in some other way?
- If the technology entails computation of end-to-end routes through the network, by what delay-tolerant mechanism(s) does it obtain the time-varying topological information on which routes are computed? For example, does it expect this information to be managed? Does it expect to discover this information in some other way?
- How does this technology:
    - Cause high-value (nominally, high-priority) data to be delivered before lower-value data?
    - Maximize the utilization of transmission opportunities?
    - Maximize throughput in the network?
    - Scale up to a network of 100,000 nodes?
    - Avoid congestion or lock up of communication?

State of the Art

From the earliest days of research into interplanetary networking, problems in routing and forwarding have received more attention than any others. There are on-going efforts within the IETF (TVRWG)[27], CCSDS and in universities world-wide to devise and test various routing and forwarding approaches for a large, generalized delay-tolerant network.

[27] https://datatracker.ietf.org/wg/tvr/about/

While there isn't a single universal standard at the time of this report, many solutions have been identified, implemented, tested, and in some cases deployed; several of the most prominent are briefly discussed in Appendix A.

Recommendations

No matter which technologies are finally selected for deployment of the Solar System Internet, we believe the following principles must be observed:

1. Autonomy and Automation

To assure that the time-variant network can scale up as necessary, routing and forwarding technologies are needed that do not require continuous human intervention or management from Earth.

2. Standards

Autonomy, in turn, requires standard methods of:

- propagating whatever information is needed to support route computation
- utilizing that information in common ways that assure coherent forwarding

3. Interoperability

If a multi-regional network topology is adopted, different routing and forwarding procedures might be adopted within different regions but the same routing and forwarding procedures for inter-regional routing must be adopted universally.

The implementations of both intra-regional and inter-regional routing and forwarding technologies must interoperate within applicable scope.

4. Scalability

Technologies that would necessarily limit the ultimate size of the Solar System Internet must be avoided. Routing and forwarding procedures must be adopted that enable the network to grow to many thousands or even millions of nodes.

4.3 Security

The transition from a link-based, tightly controlled space communication architecture towards an open, network-centric communication paradigm poses many challenges in terms of information security. For example, threats like denial-of-service attacks are aggravated by the current scarcity of space communication resources like storage space, processing power and available bandwidth. In addition, the specific challenges of relayed space communication with potential long delays and disruptions between communication entities make the adoption of terrestrial-deployed security concepts difficult.

To address these specific challenges, BPSec[28] has been defined and standardized by IETF together with BP and is being adopted by CCSDS. BPSec allows application of integrity, authenticity, and confidentiality security services between bundle processing nodes within the network. The flexibility provided by BPSec allows to protect different parts of the bundles individually and also secures bundles resting in storage[29]. For example, the authenticity of the bundle source can be provided by digital signatures while confidentiality of the payload can be achieved by separately encrypting the payload block[30].

BPSec is only one piece of the necessary Solar System Internet security architecture. There are several known challenges which need to be addressed by further research, standardization, and policies. In addition to that, a thorough risk assessment on the Solar Internet architecture may result in additional challenges and security needs to be addressed.

- Secure distribution and management of security related auxiliary information such as cryptographic keys and security associations: while there have been some proposals in that area for delay tolerant key management, no standardized approach has been defined.
- Establishment of trust in interplanetary networks: although trust can be initially based on the mutual exchange of key material this will become unmanageable even for relatively small networks involving several partners. De-centralized certification authorities are being considered as a medium-term solution. In the long term, completely new concepts may be needed.
- Definition and enforcement of network wide security policies: to guarantee secure communications in the whole network or a sub-network, participating nodes may need to define or adopt compatible security policies. For example, it might be required that all source

[28] Birrane, E., McKeever, K., "Bundle Protocol Security (BPSec)", RFC 9172, DOI 10.17487/RFC9172, January 2022, https://www.rfc-editor.org/info/rfc9172.

[29] Edward J. Birrane; Sarah Heiner; Ken McKeever, "The BPSec Security Mechanism," in Securing Delay-Tolerant Networks with BPSec , Wiley, 2023, pp.93-114, doi: 10.1002/9781119823513.ch6.

[30] Edward J. Birrane; Sarah Heiner; Ken McKeever, "Achieving Security Outcomes," in Securing Delay-Tolerant Networks with BPSec , Wiley, 2023, pp.240-259, doi: 10.1002/9781119823513.ch13.

nodes add integrity protection for essential information in a bundle to allow forwarding nodes to verify authenticity of the source and drop inauthentic or unauthorized bundles. The definition of such security policies and selection of cryptographic algorithms will be needed for interoperability. In addition to mutually agreed network-wide policies, certain additional security policies will be applied in certain parts of the network. There is a need to document and publish information about such policies as they may affect forwarding decisions. Furthermore, network security management protocols are required that manage the distribution and enforcement of security policies in the network.

- Protection against unintended failures: in addition to protection against malicious intent, it is important to consider protection against malfunctioning nodes. This includes nodes which become unresponsive and consistently fail to forward bundles or create excessive traffic. A network-wide coordinated network management approach is needed to detect and react to such failures.

Recommendations

To begin addressing the described challenges, the following recommendations shall be followed:

1. Security Awareness

Security needs to be considered within BP Suite implementations, for individual node deployments including physical security, for subnetworks and at overall Solar System Internet level. It is strongly suggested that security assumptions and requirements are documented, threats and vulnerabilities are analyzed and security risks are assessed and mitigated.

2. Security Architecture & Governance

An overall security architecture has to be conceived for the whole SSI taking heterogenous sub-networks into account operated by different entities with additional and stricter security requirements. All service providers within the Solar System Internet need to agree on a minimum set of security policies and interoperable security implementations based on the security requirements of the SSI users. This is considered as a continuous activity as security threats evolve. As security policies evolve and new algorithms may be required, sufficient flexibility will need to be provided within deployed BP nodes and networks. Security policies may be enforced by excluding non-compliant nodes from the network

3. Security Operations and Information Exchange

Provision of security services will require the management and exchange of security related information such as cryptographic keys, security configuration / associations, and identity information. Mechanisms and data formats for the exchange of such information must be standardized. A corresponding infrastructure should be deployed and maintained taking the specific challenges of disrupted and delayed communication into account. In addition, mechanisms for the timely exchange of security incident related information to protect the overall network should be established between service providers.

4.4 Local Applicability of the Internet Protocol Suite in Space

On celestial bodies, such as Mars as well as the Moon and its cislunar vicinity, the Internet Protocol (IP) suite can be used for communications between local nodes, since locally there is no substantial delay or interruptions. Indeed, space agencies are considering the use of IP over Wi-Fi and 5G on the Moon[31] and Mars[32].

For that purpose, the reuse of the whole IP stack is possible locally, including IP addressing, interior and exterior routing protocols (BGP), naming (DNS), applications protocols such as HTTPS, email standards, network management protocols and infrastructure, and mobility and security protocols. This is possible with the right requirements and underlying configuration. Given the remote location, network management reliability becomes even more critical.

However, as discussed in previous sections and summarized in the Delay-Tolerant Networking Architecture RFC[33], the IP protocol stack, as used today on the Internet, is not well suited for deep space long delays and disruptions. The general DTN architecture concept and the Bundle Protocol (BP)[34] suite were defined for these use cases. Using both has the consequence of handling and managing a space-wide global dual-stack network: BP and IP. As the current transition from IPv4 to IPv6 on the Internet suggests, dual-stack networks are more difficult to manage and deploy than single-stack networks. In a more difficult environment such as space, the number of network technologies should be limited as much as possible to minimize risk and complexity. Therefore, only one IP version must be used in space: either IPv4 or IPv6, to avoid running three network protocols: BP, IPv4 and IPv6.

Given that the transition of IPv4 to IPv6 on Internet is already at good pace, where some statistics show >40% of Internet traffic is over IPv6[35], and given the long lifetime of space missions where major software changes on already flying nodes is to be avoided, IPv6 becomes the only sensible IP version to be used in space. Moreover, given the lack of sufficient IPv4 non-overlapping address space, deploying IPv4 in space means using private address space that will overlap

---

[31] The Future Lunar Communications Architecture, Report of the Interagency Operations Advisory Group, Lunar Communications Architecture Working Group, Interagency Operations Advisory Group, January 2022

[32] The Future Mars Communications Architecture, Report of the Interagency Operations Advisory Group Mars and Beyond Communications Architecture Working Group, Interagency Operations Advisory Group, February 2022

[33] Cerf, V., Burleigh, S., Hooke, A., Torgerson, L., Durst, R., Scott, K., Fall, K., and H. Weiss, "Delay-Tolerant Networking Architecture", RFC 4838, DOI 10.17487/RFC4838, April 2007, https://www.rfc-editor.org/info/rfc4838.

[34] Burleigh, S., Fall, K. and E. Birrane, "Bundle Protocol Version 7", RFC 9171, DOI 10.17487/RFC9171, January 2022, https://www.rfc-editor.org/info/rfc9171.

[35] Google IPv6 Statistics, https://www.google.com/intl/en/ipv6/statistics.html.

between networks, therefore breaking direct connectivity. Network Address Translation (NAT) used to mitigate that issue on the Internet will make remote management in space very difficult when crossing network boundaries where a NAT is present. Remote management is an absolute requirement for space networks.

We conclude that IPv6 should be the only IP version used in space. The use of IPv6 will also bring new enabling technologies such as Prefix Delegation[36] adding the capability to delegate in real time an IPv6 address range to a spacecraft docking to a network, therefore enabling the spacecraft internal network to be recognized by the attaching network as connected, without complex and manual operations.

Applications can be developed over native BP if the end-nodes are both BP enabled and there is an end-to-end path running BP.

If the end-nodes are IP capable, then Internet applications can be reused if there is an end-to - end path running IP, such as on and around celestial bodies like the Moon or Mars. For some applications, an optimized configuration for that environment is needed.

Where the end-nodes are IP capable but BP is only the network layer in between, then application protocols such as HTTP or Email can have their payload encapsulated into bundles and both networks' edges will act as application level gateways[37] [38]. This enables the use of HTTP from Earth to Moon or Mars while being carried over BP.

Network management, especially remote from Earth to Moon or Mars, can be done either using native BP DTNMA[39] or, for IP capable end nodes, Netconf[40]/RESTConf[41] , used for Internet Network Management. RESTConf running over HTTP, is also carried similarly over BP on BP-only links.

As discussed throughout this report, it is expected that multiple organizations will provide various services on the celestial bodies networks. Therefore, peering will be needed to interconnect those networks on each celestial body. The same protocol used on Internet for this purpose,

---

[36] Troan, O. and R. Droms, "IPv6 Prefix Options for Dynamic Host Configuration Protocol (DHCP) version 6", RFC 3633, DOI 10.17487/RFC3633, December 2003, https://www.rfc-editor.org/info/rfc3633.

[37] Blanchet, M., "Encapsulation of Email over Delay-Tolerant Networks(DTN) using the Bundle Protocol", draft-blanchet-dtn-email-over-bp, https://datatracker.ietf.org/doc/draft-blanchet-dtn-email-over-bp/, April 2023.

[38] Blanchet, M., "Encapsulation of HTTP over Delay-Tolerant Networks(DTN) using the Bundle Protocol", draft-blanchet-dtn-http-over-bp, https://datatracker.ietf.org/doc/draft-blanchet-dtn-http-over-bp/, July 2023.

[39] Birrane, E., Heiner S. and E. Annis, "DTN Management Architecture", draft-ietf-dtn-dtnma, https://datatracker.ietf.org/doc/draft-ietf-dtn-dtnma/, July 2023.

[40] Enns, R., Ed., Bjorklund, M., Ed., Schoenwaelder, J., Ed., and A. Bierman, Ed., "Network Configuration Protocol (NETCONF)", RFC 6241, DOI 10.17487/RFC6241, June 2011, https://www.rfc-editor.org/info/rfc6241.

[41] Bierman, A., Bjorklund, M., and K. Watsen, "RESTCONF Protocol", RFC 8040, DOI 10.17487/RFC8040, January 2017, https://www.rfc-editor.org/info/rfc8040.

Border Gateway Protocol (BGP)[42], can also be used on celestial bodies' networks. Use of BGP requires the use of Autonomous System Numbers (ASN) to be assigned to the various networks.

IP networks and protocols require a naming system, such as the Domain Name System (DNS) used on the Internet. DNS enables a hierarchical delegation of names useful for multi-organization networks. DNS can be run on a disconnected network environment, but requires special care and configuration to work flawlessly.

Recommendations

1. Use of IPv6 and BGP

IPv6 should be the only IP version used in space. As mentioned earlier, the global IPv4 address space has been exhausted. Implementing IPv4 will necessitate the deployment of NAT(s) on celestial bodies, resulting in increased costs and launch mass. Moreover, this approach would pose challenges for remote network and component management. Transitioning to IPv6 at a later stage would also incur additional expenses and could potentially require component replacements. BGP shall be used for interconnecting IPv6 networks on celestial bodies.

2. IP applications

Since the IP protocol suite can be reused in local (non-delayed/disrupted) environments and because of our familiarity with IP-based applications, it makes sense to look for ways to 'extend' IP-based applications across potentially delayed/disrupted paths using BP. For example, when an Email is sent from Earth to the Moon, application-layer proxies can be used to make it work. As this method allows Email (an IP-based application) to be used intact even over delayed/disrupted paths, careful consideration is needed before reinventing new application protocols for BP. DTNMA or Netconf/RESTConf should be used for BP and IP remote network management respectively. Refer to Appendix B for more technical details.

There are still several remaining technical challenges in interplanetary networking that require further work and can be found in Appendix C.

[42] Rekhter, Y., Ed., Li, T., Ed., and S. Hares, Ed., "A Border Gateway Protocol 4 (BGP-4)", RFC 4271, DOI 10.17487/RFC4271, January 2006, https://www.rfc-editor.org/info/rfc4271.

5. Solar System Internet Governance in Space

The exploration and use of outer space shall be the "province of all mankind," according to the United Nations 1967 Outer Space Treaty (OST). This has served as a shared principle for space governance amongst all nations. Several provisions[43] in the OST form the basic framework for international space law. Here are some of the key principles provided in the OST. Under current international law, there is no national *sovereignty* with respect to the Moon and other celestial bodies.

- Open for everybody to use: Outer space is free for exploration and use by all States
- Responsibilities of States: States shall be responsible for national space activities whether carried out by governmental or non-governmental entities
- Avoid harmful Interference: States shall undertake international consultations as appropriate if state activity could potentially cause harmful interference to activities of other States
- No occupation or appropriation: Outer space is not subject to national appropriation by claims of sovereignty, by means of use or occupation, or by any other means.[44]

While the terrestrial Internet crosses borders in ways that have complicated nation-state jurisdiction and governance structures, the absence of inherent sovereignty in space is a political starting point of Solar System Internet governance.

Space is already governed by a constellation of treaties and agreements, many of which arose during the Cold War. In addition to the Outer Space Treaty, there are four other United Nations International Space Treaties, including the Rescue Agreement, the Space Liability Convention, and the Registration Convention. Notably the 1979 Moon Agreement was not signed and ratified by the major spacefaring states.

These treaties predate modern space communication systems, and even predate the dependency of Earth communication systems and national security on satellites. They do not directly address Internet technologies or information and communication technologies more broadly. They also arose in an era in which space exploration was the province of a small number of spacefaring nation states and not yet involving commercial exploration.

This multilateral feature of traditional space governance treaties, and the inattention to communication technology governance, is quite different from how Internet governance has evolved over time. Internet governance is largely multistakeholder governance, involving many

[43] United Nations. "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies" https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html

[44] *Op. cit.* Article II

different coordination and oversight tasks carried out by a combination of traditional governments, the private sector, technical communities, and global multistakeholder organizations involving a combination of actors.

