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ESA's Steps towards the Solar System Internet

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Abstract

The European Space Agency (ESA) is committed towards establishing the Solar System Internet (SSI), an advanced network for deep space radio frequency and optical communication, as well as Positioning, Navigation, and Timing (PNT) services. Building on ESA's Moonlight programme, SSI will provide interoperable and secure communication services for institutional and commercial missions across the solar system, following international standards and in collaboration with global partners. This will result in a transition from traditional point-to-point communication links to network-based space communication based on Disruption Tolerant Networking (DTN) which has been successfully demonstrated with international partners. Further, for deep space navigation, future SSI nodes will need to provide highly autonomous space-based Orbit Determination and Time Synchronization (ODTS) and long-range ranging capabilities. The SSI vision aligns with ESA's Strategy 2040 and will enhance mission data return while reducing mission cost, enable greater spacecraft autonomy, and optimize use of communication resources. The paper outlines ESA's activities related to Solar System Internet, focusing on three key technology areas: DTN, Communication Technologies, and PNT. It also introduces the planned ASSIGN (Advancing Solar System Internet and GrouNd) activity, aimed at harmonising these efforts and providing the overall system architecture towards gradual implementation. Preparatory activities for ASSIGN included a Solar System Internet Pre-Phase A study and the concurrent design of a lunar SSI Pathfinder mission which will be briefly described.

Keywords: Deep Space Navigation, Positioning, Navigation and Timing (PNT); Disruption Tolerant Networking; Optical Communications; Radiofrequency Communications; Solar System Internet; Orbit Determination and Time Synchronization (ODTS)

1. Introduction

Deep Space communication is typically based on pre-planned, explicitly managed point-to-point links [1]. However, networked-based space communication concepts indicate a shift towards a new paradigm, as described the IOAG Lunar and Mars Communication architectures [2, 3] and the LunaNet Interoperability Specification [4]. The operational DTN (Disruption Tolerant Networking) Service for ISS payloads [5], the first employment of DTN in an Earth Observation mission [6], and various demonstration activities [7, 8, 9] have proven the feasibility of this approach and its benefits.

The vision of 'extending the Internet beyond Earth' and making space connectivity as easy and ubiquitous as current Internet connectivity has also been put forward by the Interplanetary Chapter of the Internet Society (IPNSIG) [10, 11]. At ESA, an Inter-Directorate Working Group has developed a common vision on Solar System Internet:

> *"Establish a European-led interoperable infrastructure with an appropriate governance and operational concept to provide network-based radio frequency and optical communication as well as navigation services for institutional and commercial missions within the (inner) solar system. This infrastructure should adhere to recognized international standards and be developed in collaboration with international partners."*

The significance of Solar System Internet for ESA is also apparent in ESA's Strategy 2040 [12] which identifies related strategic actions and identifies it as a key technology contributing to several of ESA's strategic mid- and long-term goals. 'Solar System Internet, Navigation and Communication Technologies' is among the Technology Themes selected for the ESA Technology Vision 2040 with the aim to '*... provide secure and interoperable networked communication services to ESA and other missions*'. In the context of ESA missions, goals are to enhance data return, reduce the cost of missions, enabling advanced on-board autonomy, increased resilience and optimise the use of communication resources across multiple providers.

For ESA, the Solar System Internet encompasses both communication and Positioning, Navigation, and Timing (PNT) services, which must then be considered together from the beginning. Combining these functionalities is required due to the high cost of placing assets in space and their interdependence: PNT services require communication, e.g. sharing information for time synchronisation, while communication services require PNT services, e.g. for calculation of contact windows between two communicating assets. Additionally, the combined availability of Communication and PNT services creates a unique synergy, significantly enhancing service opportunities and operational applications.

This paper will first provide a brief overview of ESA activities related to Solar System Internet and then describe the three main technology pillars: Disruption Tolerant Networking (DTN), Optical and RF Communication Technologies, and Positioning, Navigation and Timing (PNT). To provide harmonisation across the various different activities and technologies, a future activity called ASSIGN (Advancing Solar System Internet and GrouNd) is currently being prepared. The intentions for this activity and the current state including some results of preparatory activities are presented. The paper concludes with a brief summary.