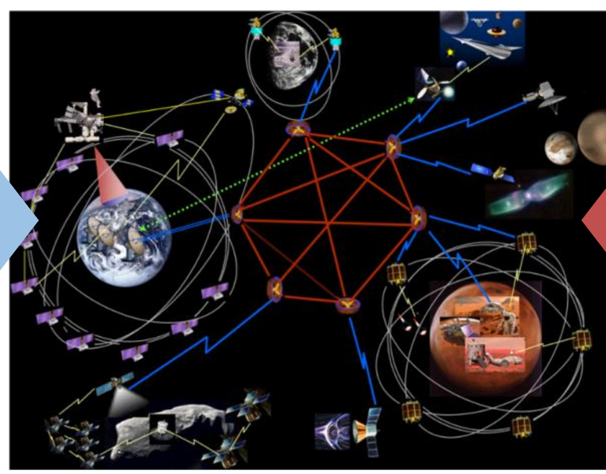
The IPNSIG has sought to address several core questions about the governance of the Solar System Internet (Refer to Figure-2).

- What are the fundamental tasks of Internet governance in space and how are these similar to and different from terrestrial Internet governance?
- As commercial activity proliferates in space and more states join the space exploration endeavor, what multistakeholder structures and practices can support and interconnect these efforts?
- What existing Earth-based governance mechanisms and institutions could be leveraged for space governance and what new governance practices are necessary?

These are the fundamental questions that require attention as we enter a new era in space exploration.

ARCHITECTURE

How could the various networks "work as a whole" to form a common Solar System Internet? What are the key technologies and future challenges?



GOVERNANCE

What institutions and governance practices would be needed to support multi-party complexity?
What do we need to govern anyway, and why?
Who does the job?
How could we avoid harmful interference?
How might international law and treaty effectuate in the process?

Figure-2 The Solar System Internet

For the purpose of this study, governance is defined as *"The administration and management mechanisms, their supporting institutions and their practices toward an open, accessible and common Solar System Internet that is built, operated and used by various entities."*

6. Lessons from history

Evolution of Internet Governance

What is important to understand from history is that the creation of various Internet institutions only occurred when the need arose and were purpose-built to deal with specific standards and policy coordination. By and large, all of these institutions are so-called “Multi-stakeholder” organizations because all interested parties are free to attend meetings and to participate in policy development. There is a loose coupling of relationships among these governance entities that give the system coherence and structure without the rigidity that sometimes leads such systems to break. A summary of Internet governance is found in Appendix D.

It seems likely that the Solar System Internet and its public/private processes will experience a need like the terrestrial Internet’s to create new institutions to manage both the technology of Delay and Disruption Tolerant Networking but, more important, questions of jurisdiction and dispute resolution as humanity pursues its decades long exploration of the Solar System.

7. SSI Governance

When humans last visited the lunar surface, the Internet did not exist and all communications and navigation functions were under the control of a single country (the United States). While there were ground stations around the world, governance was relatively simple and largely under one government agency (NASA) and its contractors. For communication systems during the Apollo program, refer to Figure-3.

As humans return to the Moon and venture deeper into space today, expectations are for open, relatively seamless, communications amongst a large and growing number of diverse users – in effect, the Solar System Internet (SSI). Governance of the SSI is a more complicated matter than the Apollo era of deep space communications as it needs to service not only NASA and other international space agencies, but also diverse private sector actors in industry and academia.

The Internet began with the Arpanet and evolved into a global enterprise with a collaborative, multistakeholder governance ecosystem involving the development of common standards, the administration of names and numbers, agreements to interconnect networks using common protocols, and shared architectures for cybersecurity governance such as the use of public key cryptography for authenticating online resources.

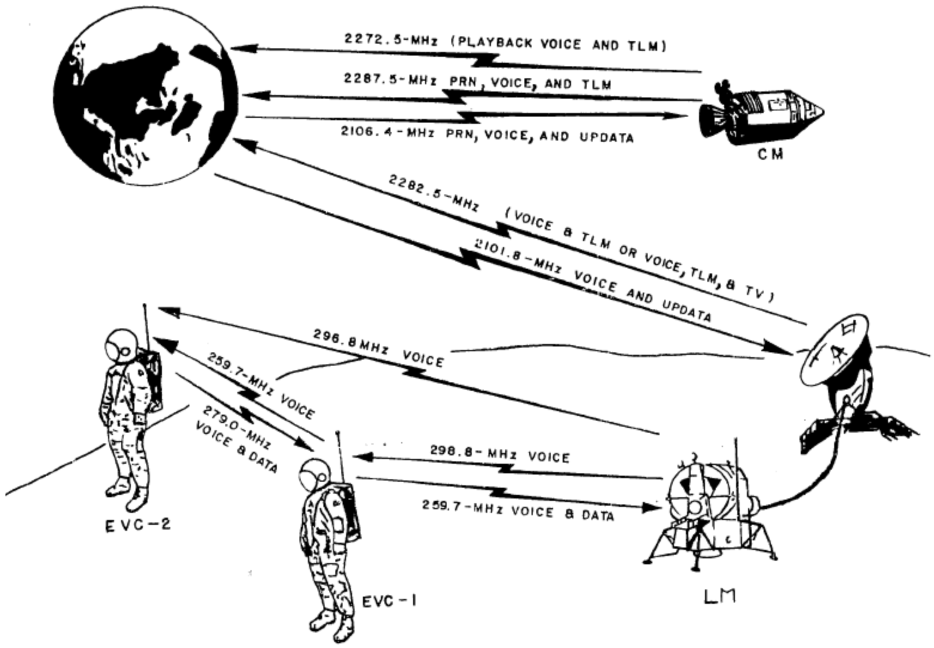
Governance of the SSI may be more complicated than the terrestrial Internet, but not necessarily. On one hand, the primary initial users of the SSI will be international space agencies, mostly those in the Artemis program, but not limited to lunar operations. On the other hand, coordinating SSI operations will be more complicated than the Internet due to some complex technical realities. Sending a message on the Internet might be thought off as driving between Washington and New York. There's a freeway, there are rules for using the freeway, and it's clear how to get on and off. Sending a message on the SSI will be more like traveling from Washington to Jakarta. First, you have to get to an airport, then catch a flight, which may in turn require several changes, before arriving. There are multiple transportation modes (cars, planes), constraints on when some modes can be used (flight schedules), and multiple events can occur enroute that will trigger replanning.

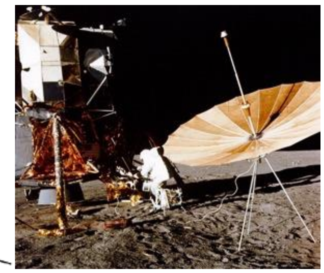
NASA is currently developing a communications/navigation architecture to support Artemis operations on and around the Moon that will become part of LunaNet. The LunaNet architecture envisions a collaborative network of interoperable LunaNet Service Providers similar to terrestrial Internet Service Providers in the cislunar environment and is designed for further use in the Mars environment. Activities at various space agencies are underway to establish such LunaNet service providers, such as ESA's Moonlight Initiative[45].

[45] https://www.esa.int/Applications/Connectivity_and_Secure_Communications/Moonlight

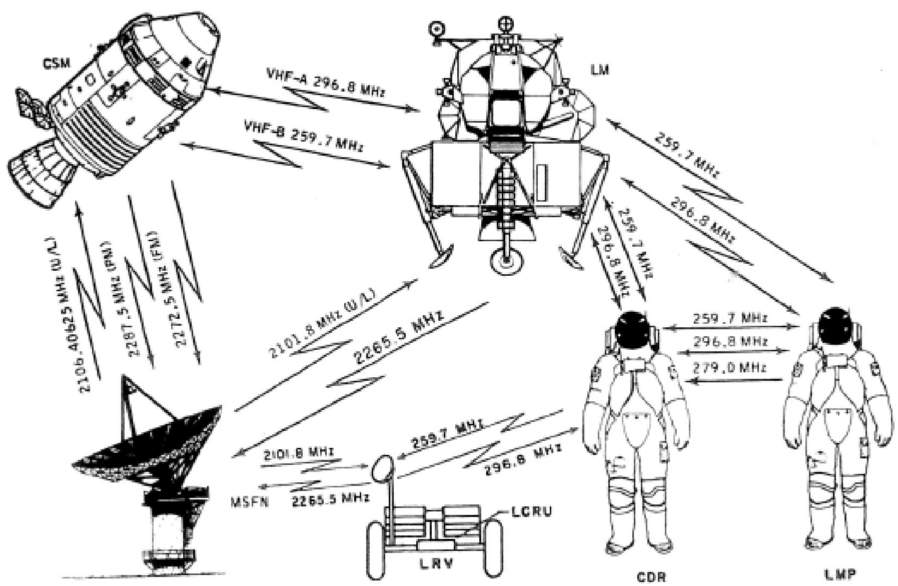
The goals of the LunaNet architecture include being resilient, open, and secure while capable of handling a wide variety of users.[46] These users may include space agencies, intergovernmental and international organizations or private parties. That is, the architecture is intended to be technically capable or being open to any agreed user following transparent technical specifications. Whether SSI will in fact be open to any user would likely be a decision taken by its stakeholders. Like Arpanet was for the Internet, LunaNet may become a foundational part of the Solar System Internet, but major technical and governance issues will arise sooner and need to be resolved for that to occur.

[46] Schier, James. "LunaNet Overview," presentation to NESC Unique Science from the Moon in the Artemis Era Workshop, NASA Headquarters, Washington, DC. June 7-9, 2022.





10' diameter erectable S-band surface subsystem connected to LM by 65' cable



Apollo 15

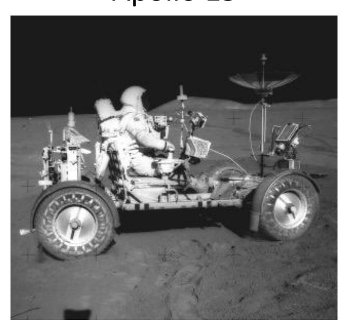


Figure-3 Communications Systems during Apollo

General Approach

The basic idea on SSI governance would be to inherit the positive properties that led the Internet to its success, while acknowledging the current rather negative terrestrial Internet Governance issues that could potentially propagate to space (Refer to Figure-4). The generic approach to SSI governance could be:

- Introducing a common way of doing things - Provide a common method for devices and networks to communicate and interconnect. They would be protocols like BP/LTP for the SSI and TCP/IP for the Internet.
- Open forums – The use of open forums and a bottoms-up approach should continue to refine and advance standards for the SSI.
- Hierarchical management – Critical resources of the SSI such as identifiers should be hierarchically managed. Authority and responsibility should be dispersed.
- Multi-party policy making process – The SSI is envisioned to be a shared asset. Thus multi-parties should be involved in the policy making process, like the Internet.
- Awareness of Internet governance issues – Several rather negative Internet governance issues could propagate to space, such as, Internet infrastructure co-opted as proxy for political power, used for misinformation or disinformation etc[47].

Applicable Space Law

There are several space treaties applicable for activities in space. For example, states are responsible to assure the behavior provided in the 1967 Outer Space Treaty (OST) for all space activities, whether carried out by governmental or non-governmental entities. These rules apply to the SSI. As the OST was developed more than half a century ago, it does not take into account the modern commercialization of space. What clashes may occur between public and private interest in the SSI remains unknown.

[47] More details on Internet Governance flashpoints applicable in space can be found in a paper by Dr. Laura DeNardis, "Interplanetary Internet Governance", CIGI Papers No. 277, June 2023.

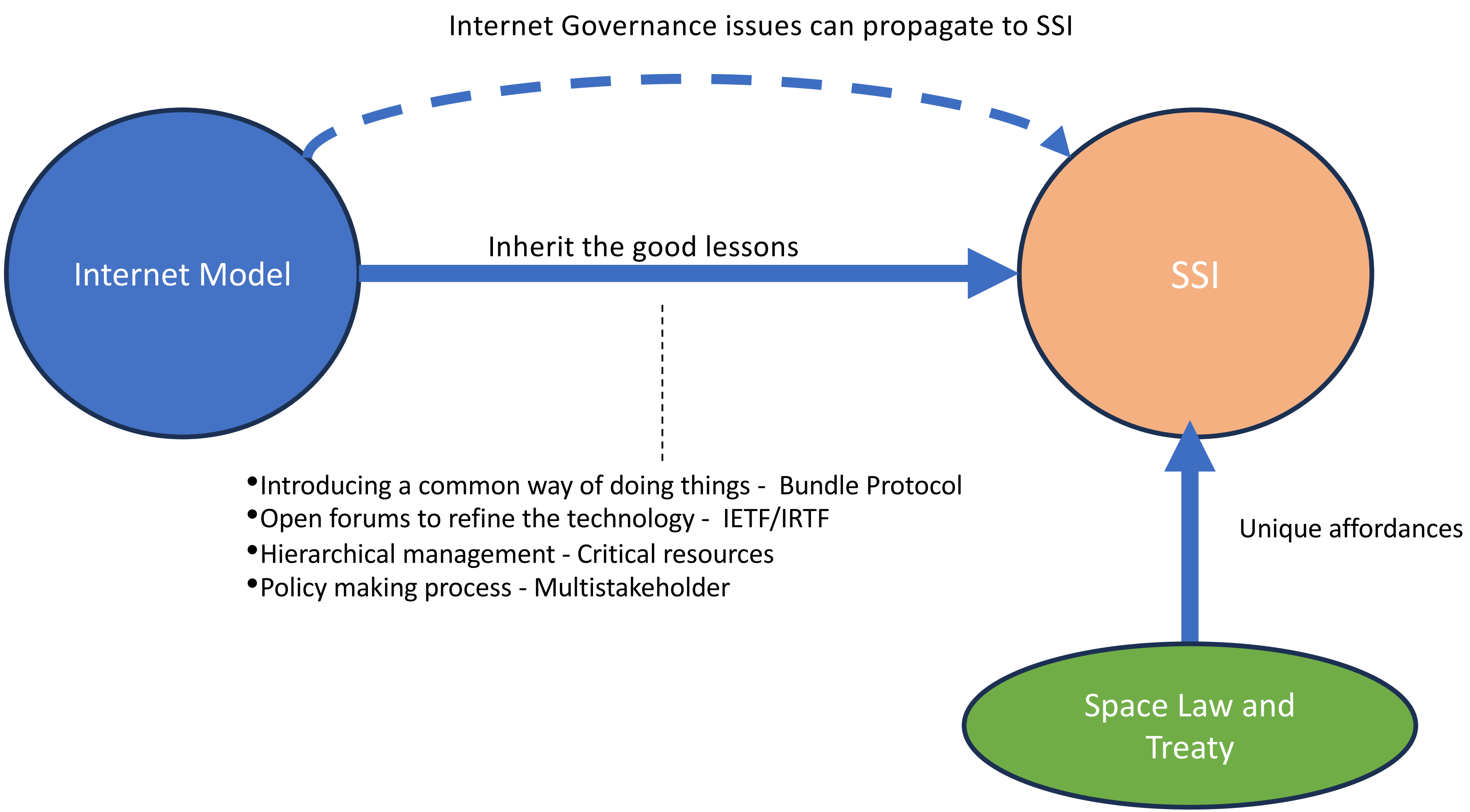


Figure-4 The Big Picture

Artemis Accords

The United States has proposed the Artemis Accords to promote a common set of international principles for operation on and around the Moon. The Accords are not legally binding or new international law, but rather are a common framework to reinforce and implement existing international space law, such as the Outer Space Treaty, the Registration Convention, the Agreement on the Rescue of Astronauts, the Liability Convention, and other norms of behavior that NASA and its partners have supported, such as the full and public release of scientific data. This framework is meant to "increase the safety of operations, reduce uncertainty, and promote the sustainable and beneficial use of space for all of humanity." The content of the Artemis Accords are posted on the NASA website.[48]

As of September 15, 2023, there are 29 signatories: Argentina, Australia, Bahrain, Brazil, Canada, Columbia, Czech Republic, Ecuador, France, Germany, Israel, India, Italy, Japan, Republic of South Korea, Luxembourg, Mexico, New Zealand, Nigeria, Poland, Rwanda, Romania, Saudi Arabia, Singapore, Spain, Ukraine, United Arab Emirates, United Kingdom, and the United States. Russia, and China are among the notable spacefaring nations that have not signed or expressed an intention to sign. Also of note, the Accords can be signed by any United Nations member state and the signatories are not required to have ratified the binding international treaties and agreements referenced in the Accords. Signature does not require the approval of the United States or the other signatories.

Section 5 of the Artemis Accords is perhaps most relevant to the SSI as it calls for interoperability across all partners. Specifically:

> The Signatories recognize that the development of interoperable and common exploration infrastructure and standards, including but not limited to fuel storage and delivery systems, landing structures, **communications systems**, and power systems, will enhance space-based exploration, scientific discovery, and commercial utilization. The Signatories commit to use reasonable efforts to **utilize current interoperability standards** for space-based infrastructure, to **establish such standards when current standards do not exist or are inadequate**, and to follow such standards.[49] (emphasis added)

---

[48] NASA, "The Artemis Accords," accessed at https://www.nasa.gov/specials/artemis-accords/index.html
[49] *Ibid*.

7.1 Solar System Internet Governance Organizations

There is no single international organization that could logically claim responsibility for developing or governing an SSI. Just as the Internet resulted from the actions of multiple stakeholders, so too will the SSI be an "emergent property" of the actions of multiple, new stakeholders. Several organization at present have claims to parts of the SSI challenge:

- The International Space Exploration Coordination Group (**ISECG**) brings together all space agencies involved in deep space exploration, particularly to the Moon and Mars, to share plans in a common framework and creates an integrated Global Exploration Roadmap (GER). This can and should include communication/navigation services.
- The International Telecommunication Union Radiocommunication sector (**ITU-R**) allocates radio frequencies to particular services, e.g., radio-navigation satellite services, mobile satellite services. These allocations are codified in the international Radio Regulations which have treaty status as part of the international treaty that mandates the ITU. Individual spectrum administrations then assign allocated frequencies to particular systems as part of national licensing processes. The ITU does not currently allocate or assign optical frequencies.
- The International Telecommunication Union standardization sector (**ITU-T**) deals with telecom standards, including those dealing with precision time.
- The Interoperability Plenary (**IOP**) is a collective group of the major space agencies (11) to reach multi-agency agreement on the need for interoperable space communications and navigation architectures.
- International civil space agencies coordinate space communications standards for cross support via the Interagency Operations Advisory Group (**IOAG**). It was established by the IOP. The IOAG provides a forum for identifying common needs and coordinating space communications policy, high-level procedures, technical interfaces, and other matters related to interoperability and space communications. Recently, the IOAG established a Security Working Group to address in particular the security challenges related to the development of lunar communication infrastructure. The standards development is then accomplished by the Consultative Committee for Space Data Systems (**CCSDS**), a multi-national forum comprising the world's major space agencies. Consensus must be reached by the member agencies before a CCSDS standard can be published. The CCSDS also serves as the Space Data Communications Subcommittee (TC20/SC13) within ISO, and the standards issued by CCSDS are automatically processed for ISO documentation.
- The Space Frequency Coordination Group **(SFCG)** provides a less formal and more flexible environment, as compared to the ITU. The SFCG is concerned with the effective use and management of those radio frequency bands that are allocated by the Radio Regulations of the ITU to various Space applications.

- The Space Assigned Numbers Authority **(SANA)** is the registrar function for the protocol registries created under the CCSDS. Typical examples of registries are for spacecraft IDs, protocol version numbers and BP node identifiers.
- The United Nations Committee on the Peaceful Uses of Outer Space (**UNCOPUOS**) was created by the UN General Assembly in 1959 and is one of the largest UN committees, with 102 members. The committee's main tasks are to review and foster international cooperation in the peaceful uses of outer space, as well as to consider legal issues arising from the exploration of outer space.
- The UN International Committee on Global Navigation Satellite Systems (**ICG**), promotes voluntary cooperation on matters of mutual interest related to civil satellite-based positioning, navigation, timing, and value-added services. The ICG contributes to the sustainable development of the world. Among the core missions of the ICG are to encourage coordination among providers of global navigation satellite systems (GNSS), regional systems, and augmentations in order to ensure greater compatibility, interoperability, and transparency, and to promote the introduction and utilization of these services and their future enhancements, including in developing countries, through assistance, if necessary, with the integration into their infrastructures.
- The Interplanetary Networking Special Interest Group (**IPNSIG**) is a venue to help facilitate the development of a sustainable network in Space. It explores the technical and policy implications of a multi-party Solar System Internet. It is affiliated with the Internet Society and also operates as a not-for-profit organization in the US. There are more than 950 members across the globe, at the time of this writing.
- The Internet Engineering Task Force **(IETF)** is the premier standards development organization for the Internet. The mission of the IETF is to produce high quality, relevant technical and engineering documents that influence the way people design, use, and manage the Internet in such a way as to make the Internet work better. These documents include protocol standards, best current practices, and informational documents of various kinds.[50] The IETF works according to a few basic principles such as "open process," "technical competence," "volunteer core," "rough consensus and running code," and "protocol ownership."[51] As a consequence, the IETF contains multiple stakeholders, not just those who might be "authorized" but some governmental, academic, technical or commercial interests. Furthermore, it operates in a decentralized, "bottom up" manner rather than a "top down" directed manner. The IETF is not a "space" organization nor is the SSI just an extension of the Internet into space. Thus the IETF alone is not sufficient to address the needs of the SSI. The analogy is helpful in explaining the goals of the SSI, and there will be technical heritage from the Internet that will be applied in space, the SSI is a larger construct (both literally and figuratively). The naming and numbering scheme for the SSI is an immediate issue and one where there are lessons (good and bad) from the IETF.

---

[50] Introduction to the IETF, web site at https://www.ietf.org/about/introduction/
[51] *Ibid*

- The Institute of Electrical and Electronics Engineers (**IEEE**) is dedicated to the standardization of protocols across various layers within the OSI (Open Systems Interconnection) model. While the scope of IEEE is extensive, its primary emphasis lies within the lower layers of the protocol stack, encompassing areas such as physical transmission, data framing, and link management.
- The Third Generation Partnership Project (**3GPP**) is a collaborative effort among telecommunications standards organizations to develop specifications and standards for mobile communication systems. Its main role is to create and maintain the standards that enable the interoperability and compatibility of mobile communication networks, devices, and services.
- The World Wide Web Consortium (**W3C**) is a multistakeholder platform where its primary role is to standardize and evolve the technologies and protocols that make up the web, thus enabling a consistent and interoperable experience for users worldwide.

Figure-5 illustrates our view of the relationships and dependencies amongst the organizations today.

Like the Internet, the SSI will consist of a wide variety of hardware and software, interface standards, and operating procedures. SSI hardware providing nodes, servers, and reference services will exist in space as well as on celestial bodies. There can be no single owner or centralized authority if the system as a whole is to be open, transparent, and scalable. For a fully compatible and interoperable SSI, a federated approach, that is giving the autonomy to various entities while adhering to common behavior should allow for different scales of collaborations – within projects and programs, across nations, and fully international.

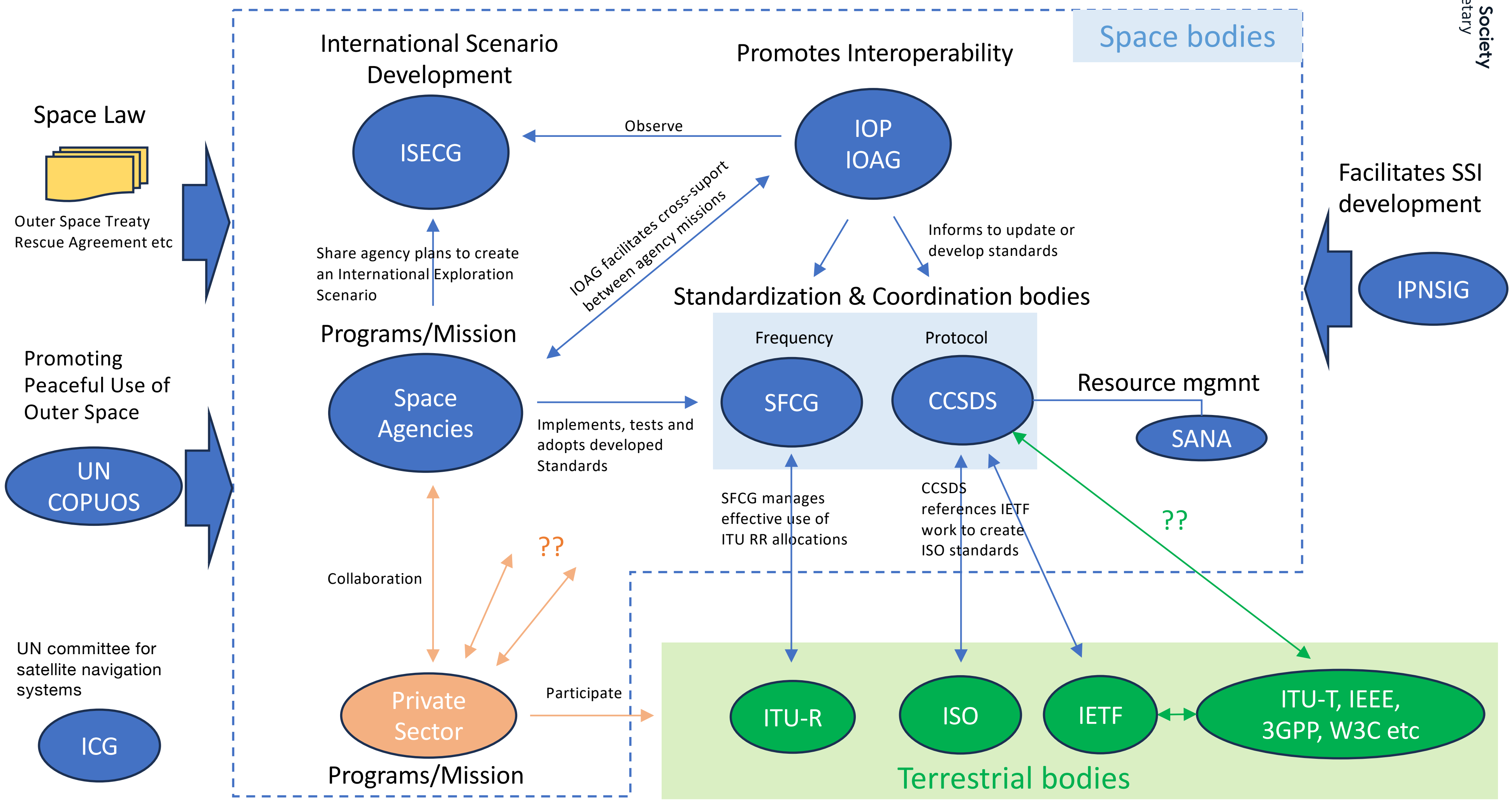


Figure-5 Space governance organizations related to SSI

7.2 Governance Elements

Like the Internet, the SSI will depend on standardized technical identifiers and interface protocols. It will also rely on additional resources such as radio frequency spectrum and the alignment of planets and satellites to support links from Earth to space locations and back. Precise time synchronization could be an issue for positioning and navigation services in cislunar, and possibly for some SSI applications. Unlike the Internet, however, precision timing will have to handle latencies across interplanetary distances and account for complex gravitational corrections using general relativity. (Note that performing such corrections would not be completely novel as GPS time signals are also corrected for general relativity effects.) The policy making process for the SSI is also crucial for its sustainability.

Several governance elements, primarily related to infrastructure governance, have been identified in forming the SSI. These include:

- The Policy-making process
- Critical resource management
    - Spectrum
    - IP addresses, Autonomous System Numbers
    - Bundle Protocol identifiers
    - Domain names
- Standards
    - Time & coordinate systems
    - Communication Protocols
- Cybersecurity Governance
    - Certification authorities and identity management
    - Security policies and procedures
- Interconnection of networks

We recognize that this list is not exhaustive and further work is needed, particularly in the area of cybersecurity at the international level. For example, there could be agreements to refrain from cyberattacks on the SSI as well as agreements to refrain from stockpiling known vulnerabilities (e.g. the Vulnerabilities Equities Process. Such agreements would be consistent with Article 9 of the 1967 Outer Space Treaty in terms of avoiding harmful interference to space activities. However, such steps are not unique to the SSI and thus are not addressed in detail here.

7.2.1 Policy Making Process

The future of the SSI is greatly influenced by its policy making process. In the Internet, it's the multistakeholders - including the technical community, civil society, governments, academia, and the general public that shape the Internet today – they all ideally have a voice, and a venue for expression, known as "Multistakeholder" governance. Reference Figure-6 for how the Internet ecosystem works today.

This multistakeholder policy making process can be viewed as one of the most essential aspects of upholding the Internet, and should be inherited for the SSI, if we were to pursue a common and shared network even in space - whether builders, operators, or users of the network, they should all have a stake in the policy making process.

As the architecture and users change, so will governance adapt accordingly (see Section 3). Governance of the Solar System Internet in the space regime today is carried out by the builders and users of the network, who are primarily government space agencies. However this landscape may quickly change with more commercial interest and involvement in exploration. This suggests that the multistakeholder model be pursued starting now, to include future providers and users of the network, such as commercial actors and non-governmental organizations. Today, there are good grounds to start sharing developments in space, such as the Internet Governance Forum (IGF) - a multistakeholder body that could be leveraged to start early discussions on SSI governance. Also, the multistakeholder governance approach for SSI resonates with the widely embraced OST principle of "Space for all," fostered amongst numerous nations.

Affordances to SSI Governance

UNCOPUOS is unlikely to have a direct governance role for the SSI, but it can be a forum for promoting standards and best practices developed by expert stakeholders. In addition, some COPUOS guidelines may affect SSI operations, such as end of life disposal of orbital assets.

A major focus in recent years has been voluntary guidelines to promote the long-term sustainability of space activities. A major topic of work for the UNCOPUOS for more than a decade has been the development of voluntary, non-binding guidelines for the long-term sustainability of space activities.[52] Working groups have addressed space utilization supporting sustainable development on Earth; space debris, space operations and tools to support collaborative space situational awareness; space weather; and regulatory regimes and guidance for actors in the space arena. Guidelines approved by consensus provide guidance on the policy and regulatory

---

[52] United Nations. "Long-term Sustainability of Outer Space Activities" web site accessed at https://www.unoosa.org/oosa/en/ourwork/topics/long-term-sustainability-of-outer-space-activities.html

framework for space activities; safety of space operations; international cooperation, capacity-building and awareness; and scientific and technical research and development. Political and technical conditions for the past several decades have made the development of new international space treaties difficult if not impossible. As a result, and in recognition of the global importance of space activities, attention has shifted to voluntary measures rather than binding legal agreements. UNCOPUOS is not an environment for new technical work but is dependent on expert technical input that can then be discussed and understood in a fully multilateral environment. Voluntary measures which achieve consensus, and measures for the mitigation of orbital debris, are internationally recognized and may be implemented through national law and regulation. In this process, technical expertise is provided in a "bottom up" manner, guidelines are developed with multilateral consensus, and implemented by sovereign states – not a transnational authority.

The ITU is likely to have a greater direct impact via ITU-R in spectrum allocations. ITU-T has had no role in BP development, but some ITU recommendations have been incorporated by reference in the work of the CCSDS and IETF. That said, there are two potential areas which should be monitored for future impacts. The first is the creation of a radiofrequency quiet zone on the lunar far side and the second is for space safety services. A quiet zone on the Moon could be implemented in a number of ways, such as through the ITU. It would need to be wider than just the Artemis program members and thus the UN would be a logical venue for acceptance. Regarding space safety services, the 1968 Agreement on the Rescue and Return of Astronauts imposes positive obligations on member States to treat astronauts as "envoys of mankind" and provide aid to those in distress.[53] SSI support for emergency communications, regardless of nationality, could be an example of what needs to be fulfilled under this treaty.