2. Related Activities

There is already existing infrastructure and several on-going activities at ESA related to deep space communication and PNT, which can be considered as starting point towards the Solar System initiative by providing a potential reuse of technologies and of applicable international standards. In addition, it is important that any future SSI architecture considers their smooth and seamless integration in a gradual manner. The goal is to create a system of systems encompassing existing infrastructure and assets, the different planned constellations for providing communication and PNT service and complementing those with the dedicated SSI concept. This is not limited to institutional actors or ESA. Interoperability is at the core of the SSI concept and does include other space agencies and commercial entities where viable business cases exist. Some of the ESA-related activities are described hereafter:

2.1 ESTRACK, Mars Relay Network and Optical Nucleus Network

The ESA ESTRACK Core Network with four smaller stations and three 35m Deep Space Stations (a fourth Deep Space Station is under construction) is the backbone for space communication and tracking services to all ESA missions. ESTRACK is providing communication services across the whole Solar System, including Earth-Sun L2 astronomy, lunar, planetary and asteroid missions. Tracking services do not only include spacecraft but also launcher tracking. ESTRACK is complemented by commercially operated ground stations, in particular during LEOP and critical operations phases but also routinely, mainly for Earth Observation missions. ESTRACK is also making use of stations from partner agencies and is providing support to them under cross-support agreements. Routine operations are fully automated and supervised from the Network Operations Control Centre at ESOC, Darmstadt. ESOC is also hosting the European Relay Coordination Centre (ERCO) [13] interfacing with NASA's Mars Relay Operations Service (MaROS) [1] for coordination, planning and execution of Mars relay communication. The Mars Relay Network is the first interplanetary network and is essential for data return and operations of Mars rovers.

The Optical Nucleus Network is ESA's strategic initiative to consolidate and enhance a core set of optical ground stations, developed in close collaboration with national space agencies and international partners. It aims to establish a scalable and interoperable infrastructure supporting the progressive introduction of Direct-to-Earth (DTE) optical communication capabilities in Europe. By leveraging existing assets and aligning developments across institutions, the network serves as a coordinated backbone for technology validation, cross-support demonstrations, and built-up of an operational capability.

2.2 Moonlight LCNS

ESA's Moonlight programme [14] aims to become Europe's first off-planet telecommunications and navigation provider by offering a lunar communications and navigation services with its Lunar Communication and Navigation System (LCNS) which will be developed through a public-private partnership, supporting both institutional and commercial lunar exploration missions. Moonlight LCNS will consist of a constellation of five lunar-orbiting satellites, strategically placed in Elliptical Lunar Frozen Orbits (ELFO) to prioritize coverage of the lunar South Pole. Development of the first high-rate communication and navigation satellites started in 2024, aiming for initial operational capability with one communication satellite and one navigation satellite in 2029. Three additional navigation satellites will be developed and launched to achieve full Moonlight operational capability by 2030. The Moonlight LCNS system will comply with the lunar interoperability standards and specifications as defined by the LunaNet interagency working group [4], which includes ESA, JAXA, and NASA.

2.3 HydRON

HydRON is an ESA initiated partnership project developing a high-throughput optical space network [15, 16]; thus, an end-to-end system that will bring connectivity to multiple users across different orbits and integrate space and terrestrial networks including routing capabilities. Both commercial applications and institutional use are in focus. HydRON's target capacity is orders of magnitude greater compared to today's satcom systems: terabit-per-second compared to gigabit-per-second.

The HydRON demonstration system (HydRON-DS), currently in its implementation phase has the goal of demonstrating and validating service driven by future commercial needs, with two main mission objectives:

- <u>Technology verification and end-to-end system demonstration</u>: to achieve the end-to-end system demonstration, HydRON-DS will mature the required technologies, which are not yet on a technology readiness level required by the target commercial applications.
- <u>Validation of operational concepts in support of Service Demonstration</u>: HydRON-DS will support European and Canadian industry in de-risking the implementation

Current HydRON-DS is constituted by three elements,

- HDS-Element#1: constituted by a high-throughput optical LEO-Ring Layer of 10 satellites featuring a total of 40 laser terminals, 2 optical ground stations and one control centre. This element implemented by a consortium led by Kepler Communications.
- HDS-Element#2: a high-throughput optical LEO Multi-Orbit Extension Layer constituted by one LEO satellite, one MEO/GEO satellite, 2 optical ground stations and one control centre. This element is implemented by a consortium led by TAS-I.
- HDS-Element#3: a demonstration/service user segment, with contributions from commercial/institutional partners interested in experimenting/evaluating the HydRON-DS (i.e. demonstration users) or exploiting its commercial services (i.e. service users). Furthermore, this element will support new entrants to develop terminals for space, ground, airborne, HPAS or maritime usage to enlarge the ECO system in Europe and Canada. Ultimately Element#3 will contribute to the evolution HydRON to extend its system and service concept including a deep space extension of the HydRON-network.

In general, the HydRON concept is expandable in terms of users, nodes on ground, nodes in space and applications. In particular a deep space extension is being researched, that would allow connecting the near-Earth constellations with networks across the Solar System.

2.4 MARCONI / LightShip

Mars Communication and Navigation Infrastructure (MARCONI) is conceived by ESA as a future Mars-dedicated communication and PNT institutional service, aimed at being gradually built over the next decade, taking advantage of the planned development of the LightShip generic propulsive tug, currently under study. The first LightShip mission, LightShip-1, is currently in an industrial Phase A/B1 for an intended launch in 2032, providing the first MARCONI communication and navigation node and being augmented by the first passenger spacecraft called SpotLight, which is intended to carry a exploration science payload and a MARCONI augmentation payload in a Low Mars Orbit (LMO). LightShip-1 also carries an optical demonstration payload. Future LightShip missions (with subsequent Mars launch windows in the 2030s) host additional MARCONI nodes, allowing the achievement of the reference end-state MARCONI infrastructure (currently conceived as a 6-node constellation) by the 2040s. A maximum reuse, as far as possible, of Moonlight technologies and standards is today planned for the MARCONI future infrastructure.

2.5 Standardisation an International Coordination

Interoperability based on common open standards is key for the creation and operation of the Solar System Internet. ESA is actively contributing to standardisation in international standardisation bodies like the Consultative Committee for Space Data Systems (CCSDS) and following related standardisation activities in the Internet Engineering Task Force (IETF). ESA missions are largely based on the CCSDS standards and are applying for example, the space data link protocol standards for layer-2 communication. ESA is coordinating the discussion in ESTOL (ESA Specification for Terabit/sec Optical Links) [17] working group, for the specification of high-throughput optical free-space air interfaces. This working group is constituted by industry and entities from ESA member states and Japan. This specification is used as input for further standardization activities. ESA is coordinating with other space agencies in the Interoperability Operations Advisory Group and within domain specific working groups such as the International Mars Exploration Working Group (IMEWG) and the LunaNet working groups. The LunaNet Interoperability Specification (LNIS) [4] defines today a framework of mutually agreed-upon standards and interfaces to be applied by future service providers supporting missions in transit to, around, and on the Moon. LunaNet and associated documents aim at covering direct with Earth communications, inter-satellite links, surface-relay communications and PNT capabilities. Among others, it defines the Global Navigation Satellite System (GNSS) like Augmented Forward Signal (in S-band) that is broadcast by the various LunaNet Service Provider (LNSP) nodes to achieve a concept called LANS (Lunar Augmented Navigation Service). For communication, the full communication protocol stacks for realising the Real-Time Link Layer Communications Service, the Real-Time IP Network Layer Communications Service and the DTN Network Communications Service are specified.

3. Solar System Internet Technologies

For ESA, three technology pillars have been identified for the realisation of the Solar System Internet: Disruption Tolerant Networking for internetworking across multiple providers and bridging across heterogenous communication networks and links, optical and RF technologies for communications, and PNT. Obviously, all these technologies are not only essential for Solar System Internet but are already required or provide benefits in much smaller, specific-mission related scenarios. Also, these technologies do not only include specific software or hardware systems, such as Laser Communication Technologies, but also need to include system-of-system aspects such as network management and operations, security and end-to-end aspects. Special attention needs to be given to synergies across the different technology domains, such as the use of communication links for PNT purposes or optimisation across the full communication protocol stack to address issues such as communication reliability in an efficient way and optimise goodput.

3.1 *Disruption Tolerant Networking*

Within ESA, use cases for Disruption Tolerant Networking and related communication protocols have been identified in Earth Observation, Lunar and Deep Space Communications [18]. The store-and-forward principle of Bundle Protocol supports intermittent connectivity, typical for a lot of space communications scenarios, and provides implicit buffering of data. This is also important in cases of networks with very heterogenous links in terms of data rates which is often the case in high-data rate downlink scenarios where the space downlink data rate often exceeds the available terrestrial data rate by far. Implicit buffering in combination with advanced routing, the capability to make use of opportunistic contacts, and options for E2E data accounting provides also a high degree of resilience in case of communication failures. In addition, Bundle Protocol allows to operate over different underlying communication protocols, such as Internet Protocol and CCSDS packet protocols, and communication technologies, like RF and optical links. This capability allows the protocol to be applied in numerous use cases and mission scenarios, making it a fundamental network communication protocol for Solar System Internet.