Like the UN Internet Governance Forum, UNCOPUOS is not an effective forum for technical development or operations, but it is a forum for information exchange. As more satellite navigation systems joined GPS and Glonass, the International Consultative Group (ICG) on Global Navigation Satellite Systems (GNSS) under the UN Office for Outer Space Affairs had been formed. The ICG's role is to "encourage and facilitate compatibility, interoperability and transparency between all the satellite navigation systems, to promote and protect the use of their open service applications and thereby benefit the global community."[54] The ICG for GNSS has been successful in bringing all satellite navigation providers together to improve policy and technical

[53] United Nations. *Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space*, accessed at https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introrescueagreement.html

[54] United Nations. "International Committee on Global Navigation Satellite Systems" web site accessed at https://www.unoosa.org/oosa/en/ourwork/icg/icg.html

transparency. For example, this group was instrumental in defining an internationally accepted "space service volume" definition for GNSS signals.[55]

Like GNSS, SSI development may similarly benefit from the creation of an International Consultative Group on Lunar Operations (ICGLO). Such a group could provide a forum that would be accessible to all UN members facilitating information exchange on a broader range of lunar operations beyond just the SSI. Technical input would formally come from UN member states, but input could be based on technical work already done by groups such as CCSDS, the IOAG, IETF and ITU working parties, collectively the multistakeholders. Since the UN is not the place for new technical work, there would be strong incentives to ensure technical consensus before presenting to a UN committee. If warranted, the scope of the ICG could expand from just lunar operations to space operations more generally.

Another observer organization to the UN COPUOS is the Global Expert Group on Sustainable Lunar Activities (GEGSLA). This Group is composed of members from space agencies, government, industry, international organizations, Non-Governmental Organizations (NGOs), universities and research centers. GEGSLA promotes the development of a neutral forum for multistakeholder discussions on lunar exploration with results published in their report: "Recommended Framework and Key Elements for Peaceful and Sustainable Lunar Activities''. While GEGSLA's scope is the strategic development of lunar colonies, this is recognized as including utilities and infrastructure such as communications.

A reliable and secure SSI will need a continuous exchange, discussion on and governance of security related matters. The organization of such cybersecurity governance remains currently open; it seems clear that at least some sort of certification authority and a forum to coordinate on security architecture and policies is required. Entities like CSIRTS, CERTS may also be needed to respond to cybersecurity incidents within the SSI. While some security functions may require new organizations or can be taken over by existing organizations related to space communication it is also important to integrate with the existing security organizations of all stakeholders, in particular with already existing functions related to network and communication security.

---

[55] United Nations. "The Interoperable Global Navigation Satellite Systems Space Service Volume," accessed at https://www.unoosa.org/res/oosadoc/data/documents/2018/stspace/stspace75_0_html/st_space_75E.pdf

Figure-6 Internet ecosystem map

7.2.2 Critical Resources

There are areas where central coordination is required, such as avoiding overlap or identifier conflict - in the Internet, these would be IP addresses, autonomous system numbers, and Domain Names. For the SSI, it would be spectrum and BP numbering identifiers and potentially domain names used in the network. Although these identifiers essentially require central management, it also requires an orderly set of coordinated controls to ensure fair and consistent distribution.

Spectrum

The ITU-R is a UN technical agency that coordinates and manages radio frequency allocations. It is not an operational agency. Member states can choose to take "national exceptions" to the Radio Regulations within their territory, but this is problematic for space allocations which are inherently global. Space services are categorized by whether they are for geostationary satellites (GSO) or non-geostationary satellites (NGSO), or are feeder links to terrestrial sites. Services are further characterized by whether signals are operated Earth to Space (E-S), Space to Earth (S-E), and Space-to-Space (S-S). Currently, operations on and around the Moon would be considered NGSO as they are not GSO. At some points, ITU-R may need more localized categories (e.g., Moon, Mars) to deconflict spectrum use and prevent harmful interference.

Updates to the Radio Regulations occur every 3-4 years at World Radio Communication (WRC) conferences. The last one was in 2019, the next one is in November 2023. These conferences deal with agenda items set at previous conferences and for which inter-sessional working parties have evaluated options and sought consensus recommendations. The United States is proposing a new agenda item at WRC-23 to consider spectrum allocations for lunar communications and navigation. Work would then proceed over the next four years and (hopefully) recommendations adopted at WRC-27. The U.S. proposal states:

> LunaNet will include networking services capable of moving data between nodes; positioning, navigation, and timing services for orientation and velocity determination; and time synchronization and dissemination and science services providing situational alerts and scientific measurements. Other space agencies around the world are developing similar initiatives, and some space agencies are encouraging commercial development of lunar and cislunar communications systems in the form of public/private partnerships that are now characterizing significant aspects of space activities – from launch services to space habitats and more. The envisioned lunar and cislunar communications system is being designed to enable communications to and from Earth (Earth station) for lunar assets (service user) through lunar orbiting relay satellites (space stations). Surface-to-surface communications would be enabled through the satellite relay link in lunar orbit for surface assets. Communications links, coupled with radiometric navigation techniques to provide location, velocity, and time information to assets on the lunar surface and in lunar orbit, will also be

used. The planned system will provide real-time relay capabilities when both ends of the link (Moon and Earth) are visible.[56]

This description is silent on whether all the hardware will be U.S. government owned, internationally owned, or privately owned, and this may not matter. What is notable is that NASA proposes to operate through existing international mechanisms. NASA already uses the Space Frequency Coordination Group to coordinate its views with those of other government space agencies for ITU purposes. The more common challenge for space services is opposition from terrestrial commercial spectrum users who may want the same spectrum or fear constraints on spectrum usage. Hopefully, the distance of space operations from Earth will mitigate any terrestrial interference concerns; or at least confine them to those allocations providing up-link and down-link functions.

Internet Protocol Address, Autonomous System Numbers in Space

Given the use of IP on celestial bodies' networks, the network identifiers need to be allocated and managed, as done on the current Internet, in order to avoid duplicative assignments in networks. As discussed above, the Internet multistakeholder governance uses the IANA and the Regional Internet Registries (RIRs) to allocate IP addresses and Autonomous System Numbers (ASNs) to organizations deploying networks[57]. The current space organizations can still use their respective RIRs to request those identifiers as needed for use in space. However, it should be noted that the current RIR allocation policies do not take into account the specifics of space deployments, so over time, these policies may need to be adapted. A study on this should be further pursued. If it becomes difficult to adapt RIR policies for space usage, a new Space Internet Registry (SIR) should be considered to be created for managing IP addresses and ASNs for space networks. The SIR is envisioned to include all space-related stakeholders in the development of proper policies, with input from multiple stakeholders.

Bundle Protocol Identifiers

For the SSI, we recommend the adoption of the Bundle Protocol (BP) which uses a different set of network identifiers. These are currently allocated by IANA[58] and SANA[59]. Those identifiers can also be managed by RIRs if they are willing to provide those services and that allocation policies are defined. Similar to IP addresses, a Space Internet Registry (SIR) may be needed to manage BP identifiers for space networks, with developed proper policies.

---

[56] Federal Communications Commission, "Spectrum allocations and associated regulatory provisions to support lunar and cislunar communications in specific frequency bands," DA-22-954, September 16, 2022.

[57] Number Resources, https://www.iana.org/numbers

[58] Bundle Protocol Compressed Bundle Header Encoding Node Numbers, https://www.iana.org/assignments/bundle/bundle.xhtml#cbhe-node-numbers

[59] Bundle Protocol Compressed Bundle Header Encoding Node Numbers, https://sanaregistry.org/r/bp_cbhe_node_numbers/

Domain Names

Since IP networks will be deployed in space, IP applications and protocols assume the use of domain names in most cases. Since queries and responses should not travel deep space given long delays and disruptions, not only proper Domain Name System (DNS) infrastructure should then be put in place on celestial bodies networks to support that usage, but also the hierarchy of names to be used in space should be carefully designed for that purpose. One design could be based on the usage of a special Top-Level Domain (TLD) under the current Internet DNS root managed by IANA[60], in which case specific policies for space usage need to be put in place for domains under that TLD. Other designs may not use a special TLD. Similar to IP addresses and BP Identifiers, a Space Internet Registry (SIR) may be needed to manage domain names for space networks, with developed proper policies. An architecture on how to properly deploy and use DNS in space is yet to be developed.

7.2.3 Standards

Standards that are useful and widely accepted are critical for architecture implementation and evolution. This section discusses both standards for communication protocols and standards for time and coordinate systems.

Communication Protocol Standards

CCSDS

The International Organization for Standardization (ISO) traditionally relies on the Consultative Committee for Space Data Systems (CCSDS) for space communications and data standards. CCSDS was formed in 1982 by the major space agencies of the world to provide a forum for discussion of common problems in the development and operation of space data systems. It is currently composed of 11 member agencies, 32 observer agencies, and over 119 industrial associates. Since its establishment, it has been actively developing standards for data-systems and information-systems to promote interoperability and cross support among cooperating space agencies, to enable multi-agency spaceflight collaboration (both planned and contingency) and new capabilities for future missions.

Many space agencies require the use of CCSDS standards if they exist and fulfill mission requirements. CCSDS is actively working with the other organizations mentioned here, especially the IETF, to ensure that DTN and the BP suite in particular, evolve in such a way that it can meet space mission needs while also providing services to a wider set of terrestrial applications. CCSDS can then incorporate the IETF-developed standards into CCSDS through

[60] Domain Name Services, https://www.iana.org/domains

‘protocol profiles’ that ‘tune’ the standards for the space environment while maintaining interoperability with the general community.

ITU-T

Closely related to the work of the CCSDS is the standards sector of the International Telecommunication Union (ITU-T). The ITU-T mission is to ensure the efficient and timely production of standards covering all fields of telecommunications and Information Communication Technology (ICTs) on a worldwide basis, as well as defining tariff and accounting principles for international telecommunication services. (Presumably, the SSI will avoid complex settlement fees.) The international standards that are produced by the ITU-T are referred to as "*Recommendations*" (with the word capitalized to distinguish its meaning from the common parlance sense of the word "recommendation"), as they become mandatory only when adopted as part of a national law. Since the ITU-T is part of the ITU, which is a United Nations specialized agency, its standards carry more formal international weight than those of most other standards development organizations that publish technical specifications of a similar form. The CCSDS can and does draw on ITU-T standards. The ITU-T generally does not focus on space-related standards, but its decisions can have an indirect effect on CCSDS work. From the views of the private sector, there is limited and indirect involvement in CCSDS work. As CCSDS standards become innately ISO standards, frequently adopted to state-level programs, CCSDS only allows a single agency representing a given country or multinational organization as a member agency. Private sectors can, upon approval by the member agency, support the work of the CCSDS but only indirectly through its representing agency.

IETF

While work on DTN and the BP suite has its roots in CCSDS and the space sector, much of the standardization has been done in the context of first the Internet Research Task Force (IRTF) and more recently the Internet Engineering Task Force (IETF). The IETF is the standards body tasked with shepherding the protocols used in the Internet, and is a large organization allowing the DTN community to leverage expertise on a whole range of topics beyond just network / transport including security, network management, routing, etc. The standardization work for the current BPv7 suite was all done in the IETF, and CCSDS is working to adopt ‘protocol profiles’ of the RFCs that maintain compatibility with the IETF specifications while appropriately tuning them for use in the space environment. The open nature of IETF working groups provides an excellent way for all parties with needs for Bundle protocol services to develop generalized solutions that can be applied across environments.

Parameter Registries

Both the IETF and CCSDS have associated registry management organizations (IANA in the Internet world, the Space Assigned Numbers Authority (SANA) in CCSDS). The registries provide a way to deconflict BP node names, services, additional protocol features, etc. IANA in particular has experience dealing with the international, multistakeholder environment of the terrestrial Internet and we recommend continuing to use it as the main registration mechanism for BP managed parameters.

IEEE

IEEE members are actively investigating DTN capabilities, publishing papers in IEEE journals and participating in IEEE-sponsored workshops like the Space-Terrestrial Internetworking Workshops (STINT). The set of available papers is somewhat overwhelming, with over 125 papers in more than 25 IEEE journals in the last year alone. These works represent a rich resource both for understanding existing topics and extending DTN to areas such as DTN routing, MANET-DTN hybrids, machine learning in DTN environments, and many more.

3GPP

From another perspective, 3GPP, a project aimed at developing technical specifications and reports for cellular telecommunication technologies, currently sees less involvement from space agencies. However, several national space programs envision cellular networks becoming a part of the communication architecture on the lunar surface.

Working Together

Given such a landscape, one might consider that involving non-conventional stakeholders in the work cycles of existing standardization bodies would be beneficial. For instance, CCSDS member agencies can enhance their engagement with their respective domestic industries, including the new space sector, in order to collectively advocate for their industries' interests within international standardization efforts. Similarly, if space agencies had been more engaged with 3GPP, the project might have incorporated solutions for addressing the unique challenges posed by space environments into its technical work.

While differences exist between industry-driven standards (such as 3GPP and IETF), and a more formal standard (such as CCSDS/ISO), strengthening their connections would create a value chain and technological harmony, both of which are crucial for achieving interoperability and commonality of the SSI.

Time and Coordinate Systems

After naming and numbering protocols, and spectrum allocations, decisions are needed on standards for physical aspects of the SSI. Today, neither scientific conventions, international treaties, or engineering definitions have a consistent definition for "cislunar" space. Additionally, the defined GNSS space service volume is not tied to the cislunar term (e.g. while the US defines a Cislunar Space Service Volume relative to its GPS, there is no agreement on this at an international level for other GNSS).

For example, platforms in near Earth orbit may be part of the Earth domain while Lunar Gateway and lunar surface operations are part of the Moon domain. Sub-regions of the Moon domain could include shadowed craters and underground tunnels not directly accessible to communications from Earth. The relationship of SSI domains to physical domains is a topic for discussion among Artemis Accord signatories, starting with decisions by LunaNet.

In particular, recommendations are needed on:

- Definition of domain name boundaries (between Earth-domain and non-Earth domains). These could be based on some physical characteristic, such as gravitational sphere of influence, or transmission times (e.g., light-seconds). Alternatively, topological connectivity (e.g. sharing of a common contact graph) may be a more pragmatic mechanism.
- Adoption of coordinate systems for management of SSI operations across physical domains (e.g., barycentric celestial reference system or BCRS).
- Requirements for SSI time standards and the distribution of precision time for the efficient functioning of the network.

The SSI will need a common space and time coordinate system. Fortunately, astronomical work and deep space missions have developed coordinate systems that appear directly applicable without additional work. For the barycentric celestial reference system (BCRS), Wikipedia notes that "BCRS defines its center of coordinates as the center of mass of the entire Solar System, its barycenter. This stable point for gravity helps to minimize relativistic effects from any observational frames of reference within the Solar System." [61]

Barycentric Coordinate Time (also known as TCB, from the French *Temps-Coordonnée Barycentrique*) is the corresponding time frame for BCRS. Wikipedia notes that TCB is used “as the independent variable of time for all calculations pertaining to orbits of planets, asteroids, comets, and interplanetary spacecraft in the Solar System. It is equivalent to the proper time experienced by a clock at rest in a coordinate frame co-moving with the barycenter (center of

[61] Wikipedia, https://en.wikipedia.org/wiki/Barycentric_and_geocentric_celestial_reference_systems

mass) of the Solar System: that is, a clock that performs exactly the same movements as the Solar System but is outside the system's gravity well. It is therefore not influenced by the gravitational time dilation caused by the Sun and the rest of the system." For actual deep space missions, however, Barycentric Dynamical Time (TDB, from the French *Temps Dynamique Barycentrique*) is commonly used. TDB is a relativistic coordinate time scale that is defined as a linear scaling of Barycentric Coordinate Time. Further, the 2006 International Astronomical Union (IAU) redefinition of TDB as an international standard expressly acknowledged that the long-established JPL ephemeris time argument T_{eph}, as implemented in JPL Development Ephemeris DE405, is for practical purposes the same as TDB.

Time transfer is largely a solved problem for Earth-based networks. For the SSI, the problem of determining what time it is at each node is more complicated due to large distances and time-varying relativistic effects. Once the SSI adopts a standard or standards and local barycentric times, there is the next level of the problem of correcting computer and spacecraft clock drifts. Time synchronization from Earth may be sufficient or local time references on the Moon and Mars could be used (e.g., local atomic clocks). This raises a potential policy issue in that all official UTC sites are defined as terrestrial laboratories. Using a terrestrial UTC may be acceptable out to GEO, but for beyond GEO, it may be desirable to create a UTC (Moon) or UTC (Mars) that would be recognized by the global timing community.