The flexibility and extendibility of the protocol supports the development of additional features addressing typical requirements of space missions and infrastructures. To this end, ESA is currently working on Bundle Protocol Extensions for custody transfer and compressed status reporting for providing efficient end-to-end accounting and reliability [19]. Security is an important concern, and it is considered from early design on. Therefore, ESA is also working on securing DTN with BPSEC, performs security testing of communication protocols, is developing key management approaches and is addressing security monitoring and management [20]. Other activities aim at the standardisation of Bundle Protocol Quality of Service [21] and the definition of DTN Reference Scenarios [22] to stimulate research in that area. DTN Network Management and the impact on current network and spacecraft operations will be addressed in a dedicated study, soon.

To bring DTN into operations, DTN demonstration activities with international partners and commercial entities have been performed. Early DTN demonstration involving ESA and NASA have been executed in the context of the METERON experiments [23]. More recent demonstrations included the Lunar IceCube DTN demonstration which involved ESA's Kourou ground station, the ESA operational ground segment, NASA JPL, Moorhead State University and D3TN [8]. The OPS-SAT mission featured several DTN experiments [24, 25, 26] from various entities providing valuable experience with a DTN node in space. Further demonstrations of operational DTN-based cross-support capabilities are planned with NASA and DLR. This will include deployments of DTN nodes in operational networks which will form the nucleus for an operational DTN network.

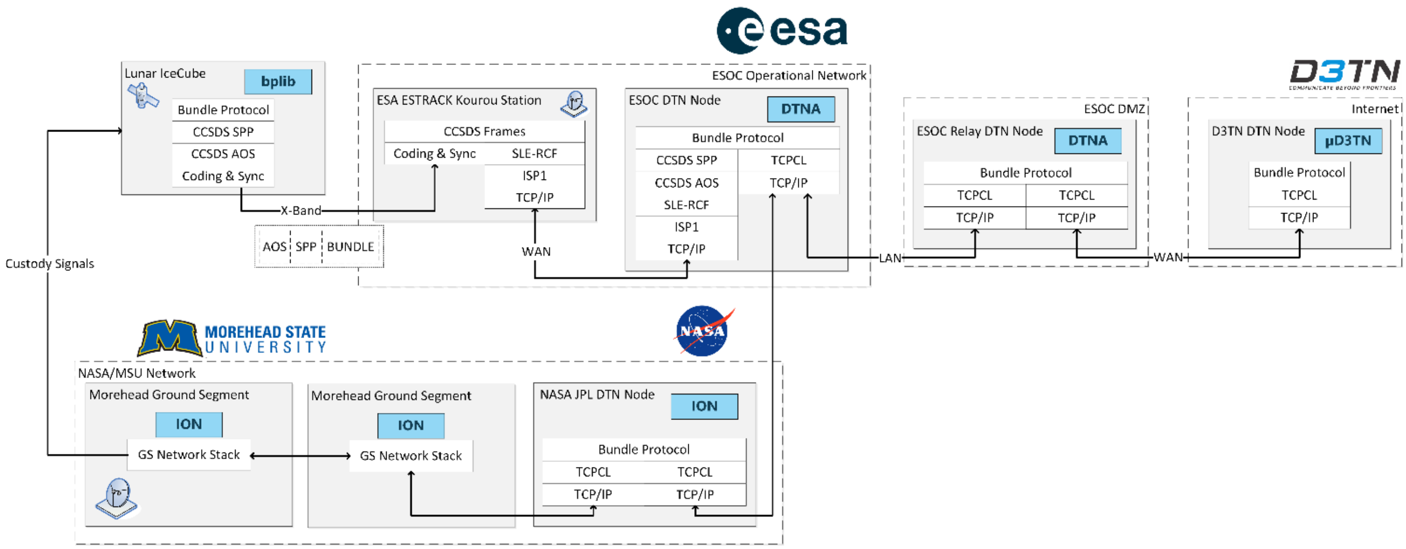

Figure 1: Visualisation of the network for the Lunar IceCube inter-agency DTN demonstration [8].