For the Internet, there is a network time protocol (NTP) for clock synchronization to Coordinated Universal Time (UTC). It is an open question on whether or how to have a Space NTP for the SSI. A potential cost/risk trade for implementing Space NTP is whether a single clock on the Moon or Mars would suffer local gravitational effects and create a single, systemic bias. On Earth, multiple atomic clocks around the world are used to develop UTC. The GPS constellation is effectively an ensemble of atomic clocks that are steered to the U.S. Naval Observatory time which is the official time for the United States: UTC (USNO). Maintaining precise time is important not only for SSI network operation, but also for determining position to the centimeter level. Such precision can be achieved on planetary bodies using supplemental reference beacons, but sub-meter accuracy may be the best practically achievable performance in free space.

7.2.4 Cybersecurity Governance

While being extremely important, the topic of cybersecurity governance is also very sensitive and difficult to address. In addition to various requirements from nation states, the space agencies and their respective security organizations, the private sector may also have a different perspective with respect to security risks. Nevertheless, a common understanding of security threats and risks is required to implement a minimum set of mitigation actions.

For the short-term it is expected that users of the network will be required to adopt security measures required by the network provider while maybe adding additional security to the data they are transmitting. Interconnection between different providers of communication services would be based on bi-lateral agreements including security aspects. However, such a bi-lateral approach will not scale well to larger networks.

In the medium-term, coordinating bodies will be required. At least the following functions need to be covered either by existing organizations or new ones:

Certification authority for digital signatures and cryptographic material in space

Integrity of information transmitted in bundles and authentication of nodes which provided that information is important for a reliable SSI. It is expected that integrity and authenticity will at least initially be based on public-key cryptography (eventually bootstrapping more efficient methods for space communication). Certification authorities are needed such as delay-tolerant infrastructure for distribution of such information. First proposals for an inter-governmental certification authority have been made in CCSDS and will be addressed by the IOAG Security Working Group.

Coordination of security architecture, security policies and algorithms

Providers of communication services need to agree to certain aspects of the overall security architecture, the security policies applied at BP nodes and the specific algorithms and their parameters to be applied (e.g. key length). Policies should include response to security incidents, responsible disclosure of vulnerabilities and coordinated mitigation activities. Such policies are expected to be implemented by the CSIRT of the individual providers eventually supported by their Security Operations Centers and in coordination with any relevant CERT. The IOAG Security Working Group will address this topic in an inter-agency context.

7.2.5 Interconnection of Networks

As the SSI shifts towards a model where private-private agreements take precedence for network interconnection, it draws parallels with governance issues seen in the terrestrial Internet. In the Internet, the interconnection of independent private networks (ISP networks) occurs through peering agreements, historically requiring smaller ISPs to purchase transit from larger ones for access to the global Internet. In contrast, larger ISPs often engage in unpaid traffic exchange.

Similarly, as the SSI matures and when private sectors become primary providers of the network, potential public policy concerns may surface. These concerns include competition and antitrust matters, particularly if dominant network providers emerge within the SSI network. Moreover, Internet Exchange Points (IXPs) - physical junctions where different networks interconnect - are considered potential points of disruption and surveillance. Their compromise could disrupt Internet connectivity and make them targets for surveillance and data collection, raising concerns about privacy, national security, and mission safety. Hence, robust security measures are essential as the SSI could also be interconnected via an IXP-like connection point.

As the SSI would be susceptible to unique space-related factors that could damage network operations, cooperation among SSI network providers and the implementation of measures, such as mutual exemption from transit (settlement) fees, or liability for damage could become desirable properties.

8. Key Principles

Drawing from the observations made above, the IPNSIG proposes a set of key principles, as recommendations for all stakeholders to pursue, in order to facilitate the development and operation of the Solar System Internet. These principles aim to facilitate collaboration, fair and consistent resource allocation, transparency, policy decisions, governance operations, and architecture evolution.

8.1 Basic Principles

Collaboration

Collaboration amongst various parties has been vital for historical space activities and will continue to be crucial for future space exploration. This underlying principle well applies to the development of the Solar System Internet. In particular, voluntary sharing of communication assets amongst the parties and allowing their mutual use (like the Internet network), will not only increase the utility of the network, but will also enhance space exploration, scientific discovery, and commercial utilization. Collaboration is key to promote the development of the Solar System Internet.

Fair and Consistent Resource Allocation

Sharing of Communications assets involves use of other parties' networks, including radio/optical links, relays, routers, and spacecraft hardware, software and storage. To enable and coordinate such sharing of assets, it is also necessary to have an orderly set of coordinated controls, on several key elements which create capacity constraints, such as spectrum and numbering identifiers used by the Solar System Internet. These resources could be globally shared amongst the parties and require administration and coordination processes to ensure fair and consistent distribution.

Transparency

To enable collaboration, it is essential to publicly share key pieces of information. For instance, network connectivity details, such as link availability periods, supported communication protocols, bandwidth and usage of key identifiers play a vital role in facilitating interconnections and interoperability between networks. Sharing information also prevents harmful interference. For example, even in interplanetary space, sharing which frequencies are used on spacecraft and their orbits becomes critical to avoid conflict and damage to other parties. Transparency of information serves as a key principle for promoting the Solar System Internet while simultaneously avoiding harmful interference. Transparency is also required in the processes used for governance and in making the decisions that will define SSI architecture and governance.

Stakeholders can only have confidence and trust in these processes and decisions if they are openly conducted and subject to inquiry and objective justification.

Interoperability

Interoperability is the defining property of the Solar System Internet. All of its component networks must interoperate compatibly for the SSI to function as intended. SSI governance should promote development, adoption and use of open international standards to the greatest extent possible to define the architecture and govern the spectrum, communication, networking, position, timing, and other functions of the modular SSI architecture, to enable resilience, security, and scalability needed for cooperative support across networks to support users. Like the terrestrial Internet, the SSI hinges on using a core set of standards implemented in widely available components that support dynamic, real-time internetworking among the component service providers.

Security

For creating a reliable and robust Solar System Internet which protects the contributing resources and enables privacy of communication, security needs to be built-in by design from the beginning. The overall network architecture needs to be accompanied by a matching security architecture and participating stakeholders should strive towards a common understanding of the security needs, necessary security policies and the implementation of those policies. A shared understanding of the threats and vulnerabilities of the Solar Systems Internet is fundamental to defining the extent and robustness of security mechanisms. All stakeholders should cooperate on the implementation of the required infrastructure to support the exchange of security related information such as security keys or certificates but also information about security incidents to allow rapid responses to protect the overall network.

8.2 Policy Decisions

Multistakeholder Governance

Drawing from the history of the Internet, we can observe how the adoption of Multistakeholder governance has contributed to its maturity and sustainability over time. This experience informs us that for the long-term sustainability of the Solar System Internet, policy decisions should be made collaboratively amongst all stakeholders, suggesting the Multistakeholder governance model inherited from the Internet. However, governance of interplanetary communications and navigation in the space regime today is carried out by the builders and users of the network, who are primarily government space agencies. The Multistakeholder model should be pursued starting now to include future providers and users of the network such as commercial actors and non-governmental organizations.

8.3 Governance Operations

International and Inclusive Decision-making

The Solar System Internet should be viewed as a shareable asset, benefiting all stakeholders involved. The development and implementation of the SSI should be done in such a way as to enable multi-national cooperation and collaboration through multistakeholder technical and governance processes that include governments, academia, the private sector and civil society.

Governance at Right Levels

Appropriate level of governance at the right levels, also known as Subsidiarity, is desirable property. There are areas where tight governance is required, such as avoiding overlap or identifier conflict - in the Internet, these would be IP addresses, AS numbers and Domain Names. Although these identifiers essentially require central management, the Internet adopts a hierarchical management approach, where the distribution and specific local needs are taken into account by the Regional Internet Registries (RIRs) and Local Internet Registries (LIRs), while not disturbing the overall interoperability of the network. In a different layer, local network peering could be governed amongst the interested parties based on private arrangements. Governance at the right levels is a concept that should be reflected in the Solar System Internet.

Conformance to International Law

There are several international space laws and treaties, such as the Outer Space Treaty and the Rescue Agreement that have been adopted through the United Nations or as customary international law. These instruments address the behavior of all actors in space, and must be observed and adjudicated as appropriate for dispute resolutions among Member States.

8.4 Architecture evolution

Standards Development

Standards that are useful and widely accepted are critical for architecture evolution. Standards development processes should consider the expertise and input from different stakeholders while seeking to benefit all actors involved in the Solar System Internet. There are good standard development practices and lessons that can be derived from the terrestrial governance regimes that can inform the standards development processes for the Solar System Internet. It is also important that standards are backward compatible to ensure continuity and sustainability of the SSI.

Open Process and Multistakeholder Engagement

The standards process should have an open and inclusive approach that allows for the participation of various stakeholders. The IETF follows an open standards development process, where anyone can participate and contribute to the creation of Internet standards. This is a multistakeholder governance practice in itself. Such openness has contributed to the sustainability and continuous advancement of the terrestrial Internet.

Having parties with Relevant Expertise and Interests

While promoting an open process, it is essential to ensure that the appropriate and relevant parties are involved, especially if those standards are considered influential and widely adopted by the industry and nation states around the world (e.g. ISO, ITU-T, IETF standards). The focus should be on engaging experts who possess the necessary knowledge and experience while being prudent in ensuring that no single nation or party is able to drive decisions based solely on political or private interests.

Collaboration between Standardization Bodies

In space, there has been a shift from primarily government and space agency involvement to increased participation from private entities. Given this transition, it will be beneficial for conventional space standardization bodies (e.g. CCSDS) to enhance their engagement with the private sector. It is also important that standardization bodies such as CCSDS, IETF, ITU-T, IEEE and such, mutually strengthen their collaboration to promote interoperability, commercialization, and cooperative activities for a sustainable and resilient Solar System Internet.

9. Way ahead

Moving forward, there do not appear to be any fundamental governance barriers to the creation of a Solar System Internet. Like the Internet itself, there is no centralized authority but rather a complex set of technical standards, interfaces and protocols that must be tended and implemented in order for the SSI to function effectively. The spectrum for lunar communications and navigation systems needs to be secured internationally and there is a proposed ITU agenda item to do that. The needs of near-term lunar operations are being addressed via the LunaNet and related concepts, which have attracted international interest. The CCSDS is working on several standards relevant to the SSI. Multiple international forums exist to explain and promote the concept of an SSI, ranging from the ISECG, IOAG and Artemis Accord signatories to IETF and UN COPUOS and GEGSLA. New forums, such as a UN ICG for space operations could be created to facilitate transparency among all spacefaring states.

LunaNet is not an exclusively NASA program or indeed something owned by multiple government space agencies. Rather, it is an example of the kind of multi-stakeholder cooperation that is creating the SSI envisioned by this report. That said, an immediate recommendation for LunaNet and the evolving SSI is the adoption of DTN, BP and IPv6 in localized areas. The infrastructure that is built in cislunar will become the scaffold for humans and robots to extend even farther and the right decision and implementation needs to be in place now, so that burdens are not paid by future generations. Time standards may also need to settle soon, as they become a driving factor for lunar operations also affecting the SSI. There are still questions for the SSI on how to reach an agreement on a naming and numbering scheme and how SSI could be protected from malicious and unintentional threats. Common sets of agreement have to be reached among all participants and built into the network from the onset considering the evolution of the SSI. Lastly, multistakeholder governance for policy making, as proven by the Internet, would become the key enabler for the long term sustainability of the SSI as the Internet expands into space.

10. Conclusion

In this report, we have explored the technical and governance challenges that might arise as humanity embarks on its re-journey to the Moon, and there beyond, with particular focus on communication. The collaborative governance framework that has been cultivated on the Internet stands as a testament to humanity's collective accomplishments over the course of many years. Given the challenging conditions of the space environment, the need for such collaboration becomes all the more evident - with nations and entities around the world working together, we hold the aspiration for the expansion of the Internet into space - the Solar System Internet. Our challenge is to seek how humanity can collaborate towards that end.

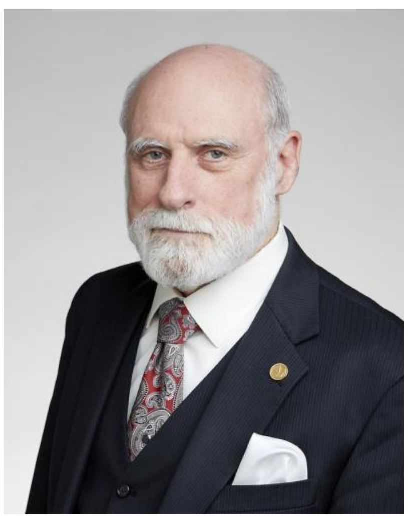
Acknowledgements

The IPNSIG has held a number of events (https://www.ipnsig.org/events) covering different aspects and views of the Solar System Internet and informing much of the content of this report. We want to extend our appreciation to Alberto Montilla, Alberto Montilla Jr., Blake LaFuente, Bostjan Grasic, Brooke Stokes, Danial Klimkin, David Gomez, Doreen Bogdan-Martin, Ernesto Yattah, Facundo Novik, John Cook, Jorge Amodio, Joshua Waszkiewicz, Juan Fraire, Larissa (Lara) Suzuki, Michael Moore, Marianne Winfield, Nadia Kortas, Sarah Withee, Scott Johnson, Ryan Brukardt, Ronny Bull and Samo Grasic.

Meet the Architecture and Governance Team

Yosuke Kaneko

Yosuke Kaneko currently serves as the President of the Interplanetary Networking Special Interest Group (IPNSIG) of the Internet Society (ISOC), an international non-profit organization that envisions expanding networking to interplanetary space. Under his dedication and along with the entire membership, in June 2022, the IPNSIG successfully became a standing chapter of ISOC, known as the Interplanetary Chapter to promote its vision and to enhance the goals of the Internet Society. Since he assumed President in September 2020, he is leading efforts toward creating a common vision and shaping the future of the interplanetary network. At the national space agency in Japan, JAXA, he had contributed to the development and operations of the International Space Station (ISS), including establishing a bi-directional communication link using Internet Protocol between the ISS and the Japanese ground system. He also led the Japanese flight control team as Flight Director between 2009 to 2010. From April 2020 to March 2022, he had served at the Strategic Planning and Management Department of JAXA Headquarters, leading the overall coordination of JAXA's human spaceflight, space science and exploration programs. Today, he is at the Space Exploration Innovation Hub Center to promote research and development of innovative technology with non-space private sectors and academia to enable future space explorations.



Vinton Cerf

At Google, Vint Cerf contributes to global policy and business development and continued spread of the Internet. Widely known as one of the "Fathers of the Internet," Cerf is the co-designer of the TCP/IP protocols and the architecture of the Internet. He has served in executive positions at the Internet Society, the Internet Corporation for Assigned Names and Numbers, the American Registry for Internet Numbers, MCI, the Corporation for National Research Initiatives and the Defense Advanced Research Projects Agency and on the faculty of Stanford University.

Vint Cerf sat on the US National Science Board and is a Visiting Scientist at the Jet Propulsion Laboratory. Cerf is a Foreign Member of the Royal Society and Swedish Academy of Engineering. Fellow of the IEEE, ACM, American Association for the Advancement of Science, American Academy of Arts and Sciences, British Computer Society, Worshipful Companies of Information Technologists and Stationers and is a member of the National Academies of Engineering and Science. Cerf is a recipient of numerous awards and commendations in connection with his work on the Internet, including the US Presidential Medal of Freedom, US National Medal of Technology, the Queen Elizabeth Prize for Engineering, the Prince of Asturias Award, the Japan Prize, the Charles Stark Draper award, the ACM Turing Award, the Legion d'Honneur and 29 honorary degrees.

Scott Pace

Dr. Scott Pace is the Director of the Space Policy Institute and a Professor of the Practice of International Affairs at George Washington University's Elliott School of International Affairs. He is also a member of the faculty of the Trachtenberg School of Public Policy and Public Administration. His research interests include civil, commercial, and national security space policy, and the management of technical innovation. Dr. Pace rejoined the faculty of the Elliott School in January 2021 after serving as Deputy Assistant to the President and Executive Secretary of the National Space Council from 2017-2020.