3.2 Communication

In deep-space scenarios radiofrequency (RF) is a mature technology, but gradual improvements are still required and expected. One major subject for further development and standardisation is related to surface and proximity communications, where the communicating assets are sufficiently close to each other to apply terrestrial technologies, such as Wifi (IEEE 802.11) or 3GPP technologies with minor adaptations if required.

In addition, optical technologies are essential for high-data-rate communications in deep space missions and this is key for the development of the Solar System Internet. Optical communications benefits on higher data-rates will enable new missions, increasing data-return in science and enabling new human and robotic missions. Optical communications have been already demonstrated, showing the potential of this technology, like the payload demonstrator on Lunar Atmosphere and Dust Environment Explorer (LADEE) [27, 28], which set a record of 622 Mbps data communication from the Moon, or more recently with the Psyche mission, where NASA successfully transmitted data at 25 Mbps from 226 million kilometres [29]. On this last mission, ESA is preparing its next major milestone in this domain with the planned cross-support demonstration for NASA's Psyche mission in July 2025. This will validate the compatibility of ESA's optical ground receiver and ground laser transmitter with NASA's in-flight terminal, paving the way for operational deep space optical links.

Nevertheless, further technology developments are required, especially in the space segment, to reach an operational status. Solar System Internet calls for a network approach, with inter-satellite links among nodes across the Solar System and near-earth orbits combined with direct links from space probes to ground stations on the Earth surface. Some applications will require high availability for safety and to support critical operations, requiring addressing the availability of the Earth-based optical ground segment and the near-earth based space segment, but also the constraints of solar-eclipses. To achieve this ambition, several technologies need to be developed and matured, for example, on-board pulsed-laser and receivers technology, or pointing and tracking approaches for inter-spacecraft links. To address the near-earth based space segment near-earth a deep space extension of the HydRON-Network is under consideration.

In parallel, ESA is advancing key ground segment technologies including segmented mirror telescopes, high-sensitivity single-photon detection systems, advanced synchronization techniques, and laser communication terminals (LCTs). These developments are feeding into the broader MARCONI system as well as SSI pathfinder preparations, establishing the foundation for scalable and autonomous optical ground infrastructure for future Solar System Internet nodes.

3.3 Positioning, Navigation and Timing

For the PNT deep space service provision, the future navigation nodes of the Solar Internet System will require the development of highly autonomous space-based node Orbit Determination and Time Synchronization (ODTS) technologies, and long-range optical and/or RF ranging capabilities (e.g., considering interplanetary distances within the inner Solar System). Figure 2 provides an example of how such system could look like where the synergy of the different systems is emphasized by the bar chart at the bottom. This possible architecture shows a satellite in transfer from Earth to Mars which is being served along its route by strategically located SSI nodes in the Earth and Mars Lagrange points. Upon arrival, it can use the dedicated MARCONI system as well as the SSI PNT nodes that are still usable for PNT and data relay purposes.