From 2005-2008, he served as the Associate Administrator for Program Analysis and Evaluation at NASA. Prior to NASA, Dr. Pace was the Assistant Director for Space and Aeronautics in the White House Office of Science and Technology Policy (OSTP). From 1993-2000, Dr. Pace worked for the RAND Corporation's Science and Technology Policy Institute (STPI). From 1990 to 1993, Dr. Pace served as the Deputy Director and Acting Director of the Office of Space Commerce, in the Office of the Deputy Secretary of the Department of Commerce. He received a Bachelor of Science degree in Physics from Harvey Mudd College in 1980; Master's degrees in Aeronautics & Astronautics and Technology & Policy from the Massachusetts Institute of Technology in 1982; and a Doctorate in Policy Analysis from the RAND Graduate School in 1989. Dr. Pace received the Order of the Rising Sun with Gold and Silver Stars from the Government of Japan in 2021, the Office of the Secretary of Defense Group Achievement Award in 2020, the NASA Outstanding Leadership Medal in 2008, the US Department of State's Group Superior Honor Award (GPS Interagency Team) in 2005, and the NASA Group Achievement Award (Columbia Accident Rapid Reaction Team) in 2004. He has been a member of the US Delegation to the World Radiocommunication Conferences in 1997, 2000, 2003, and 2007. He was also a member of the US Delegation to the Asia-Pacific Economic Cooperation Telecommunications Working Group, 1997-2000. More recently, he has served as a member of the U.S. Delegation to the UN Committee on the Peaceful Uses of Outer Space in 2009, 2011-17, and 2022. Dr. Pace was a member of the NOAA Advisory Committee on Commercial Remote Sensing (ACCRES) from 2012-2017 and was the Vice-Chair. Dr. Pace is a former member of the Board of Trustees, Universities Space Research Association, a Member of the International Academy of Astronautics, an Associate Fellow of the American Institute of Aeronautics and Astronautics, and a Fellow of the American Astronautical Society.

Jim Green

Jim Green has worked at NASA for 42 years before retiring in December 2022. He received his Ph.D. in Physics from the University of Iowa in 1979 and worked at Marshall Space Flight Center, Goddard Space Flight Center, and NASA Headquarters. During Jim's long career at NASA, he has been NASA's Chief Scientist and was the longest serving director of the Planetary Science Division with the overall programmatic responsibility for the New Horizons spacecraft flyby of Pluto, the Juno spacecraft to Jupiter, and the landing of the Curiosity rover on Mars, just to name a few. Jim has received the NASA Exceptional Achievement Medal for the New Horizons flyby of the Pluto system and NASA's highest honor, the Distinguished Service Medal. He has written over 125 scientific articles in refereed journals and over 80 technical and popular articles. In 2015, Jim coordinated NASA's involvement with the film The Martian. In 2017 Asteroid 25913 was renamed Jamesgreen in his honor.

Laura DeNardis

Dr. Laura DeNardis, a global expert in cybersecurity and Internet governance, is Professor and Endowed Chair in Technology, Ethics, and Society at Georgetown University in Washington, DC. Wired UK named her one of "32 Global Innovators Who are Building a Better Future" and her book *The Internet in Everything: Freedom and Security in a World with No Off Switch* (Yale University Press) was recognized as a Financial Times Top Technology Book of 2020. Among her seven books, *The Global War for Internet Governance* (Yale University Press) is considered a definitive source for understanding cyber governance debates and solutions. Dr. DeNardis has given keynote addresses or invited lectures at hundreds of venues on six continents, has served as an expert adviser to Fortune 500 companies, foundations, and government agencies, and was a management consultant in computer networking for Ernst & Young's global information technology practice during the dot-com era. Professor DeNardis is an affiliated Fellow of the Yale Information Society Project, where she previously served as Executive Director, and is a life Member of the Council on Foreign Relations. She holds an AB in Engineering Science from Dartmouth, a Master of Engineering from Cornell, a PhD in Science and Technology Studies from Virginia Tech, and was awarded a postdoctoral fellowship from Yale Law School.

James Schier

Jim Schier is the Chief Architect for NASA's Space Communications and Navigation (SCaN) Program at NASA Headquarters. He leads definition of the future evolution of NASA's network architecture for communications and Position, Navigation, and Timing (PNT) services, particularly LunaNet, the Lunar Internet, to meet the needs of future science and human exploration missions. He acts as liaison to the Department of Defense for space communications and PNT and is chairman of the Interagency Operations Advisory Group (IOAG), an association of 15 national space agencies which develops and recommends the technical communications and navigation architecture and evolution for interoperability among international civil space agencies. He joined NASA in 2004 after 25 years in industry where he worked on civil, defence, intelligence, and commercial space systems. At Northrop Grumman, he led the team studying the National Reconnaissance Office's ground systems architecture, led system engineering on commercial satellite systems, and was a lead system engineer on the Orbital Space Plane. Mr. Schier was Chief System Engineer on the International Space Station at Grumman. At TRW, he managed flight software development on the MILSTAR communications satellite system and led integration of materials processing experiments for the 1985 Shuttle Spacelab 3 mission. He has received the NASA Exceptional Service Award, Silver Snoopy, and the NASA group award on behalf of the team that redesigned the space station.

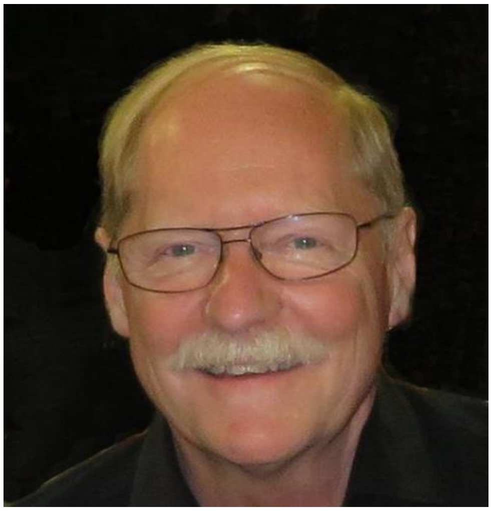
Dave J. Israel

David J. Israel is the Exploration and Space Communications Projects Division Architect and the Principal Investigator for the Laser Communications Relay Demonstration (LCRD) at NASA's Goddard Space Flight Center. He has been working on various aspects of space communications systems since joining NASA in 1989. He received a B.S.E.E from the Johns Hopkins University in 1989 and M.S.E.E. from the George Washington University in 1996.

He co-chaired the Interagency Operations Advisory Group (IOAG) Space Internetworking Strategy Group. He has led the development of various Space Network/Tracking and Data Relay Satellite System (TDRSS) operational systems and has been the principal investigator for multiple communications technology activities concerning advanced space communications concepts and networking protocols, including the Low Power Transceiver Communications and Navigation Demonstration (LPT CANDOS) experiment on Shuttle flight STS-107 and Disruption Tolerant Network demonstrations on the Lunar Laser Communications Demonstration.

Felix Flentge

Felix Flentge is a software engineer in the Ground Segment Engineering and Innovation Department at ESA's Space Operations Centre in Darmstadt, Germany. He is an expert in space communication protocols and architectures, such as the CCSDS File Delivery Protocol and Disruption Tolerant Networking. Felix is actively supporting and promoting these technologies across all space mission families - from Earth Observation up to interplanetary missions. He is managing a wide range of activities from operational implementation and deployment of communication protocols and systems, inter-agency DTN demonstration activities up to academic cooperation in the areas of real-time DTN services, bundle routing and bundle protocol extensions. Felix is actively contributing to standardisation and international coordination in these areas at CCSDS, IOAG and various international working groups including the IPNSIG Architecture & Governance WG. He is excited about the prospect of a Solar System Internet and is convinced that we shall follow an open and inclusive approach towards its establishment and governance to the benefit of all stakeholders.



Leigh Torgerson

Leigh Torgerson leads a number of efforts in the development and operation of spacecraft systems, with emphasis on end-to-end communications system technology. He has over 45 years of experience in team management, aerospace system design, digital & RF electronic system integration and flight test. He has been with Jet Propulsion Laboratory since 1990, and is currently a Space Communications Networking Architect in the Communications Architectures and Research section at JPL, managing the Protocol Technology Lab (PTL).
He has been on the Disruption Tolerant Networking team since its inception, co-authored the DTN Architecture RFC, managed the JPL Core Engineering Support team for the DARPA DTN program, and currently is leading developments of End-to-End Communications Protocol Networking Testbeds to facilitate the infusion of DTN into JPL Deep Space Comm and Mission Ops systems. In addition, he is developing a Mars DTN Relay Network Operation System, and conducting extensive ION Hardening testing to insure the maturity of the NASA baseline ION DTN software. His professional experience includes serving as a United States Naval Aviator, and 10 years in the Lockheed Skunkworks as an Avionics Flight Test Engineer and Avionics Department Manager prior to joining NASA/JPL. He obtained an M.S. in Aeronautical System Engineering from the University of West Florida, and a B.S. in Engineering, EE/CS emphasis, from UCLA.

Scott Burleigh

Scott Burleigh recently retired from the Jet Propulsion Laboratory (JPL), California Institute of Technology, where he was a principal engineer. His career has spanned over 48 years of experience in computer software development including 35 years of software engineering for space flight applications. A founding member of the Delay-Tolerant Networking (DTN) Research Group of the Internet Research Task Force, Mr. Burleigh co-authored the specification for version 6 of the DTN Bundle Protocol (BP), supporting automated data forwarding through a network of intermittently connected nodes, and was the principal author of the specification for BP version 7 (Internet RFC 9171). He led development of the Interplanetary Overlay Network (ION) implementations of BP and related protocols, which are currently in operation on the International Space Station. He was Principal Investigator and software lead for the Deep Impact Network experiment, which operated an ION-based interplanetary networking router on the EPOXI spacecraft in solar orbit more than 60 light seconds from Earth for four weeks in 2008. Mr. Burleigh has been awarded the NASA Exceptional Engineering Achievement Medal and four NASA Space Act Awards for his work on these communication protocols, and ION was JPL’s nominee for NASA’s Software of the Year award in 2010.

Marc Blanchet

Marc Blanchet is an Internet network engineer who contributed over the last 30 years to the engineering of new Internet technologies such as IPv6, Internationalized Domain Names (idn), RDAP and Delay-Tolerant Networking(DTN). He has co-authored 17 RFCs, has co-chaired more than 15 IETF working groups, including the dtn working group, was member of the Internet Architecture Board and has been IANA transition working group co-chair, and as such received the ICANN leadership award. He is also involved in the IPNSIG architecture and projects working groups. Marc likes to keep his hands dirty by developing applications in various languages and platforms. Recently, he proposed and implemented ways to reuse Internet protocols and applications, such as email, http and network management over DTN networks in space. On his Fridays, to give back to the community, Marc volunteers in a local food bank and a homeless shelter.

Ed Birrane

Dr. Birrane is a computer scientist and embedded software engineer who focuses on the adaptation of computer networking protocols for use in non-traditional environments. He has supported a variety of embedded software engineering efforts, to include the NASA New Horizons mission to explore the Pluto-Charon system and the NASA Parker Solar Probe mission to observe the outer corona of our sun.

Dr. Birrane works with industry, government, and academia on the design and development of protocols to implement the Delay-Tolerant Networking (DTN) architecture. He co-chairs both the Time-Variant Routing (TVR) and DTN working groups within the Internet Engineering Task Force (IETF) where he is a co-author of BPv7 (RFC 9171), BPSec (RFC 9172) and the default security contexts for BPSec (RFC 9173). He is a member of the principal professional staff of the Space Exploration Sector at the Johns Hopkins University Applied Physics Laboratory where he manages the Embedded Applications Group and serves as Chief Engineer for Space Networking. He is an adjunct professor of computer science at both the University of Maryland, Baltimore County and the Johns Hopkins University.

Keith Scott

After graduating from UC Berkeley and UCLA Keith spent nearly two years in the communications research section of NASA's Jet Propulsion Laboratory (JPL) characterizing the performance of Internet protocols over space links. Keith joined The MITRE Corporation in 1998 where he continued his work extending networking to austere and challenged environments, including space. Keith has supported the Consultative Committee for Space Data Systems, the international standards body regulating communications with civilian spacecraft, since 1998, and served as the working group chairman for the Cislunar Space Internetworking working group and the follow-on Delay Tolerant Networking working group, as well as area director for the space internetworking systems area. Keith has been involved in DTN since 1998, and was a member of the Internet Research Task Force's Interplanetary Internet and Delay Tolerant Networking working groups. He is co-author of the Delay Tolerant Networking Architecture document (RFC4838) as well as the Bundle Protocol version 6 specification (RFC5050). Keith retired in 2023 but continues to support the IPNSIG and CCSDS efforts to bring internetworking to space communications.

Oscar Garcia

Oscar Garcia is a Board member of the IPNSIG, where he launched and leads the IPNSIG Pilot Projects Working Group. He started the DTN Testing plan and the global DTN Network for testing the bundle protocol in scale to be used in the IPN. Mr. Garcia has developed technologies and servers for this purpose and for developing applications for space. Mr. Garcia made the first connection between cloud servers using DTN in
2020 in a team sponsored by Dr. Vinton Cerf. Mr. Garcia has been in computer programming and information systems since 1983. and has led technology projects for public and private national and international institutions. Mr. Garcia is the chief software architect of unified medical records systems. He received the Award of the World Summit on the Information Society in Digital Health for Argentina in 2005. Oscar Garcia presented the first Medical Record System for Space Exploration in 2020. This development got the interest of the Space Agencies for serving astronauts, space tourists, researchers and doctors in Space medicine. Unified Medical Records for Space Exploration was nominated to the British Interplanetary Society Arthur C. Clarke Award. Mr. Garcia is currently working to test Unified Medical Records for Space Exploration on the Moon. As speaker for DTN technologies, Mr. Garcia has lectured conferences for the United States, Europe, South America and Japan.

Kiyohisa Suzuki

Kiyohisa Suzuki is an Associate Senior Engineer at the Space Tracking and Communications Center of the Japan Aerospace Exploration Agency (JAXA). He started his career at the National Space Development Agency of Japan (now JAXA) in 2002 and has been involved in the development and operation of various works including the Wideband InterNetworking engineering test and Demonstration Satellite “KIZUNA” (WINDS), the Data Relay Test Satellite “KODAMA” (DRTS), and the Near-Earth Tracking System “Ground Network” (GN). Alongside these works, he embarked on the research and development of DTN (Delay/Disruption Tolerant Networking) in 2007 and has been contributing to the international standardization of this technology. He is also currently active in several international organizations as Deputy Chairperson of the CCSDS (Consultative Committee for Space Data Systems) DTN Working Group since 2015, Sub Lead of the Strategy Working Group at the Interplanetary Chapter of the Internet Society since 2020.

Marius Feldmann

Marius Feldmann is CEO and founder of D3TN, a company focusing on Delay- and Disruption-tolerant Networking (DTN). Together with his team, he has established several R&D projects to drive forward the technical roadmap of D3TN. Furthermore, he has set up solid partnerships with different organizations including ESA and NASA which resulted in several joint activities. Marius has helped to position D3TN in the DTN community as an entity which transforms standards, ideas and visions into materialized technical realities. Examples for this are the REDMARS project which demonstrated remote control of UAVs via combined deterministic plus opportunistic DTNs as well as the first Bundle Protocol v7 field-test in space leveraging ESA’s OPS-SAT. As he is passionate about open source ecosystems, he has been pushing forward the ALASCA association (ALASCA e.V.) focusing on open source based digital and Cloud infrastructures which he is currently supporting as chairman. Apart from his role at D3TN, Marius is working as COO at Cloud&Heat Technologies, a SME Cloud technology provider from Germany. In the past, he has worked for several national and international research projects, including projects funded by the European Union.
As a long term goal, Marius dreams about his own satellite orbiting Mars running D3TN’s network protocol stack.

Laura Chappell

Ms. Chappell is the Founder of the Protocol Analysis Institute, Inc., and Chappell University. Ms. Chappell researches, documents, and presents information on network protocols, protocol analysis, Wireshark, network forensics, and interplanetary communications. Ms. Chappell is often called in to analyze more complex network problems that require visibility into the communications system and create custom training systems for national, state, and local governmental agencies. Ms. Chappell has written several top-selling books on network analysis, troubleshooting, and Wireshark. Ms. Chappell is also the Working Group Lead for the IPNSIG Academy, a member of the IPNSIG Technical Documentation Working Group, and a member of the IPNSIG Outreach Working Group. In addition, Ms. Chappell is the Vice President of the High Technology Crime Investigation Association's Silicon Valley Chapter (htcia.org), Board Advisor for the Deep Packet Inspection Consortium (dpiconsortium.org), and has been a member of the Institute for Electrical and Electronics Engineers (IEEE) since 1990.

Ginny Spicer

Ginny Spicer is a cyber threat intelligence analyst and advocate for young technical communities. Within the Interplanetary Networking Special Interest Group (IPNSIG), Ms. Spicer is a member of the technical documentation, outreach, and architecture and governance working groups. She has previously contributed to DEFCON's aerospace village and the California Cybersecurity Institute's Space Grand Challenge.

Ms. Spicer also acts as the second Vice President of the HTCIA's Silicon Valley Chapter and an advisory board member for the Deep Packet Inspection Consortium. She is committed to ensuring that networking is for everyone and young people are involved in evolving Internet technologies, working to bring the joy of networks to young people through events, challenges, and competitions.

Henry Danielson

Henry Danielson is an experienced Space and cybersecurity strategist. Mr. Danielson has successfully been a part of the Interplanetary Networking Special Interest Group (IPNSIG), Academy Working Group (AWG), and the Technical Documentation Working Group. Mr. Danielson has collaborated with the United States Space Force, Jet Propulsion Laboratories (JPL), and Space Systems Command to help develop Space Grand Challenge, a CTF for high school students. Mr. Danielson is on staff with the Aerospace Village to promote Space cybersecurity. For over twenty years, he has been a professor at Cal Poly San Luis Obispo. He serves as the Technical Advisor and Curriculum Developer for the California Cybersecurity Institute as well as the Technology Director of the Coast Unified School District. Danielson holds multiple certifications in cybersecurity. Henry is a GOON at DEF CON, the largest hacking convention on the planet. Henry promotes awareness for middle and high school students all over the country. In 2023, Henry published a book on cybersecurity tools and tactics to combat social engineering.

Helen Tabunshchyk

Helen is a Software Engineer specialising in high-performance programming and distributed systems, but she is particularly passionate about software-defined networking. Having worked for years on multiple large-scale Edge networking solutions here on Earth, she naturally has got passionate about the idea of the Solar System Internet. Helen has been committed to improving equality here on Earth, including leading the Women Who Code community for 6 years, however, being a Ukrainian in 2023, she felt particularly dedicated to the idea of promoting unrestricted and equal access to the Internet, be it on Earth or in space. Helen has been awarded Exceptional Talent in Digital Technology by Tech Nation UK in 2021.

List of Abbreviations

AFRINIC	African Network Information Centre
APNIC	Asia Pacific Network Information Centre
ARIN	American Registry for Internet Numbers
Arpanet	Advanced Research Projects Agency Network
ARQ	Automatic Repeat Request
ASN	Autonomous System Number
BGP	Border Gateway Protocol
BP	Bundle Protocol
BPSec	Bundle Protocol Security
CCSDS	Consultative Committee for Space Data Systems
CERT	Computer Emergency Response Team
CERFNET	California Education and Research Federation Network
CFDP	Consultative Committee for Space Data Systems File Delivery Protocol
CSIRT	Computer Security Incident Response Team
DSN	Deep Space Network
DNS	Domain Name System
DOE	The United States Department of Energy
DTN	Delay and Disruption Tolerant Networking
DTNMA	DTN Management Architecture
ESA	European Space Agency
ESNET	Energy Sciences Network
FRICC	Federal Research Internet Coordinating Committee
GEO	Geostationary Earth Orbit
GNSS	Global Navigation Satellite Systems
GSO	Geostationary Orbit
IAB	Internet Architecture Board
IAHC	International Ad Hoc Committee
IANA	Internet Assigned Numbers Authority
IAU	International Astronomical Union
IEEE	Institute of Electrical and Electronics Engineers
ICANN	Internet Corporation for Assigned Names and Numbers
ICG	International Committee on GNSS
ICCB	Internet Configuration Control Board
IETF	Internet Engineering Task Force
IGF	Internet Governance Forum
ION	Interplanetary Overlay Network
IOP	Interoperability Plenary
IOAG	Interagency Operations Advisory Group
IP	Internet Protocol

IPN	Interplanetary Network
IPNSIG	Interplanetary Network Special Interest Group
IPTO	Information Processing Techniques Office
IRTF	Internet Research Task Force
ISECG	International Space Exploration Coordination Group
ISI	Information Sciences Institute
ISO	International Standards Organization
ISOC	Internet Society
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union Radio Communications Sector
ITU-T	International Telecommunication Union Telecommunications Standardization Sector
ITU-D	International Telecommunications Union Development Sector
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LACNIC	Latin America and Caribbean Network Information Center
LTP	Licklider Transmission Protocol
LIR	Local Internet Registry
NASA	National Aeronautics and Space Agency
NAT	Network Address Translation
NCSA	National Center for Supercomputing Applications
NGSO	Non-geostationary Orbit
NOG	Network Operators' Group
NTIA	National Telecommunications and Information Agency
NTP	Network Timing Protocol
NSF	National Science Foundation
NSFNET	National Science Foundation Network
NSINET	NASA Science Internet
NSN	Near Space Network
OST	Office of Science and Technology Policy
PRNET	Packet Radio Network
RESTConf	Representational State Transfer Configuration Protocol
RIR	Regional Internet Registry
RIPE	Réseaux IP Européens Network Coordination Centre
RFC	Request for Comments
SANA	Space Assigned Numbers Authority
SATNET	Satellite Network
SFCG	Space Frequency Coordination Group
SSI	Solar System Internet
TCP/IP	Transmission Control Protocol/Internet Protocol
TDB	Time and Date Broadcast
TLD	Top Level Domain

UNCOPUOS	United Nations Committee on the Peaceful Uses of Outer Space
UTC	Coordinated Universal Time
USNO	United States Naval Observatory
USC	University of Southern California
WGIG	Working Group on Internet Governance
WRC	World Radiocommunications Conference
WSIS	World Summit on the Information Society
W3C	World Wide Web Consortium
3GPP	3rd Generation Partnership Project

Appendix A – Routing and Forwarding State of the Art

Several candidate technologies for routing and forwarding in the Interplanetary Network have been developed. Several of the most prominent ones are briefly introduced here.

Managed forwarding

The European Space Agency's technology for controlling the movement of data through a delay-tolerant network relies on managed direct mapping of bundle destination endpoints to convergence-layer protocol adapters (CLAs). Enqueuing a given bundle to a specific CLA may direct that bundle to a specific network node or simply to whichever node is reachable via that CLA at the time of transmission.

(See https://indico.esa.int/event/323/contributions/5030/attachments/3729/5182/12.25a_-_DTN__CFDP.pdf.)

Schedule-Aware Bundle Routing (SABR)

SABR is a CCSDS standard for computation and selection of routes through a delay-tolerant network on the basis of known, scheduled periods of contact between nodes, a "contact plan". The contacts form a graph in which the contacts are vertices and the arcs are periods of data retention at one node while awaiting the start of the next contact to an onward node. For each destination, Dijkstra's algorithm is used to find the best path through the graph from the forwarding node to the destination node, as constrained by considerations of capacity, propagation delay, and quality of service; the bundle is forwarded directly to the first onward node in that path.

(See https://public.ccsds.org/Pubs/734x3b1.pdf.)

REDMARS

In this formulation, a list of reachable destination nodes is associated with each neighboring node in the network topology. This list is consulted recursively and bundle-in-bundle encapsulation is used to direct bundles along the path that is identified in this way.

(See https://hal.science/hal-03692361/file/_IEEE_Comms_Mag_Final__Ring_Road_Networks__Final_Doc_.pdf.)

Shortest-Path Space Networking (SPSN)

SPSN, like SABR, relies on time-varying network topology information provided by a contact plan. Unlike SABR, though, it forms a graph of BP nodes – rather than a graph of contacts – for the purpose of computing routes. The resulting graph is smaller than a contact graph, enabling faster route computation.

(See https://ieeexplore.ieee.org/document/9147134.)

PRoPHET

PRoPHET uses transitive exchange of prior connectivity information to construct a table asserting the computed probability of conveying a bundle to its destination if a copy of the bundle is transmitted to a given node. These computed probabilities control the forwarding of bundle copies through the network, avoiding the high network overhead of epidemic routing.

(See https://link.springer.com/chapter/10.1007/978-3-540-27767-5_24.)

Spray and Wait

The Spray and Wait mechanism assumes no knowledge of network topology. Instead, the optimal number of copies of a given bundle that may be in transit in the network is computed at the time the bundle is inserted into the network; contact with another node results in division of that original tranche of copies between the two nodes. This procedure is repeated until eventually one of the nodes that has a copy of the bundle comes into contact with the destination node.

(See https://dl.acm.org/doi/10.1145/1080139.1080143.)

Opportunistic Contact Graph Routing (OCGR)

OCGR is a variation on SABR by which uncertain contacts may be incorporated into the contact graph. The plausibility of a given contact is computed over time as historical records of opportunistically discovered contacts are propagated through the network; the plausibility of a computed route is limited by the plausibility of its constituent contacts. Confidence in the delivery of a given bundle is aggregated over time as copies of the bundle are forwarded over these uncertain routes until that aggregate confidence exceeds a threshold and further forwarding ceases.

(See https://ieeexplore.ieee.org/document/8637316.)

Inter-regional forwarding

As the size of the network grows, it may become helpful to collect sets of topologically proximate nodes into distinct "regions" with designated "passageway" nodes providing forwarding services among regions. This can offer some relief from computationally intensive SABR calculation by limiting the scope of any single contact plan to the contacts among nodes in a single region.

(See https://amslaurea.unibo.it/17468/1/tesi_alessi.pdf.)

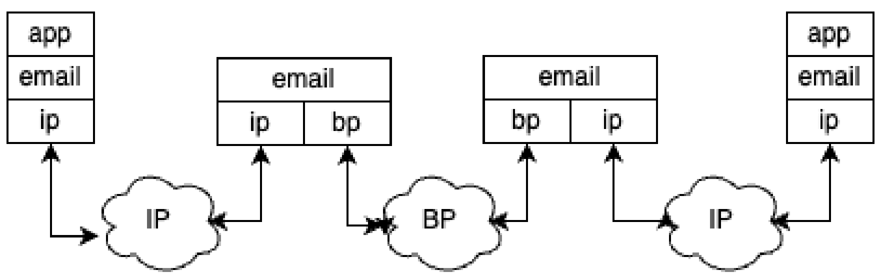
Appendix B – Use Cases of IP, Email and HTTP

This section describes in more detail the use case of the Internet Protocol suite in local environments such as on celestial bodies networks and how to use application-layer gateways to extend IP-based applications across deep space links.

If the end-nodes, such as a base station and a rover on Mars, are IP capable, then Internet applications can be reused if there is a local end to end path running IP, such as on and around celestial bodies like the Moon or Mars. For some applications, an optimized configuration for the environment may be needed.

Where the end-nodes are IP capable but BP is only the network layer in between, such as a monitoring computer on Earth Internet, a rover on Mars and a BP link between them, then application protocols such as HTTP or Email can be extended across the BP network using application-layer gateways. These application-layer gateways interact with their local IP endpoints and transfer the application-layer payloads between the IP and BP networks. This enables the use of HTTP from Earth to Moon or Mars while being carried over BP.

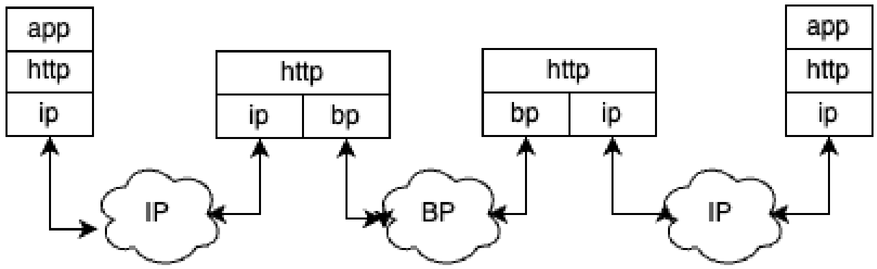
An illustration of the protocol stacks and path for an email proxy is shown below, where the IP network on the left can be the Internet on Earth, the BP cloud in center could be various deep space links networked using BP, and the IP network on the right can be the IP network on Mars. For the end to end application and user, carrying over BP is completely transparent.



End to End Email with transit over BP

An email flow would look like the following. An email from Earth is sent to some user or process on mars, with destination email address user1@mars.example. On Earth, the mars.example domain DNS record for email server (MX record) points to a mail server which receives the email. The mail server, based on its configuration, forwards the email to the BP gateway at the ground station. The BP gateway encapsulates the email raw message into a BP bundle and addresses it to the Mars BP gateway. The latter receives the bundle, decapsulates the raw email and then forwards it to the mail server on Mars via SMTP, which delivers it to the final destination.

Similarly, HTTP can be used, as shown below. In this use case, the client and the server can be at any location: an Earth monitoring system can be the HTTP client and a Mars rover can act as an HTTP server sending various data through the HTTP channel.



End to End HTTP with transit over BP

Network management, especially remote from Earth to Mars or Moon, could be done using native BP DTNMA or, for IP capable end nodes, Netconf/RESTConf , used for Internet Network Management. RESTConf running over HTTP, can be also carried similarly over BP on BP-only links, using the same HTTP over BP technique as described above. This enables a management station on the Earth network of space agencies to remotely manage IP nodes on Mars while using standard IP network management tools, instead of specifically developed tools.

The downside of application-layer gateways is that they have to actually implement the application-layer protocol (e.g. email, http) that they are converting, which requires a gateway implementation per IP protocol to be extended over BP.

It is also worth noting that encapsulating entire IP packets in bundles work for some applications, but for others, additional adjustments may be needed. So it should not be considered a general solution to extending the IP suite over interplanetary distances. For some cases, application-layer timers designed for local IP environments will likely react adversely to the potentially large and/or variable delays of interplanetary links.

Appendix C – SSI Architectural Challenges

Although a great deal of effort has already gone into the development of technology enabling interplanetary networking, some aspects of mature network operation remain under-supported. Mature technology currently exists to deploy and operate reliable delay-tolerant networks encompassing a few dozens of nodes and serving limited applications. This mature technology includes the following communication standards:

- Bundle Protocol – BPv7
- Bundle Protocol Security – BPSec
- Schedule-Aware Bundle Routing – SABR (based on Contact Graph Routing, CGR)
- Licklider Transmission Protocol – LTP; also the LTP convergence-layer adapter
- TCP/IP (Internet) convergence-layer adapter – TCPCLv4
- CCSDS File Delivery Protocol – CFDP
- CCSDS Asynchronous Message Service – AMS

Moreover, prototypes exist for technology that provides additional capabilities but is not yet in operational deployment. These include:

- Delay-Tolerant Network Management Architecture – DTNMA
- Bundle-in-Bundle Encapsulation – BIBE
- Bundle Streaming Service – BSS
- Bundle Streaming Service Protocol – BSSP

Remaining technical challenges in interplanetary networking include the following:

- Quality of service
- Reliable data delivery
- Suppression of routing loops
- Generalized neighbor discovery
- Integration of opportunistic forwarding into the network
- Data accounting
- Name service
- Network management
- Contact planning
- Scaling
- Locality of access
- Public distribution of information
- Residual security issues
- Applications

Quality of service (QoS)

An early QoS design in BPv6, supporting bundle prioritization, was removed from BP by the IETF DTN Working Group (DTNWG). There is no replacement in BPv7.

This remains a charter work item for DTNWG.

A prototype, derived from the BPv6 work and focused on the use of data labels, has been implemented and is currently available for use by BP nodes on the International Space Station.

Reliable Data Delivery

BPv6 included an ARQ reliability mechanism called custody transfer that functioned between bundle nodes, progressively moving the point of retransmission of lost data 'forward' towards the bundle destination. Because the operation of 'taking custody' of a bundle was optional (so that nodes with limited resources didn't suffer denial-of-service attacks when trying to forward bundles that required custody) computing reasonable timeouts for the ARQ mechanism was infeasible in the completely general case. Custody transfer was removed in the BPv7 protocol, which instead depends on using only reliable connections between bundle nodes. While this 'string of reliable convergence layers' approach is appealing, there are edge cases where it is not enough (e.g. unidirectional links, or cases where a bundle could be successfully received by a CLA, for instance, but the node might not be able to write it to local storage for some reason).

The Bundle-In-Bundle Encapsulation (BIBE) implementation mentioned above includes a redesigned custody transfer mechanism that relies on each bundle custodian knowing exactly which node will take custody of the bundle next. This, coupled with predicting the time required for a bundle to reach the next custodian, allows custodians to set ARQ timers. The IETF and CCSDS are looking into this and other mechanisms to augment reliable node-to-node connections.

Suppression of routing loops

Anomalies in network topology synchronization, either unintentional or malicious, could cause a given bundle to be forwarded cyclically without ever reaching its destination. This has not been a problem to date, but as the scope of the Solar System Internet grows, such forwarding malfunctions could become troublesome. Mechanisms for detecting and/or suppressing routing loops have yet to be developed.

Generalized neighbor discovery

An early draft specification for a protocol enabling BP nodes to discover new topological neighbors was posted in 2015; that protocol has been implemented and shown to work. However, it is not a published standard and, more importantly, it relies on pre-existing Internet connectivity between the mutually discovering BP nodes. A generalized neighbor discovery protocol that relies only on conformant radio configuration will be needed for opportunistic forwarding in environments beyond Earth.

Integration of opportunistic forwarding into the network

Proposed protocols for utilizing discovered contacts – rather than published information about network topology – to constrain bundle forwarding decisions in a delay-tolerant network have been prominent in the DTN research literature for decades. Procedural structures for integrating such protocols into the Solar System Internet have yet to be devised.

Data accounting

Space agencies require data accounting and tracing mechanisms similar to the Aggregate Custody Signaling that was developed for use in BPv6 on the International Space Station.

Enhanced functionality, derived from concepts in BP bundle status reporting, has been proposed within the DTN working group of the CCSDS Space Internetworking System area. Specifications for this functionality are under active development.

Name service

Some sort of association between BP nodes and human-readable names is required. Although most interplanetary network communication will be automated data exchange among robotic entities, some mechanism enabling human engagement in network configuration and troubleshooting activities will undoubtedly be necessary.

This mechanism will not be DNS, which associates names with IP addresses, which are dynamic. DNS updates must be continuous and timely, therefore not delay-tolerant. In BP there are no addresses; the name service will instead need to associate names with numeric node IDs, which need not change frequently. The required functionality would appear to be closer to LDAP in concept. No such name service has yet been prototyped.

Network management

Extensive work on an asynchronous management protocol has been performed by Johns Hopkins Applied Physics Laboratory, and a prototype implementation is provided in ION 4.1.2. Standardization of this protocol is a charter work item for DTNWG.

Moreover, the initial deployment and configuration of new nodes is currently manual, labor-intensive, and error-prone. A commercial network management framework is offered by SPATIAM CORPORATION, and a DHCP-like mechanism named DTN Node Auto-Configuration (dnac) has been prototyped.

Contact planning

Contact graph routing in Bundle Protocol is enabled by knowledge of time-varying topology as documented in peer-negotiated contact plans. But as networks scale up, the task of developing and maintaining contact plans will grow beyond the limits of cost-effective human management. An automated mechanism for developing and maintaining operator-acceptable contact plans will be needed. No initiative for development of such a mechanism is known to be currently in progress.

In addition, the minimization of conflicts in computed routes relies on agreement on contact plans among all nodes cited in those plans. It is therefore important for changes in contact plans to be automatically propagated to all affected nodes. A prototype mechanism for this synchronization (cpsd) has been implemented.

Scaling

With rapid growth in the numbers of nodes in the SSI, management of a single contact plan encompassing the entire network will become intractable (and route computation prohibitively expensive). A proposed solution would be to divide the network into multiple topological – not necessarily geographical – regions, one per contact plan. No specification for supporting protocols has been drafted at this time, but a prototype has been implemented.

Locality of access

Given the non-viability of central data servers and the implausibility of retaining all data in every node of the network, federated data access by means of replication at local (perhaps regional?) data servers may be necessary. (Cf. Preston Marshall 2006 "self-forming Akamai".) No known server federation initiative currently in progress.

A finer-grained remedy might be delay-tolerant Information-Centric Networking. Multiple initiatives along these lines have been proposed, and CalTech has filed a patent for one DT-ICN design. But no known prototypes have been developed to date.

Public distribution of information

Private exchange of data between BP nodes is well supported, but efficient public dissemination of data to multiple nodes – multicast – remains undefined. A prototype has been implemented and demonstrated in complex test cases.

Moreover, ad-hoc access to data in the Internet is supported by client/server architectures; these architectures are conversational and thus innately non-delay-tolerant. A delay-tolerant counterpart is needed; a "trusted collective" mechanism, based on multicast, has been prototyped.

Residual security issues

BPSec provides cryptographic bundle integrity and confidentiality, given security keys. Methods for reaching agreement on symmetric keys securely over delay-tolerant links remain an unsolved problem; an alternative would be to embed one-time symmetric keys within bundles and use public keys – previously and securely distributed to secure the embedded symmetric keys.

However, Internet public key infrastructure (PKI) is conversational and thus innately non-delay-tolerant; a delay-tolerant public key distribution mechanism is needed. Such a system, named Delay-Tolerant Key Administration (DTKA), relying on the "trusted collective" mechanism (which in turn relies on the multicast prototype), has been prototyped. Note that a server federation mechanism, as described above, might be needed in order to make this practical.

In addition, something along the lines of bundle-in-bundle encapsulation will eventually be needed for defense against traffic analysis. Again, a prototype has been implemented.

This is a charter work item for the IETF DTN Working Group.

Applications

Finally, it is clear that the countless Internet applications make that network as ubiquitous and indispensable as it is. Reinventing all of those applications, or porting them to use BP rather than IP, would be prohibitively expensive. Several alternatives are under consideration.

For UDP-based Internet applications, one option would be to leave all applications intact and simply adapt IP to run over BP. The Linux TUN/TAP interface, for example, can be used for this purpose; again a prototype has been implemented.

Another option for UDP-based applications would be to modify Linux and other POSIX-based operating systems by implementing a new BP socket type as an alternative to the UDP socket type (which it would closely resemble). No known initiative along these lines currently in progress.

Alternatively, for TCP-based applications it might be helpful to modify one or more performance-enhancing proxies to use BP for inter-proxy communication. Again, no known initiative is currently in progress.

One further option would be to support Web-based applications directly, by adapting RESTful interchange to operate directly over BP rather than over either UDP or TCP. Exploration of this topic continues.

Appendix D – Internet Governance History

The Internet project was started in 1973 by the Information Processing Techniques Office (IPTO) of the Defense Advanced Research Projects Agency (DARPA) on the heels of the very successful 1972 public demonstration of the Arpanet project that explored packet switching for computer communication[62]. The Internet concept was conceived by Robert Kahn, then a program manager at IPTO and subsequently managed by Vint Cerf who joined IPTO in 1976 and who, with Kahn, published the first paper on the topic[63] in 1974. Two more networks were established in addition to Arpanet, to test mobile packet radio and packet satellite concepts and the idea of a network of networks eventually called the Internet.

The initial governance of the Internet was essentially just program management under DARPA authority until about 1979 when Cerf established the Internet Configuration Control Board (ICCB) and asked Dr. David D. Clark, then at MIT, to chair it. The members were the DARPA-sponsored primary project leaders at the institutions that were carrying out the implementation and test of the Internet. In subsequent years, under new program managers at IPTO, the ICCB became the Internet Advisory Board, the Internet Activities Board and finally the Internet Architecture Board (all called "IAB"). Out of the IAB, the Internet Engineering Task Force (IETF) and the Internet Research Task Force (IRTF) were created and led by parties elected from the constituencies of these bodies and approved by the IAB. As the early and mid-1980s approached, the US Department of Energy (DOE), the US National Science Foundation (NSF) and the US National Aeronautics and Space Administration (NASA) created their own networks (ESNET, NSFNET and NSINET respectively) which used the Internet's TCP/IP protocols[64]. These networks were connected to form an expanding Internet. In this mid-1980s timeframe, an informal coordinating committee was set up called the Federal Research Internet Coordinating Committee (FRICC) consisting of program managers from DARPA/IPTO, DOE, NSF and NASA. This group morphed into the Federal Networking Council with many US Government representatives made up mostly of US research sponsoring agencies.

During the development of the Arpanet, one of the researchers, Jonathan Postel, was made the so-called "Numbers Czar" and took responsibility for the assignment of Internet Protocol addresses to hosts on the Internet. Later he also managed the Domain Name system. He was also the editor of the Request For Comments (RFC) series having been asked to take on that role by the Arpanet Network Working Group chair, Stephen Crocker who was, at the time, a graduate student at UCLA and subsequently a program manager at DARPA. Eventually Postel became

[62] Barry M. Leiner, Vinton G. Cerf, David D. Clark, Robert E. Kahn, Leonard Kleinrock, Daniel C. Lynch, Jon Postel, Larry G. Roberts, Stephen Wolff; "Brief History of the Internet", 1997; https://www.internetsociety.org/internet/history-internet/brief-history- internet/

[63] V. Cerf, R. Kahn, "A Protocol for Packet Network Intercommunication", IEEE Trans on Comms, Vol Com-22, No 5 May 1974

[64] V. Cerf, "A Brief History of the Internet & Related Networks" , https://www.internetsociety.org/internet/history-internet/brief-history-internet-related-networks/

known as the Internet Assigned Numbers Authority (IANA) and had the responsibility to track the assignment of IP addresses, Autonomous System Numbers, Domain Names and other parameters needed by the protocols of the Arpanet and Internet. He was ably assisted by Elizabeth ("Jake") Feinler at SRI International and its Network Information Center under the direction of Douglas Engelbart. At USC/ISI, Joyce Reynolds and Robert Braden assisted Postel in the editing of the RFC series. Over time, Postel's research contract moved with him at various institutions and US Government support moved from DARPA to NSF.

In 1984, the rapidly growing Internet needed a way to refer to the names of the host computers on all the Internet networks. A simple file that was updated frequently with the names of host computers and their addresses but this process became unwieldy for Postel and his colleagues. Paul Mockapetris, developed the Domain Name System (DNS)[65] to manage a hierarchical set of host names having the form <hostname>.<top level domain name> such as "example.com" where "example" is the host name and ".com" is the top level domain for commercial registrations. The DNS went into operation about 1984, under the administration of Postel. For resilience, thirteen independent "root server operators" were charged with the responsibility to maintain identical copies of the so-called "root zone" of the Domain Name System. Each root server operator can respond to DNS queries with the IP address of "name servers" for all top-level domains. The name servers form a hierarchy that can eventually deliver the IP address of any domain name to an appropriately formed query.

The first meeting of the IETF took place in 1986 and was attended by about 20 people. Today, the IETF tri-annual meetings are attended by 1500 or more people and take place around the world. All of these organizations (IETF, IRTF, IAB, IANA) operate on a consensus basis for the adoption of standards and technical decisions about the direction of Internet technology. Around 1990, the NSF which was funding the secretariat of the IETF concluded that its research funds should no longer be used for what was rapidly becoming a commercial enterprise with commercial Internet services being offered by PSINET, UUNET and CERFNET[66] and commercial equipment by companies like Cisco Systems, 3COM and Proteon among others. That decision led to the formation of the Internet Society (ISOC) in 1992 which became the host for the IAB, IETF and IRTF in addition to promoting Internet adoption around the world.

In December 1991, Tim Berners-Lee (now Sir Tim) announced the World Wide Web (WWW, Web) and its key standards: Hypertext Transport Protocol (HTTP)[67] and Hypertext Markup Language (HTML)[68]. In 1993, Marc Andreessen and Eric Bina, then at the US National Center for Supercomputer Applications (NCSA) at the University of Illinois in Champaign-Urbana, Illinois,

---

[65] P. Mockapetris, "Domain Names - Concepts and Facilities", https://datatracker.ietf.org/doc/html/rfc882
[66] https://devopedia.org/internet-engineering-task-force#qst-ans-10
[67] https://en.wikipedia.org/wiki/HTTP
[68] https://en.wikipedia.org/wiki/HTML

released the graphical user interface browser they called MOSAIC. This triggered an enormous influx of content into the Internet by people who just wanted to share the information they had with others. The Web became the most popular application on the Internet and its Uniform Resource Locators (URLs) depended deeply on domain names embedded in the URLs (e.g. http://example.com). Concurrently, Sir Tim formed a World Wide Web Consortium (W3C)[69] to maintain and extend the standards of the WWW.

About this same time, Postel began to seek assistance with IP address assignment coordination. In 1989, an organization in Europe calling itself Réseaux IP Européens (RIPE) began hosting meetings of new Internet operators in Europe. They formed a subgroup calling itself the RIPE Network Coordinating Center (RIPE-NCC) and Postel handed European IP address assignment responsibility to them around 1992. Thus was born the first Regional Internet Registry (RIR). Subsequently several other RIRs were formed including the Asia/Pacific Network Information Center (APNIC) in 1993 and the American Registry of Internet Numbers (ARIN) in 1997. Two other RIRs were created in later years serving other parts of the globe: the Latin American and Caribbean Internet Addresses Registry (LACNIC) in 2002 and the African Internet Registry (AFRINIC) in 2005.

In 1996, Postel, then at USC-ISI, was urged to move the IANA function from its University setting into an independent institution. USC was concerned that the growing commercial use of domain names might lead to complex and costly lawsuits and did not want the university to be liable for such disputes. An Internet Ad Hoc Committee (IAHC) was formed to consider how to export management of the Domain Name to an independent, non-profit institution. When it was proposed to establish an international non-profit in Geneva for this purpose, the US Congress took the view that this function should remain in the US. The dispute eventually led then-President Clinton to hand the problem to Ira Magaziner, a senior executive in the Clinton administration who orchestrated a process that eventually led to the founding of the Internet Corporation for Assigned Names and Numbers [ICANN][70] in 1998. ICANN had the basic responsibility for coordinating the assignment of domain names, Internet Protocol (IP) addresses and maintaining tables of parameters needed by protocols of the Internet Protocol Suite. At this point, oversight of ICANN and the IANA Functions moved from NSF to The National Telecommunication Information Agency (NTIA), a branch of the US Department of Commerce. In 2016, NTIA relinquished its contracts with ICANN, freeing it to operate independently as a global coordinator of domain names, Internet addresses and reference tables for various Internet protocol parameters.

Another example of this pragmatic approach arises from the formation of the World Summit on the Information Society (WSIS) in 2003 in Geneva by the United Nations as a multilateral

[69] https://en.wikipedia.org/wiki/World_Wide_Web_Consortium
[70] https://www.icann.org/history

investigation into the concept of an Information Society. This group met in 2003 and again in 2005 in Tunis. During this two year period, the organization morphed into a multistakeholder form that included participation of the private sector, academia, the technical community and civil society in addition to its original government representatives. A Working Group on Internet Governance (WGIG) was created to discuss the ways in which the Internet was a model of what an Information Society might be. In 2005, one of the outputs of the WSIS was the creation of a multistakeholder Internet Governance Forum (IGF) which has met every year since 2006 to explore ways in which Internet governance might be accomplished. Subsequent to the formation of the annual IGF literally 150 or more national and regional Internet Governance Forums spontaneously were created by local parties with an interest in this topic.

In more recent years, the Secretary-General of the United Nations, Antonio Guterres, has promoted the formation of High Level Panels, the concept of a Global Digital Compact, the creation of an office of the UN Tech Envoy, and plans for major conferences such as the WSIS+20 to review progress on the Information Society, the role of the Internet and the challenges the system poses for governance in its many dimensions.

Internet Society
Interplanetary
Chapter