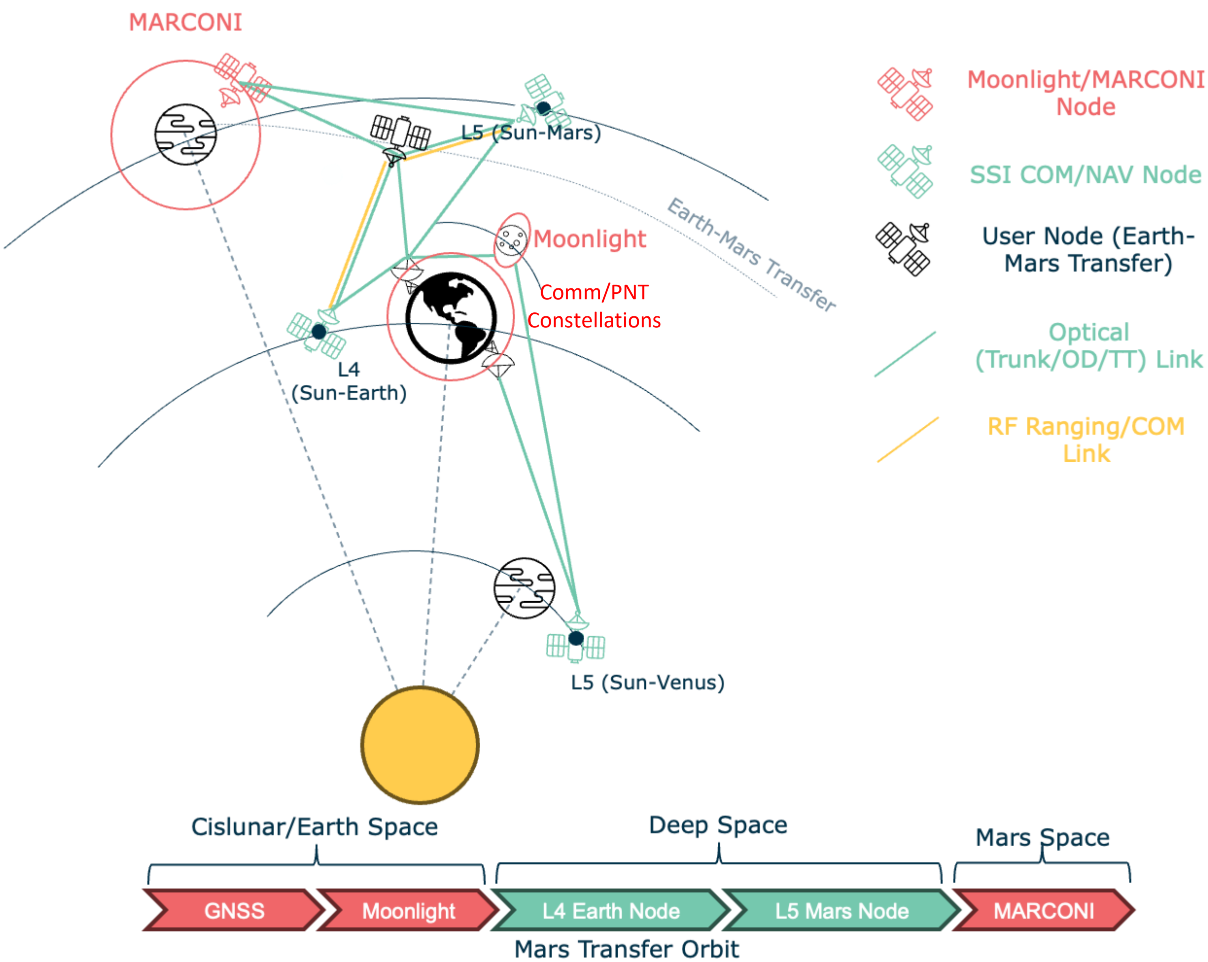

Figure 2: Visualization of a potential Solar System Internet PNT concept for an Earth-Mars transfer user (note that distances are not to scale).

To test, demonstrate, de-risk and trade-off some of the identified candidate related PNT technologies, ESA is considering the development of an early SSI pathfinder demonstrator (see Section 4.2.2), targeted to be placed in cislunar space, demonstrating autonomous ODTS and long-range optical ranging as well as local lunar orbit-to-surface optical ranging to aid reference frame realisations and transformations. Further, this SSI pathfinder mission shall also allow to extrapolate the performance levels achievable for generic SSI nodes within the Solar System, allowing then to characterise accurate end-to-end SSI PNT performance over the inner solar system.

4. ASSIGN – Advancing Solar System Internet and GrouNd

ASSIGN (Advancing Solar System Internet and GrouNd) is a proposed as a new multi-directorate activity to ESA member states for ESA's Ministerial Council in November 2025. It is jointly proposed by the Directorate of Operations, the Directorate of Connectivity & Secure Communication and the Directorate of Navigation and will consider the requirements from all programme directorates aiming at a coherent and consistent approach towards Solar System Internet across programmes and individual missions.

4.1 *ASSIGN - Preparatory Phase (2025-2028)*

It is planned to start with a preparatory phase 2025-28 which will address the SSI System Architecture in two parallel Phase 0/A studies consolidating use cases and requirements, identification of critical technologies and development roadmaps. The studies will address communication, inter-networking and PNT aspects, including the provision of Reference Frames and Times. These studies shall prepare towards the gradual implementation of the full Solar System Internet concept from 2029 onwards. The preparatory phase includes also a Technology De-Risking element to cover initial technology developments of critical SSI technologies. A third programme element, GrouNd, is targeting industry with an 'SSI Enabler' component to fund industrial developments and infrastructure and will prepare an SSI Reference Facility to enable compatibility testing for optical communications, experimentation with networked space communication and support services related to the provision of reference frames and times.

4.2 Preparation Activities

4.2.1 Solar System Internet Pre-Phase A Study

The Solar System Internet Pre-Phase A Study conducted in 2024 confirmed the high strategic and economic relevance of a Solar System Internet. ESA will need to continue investing into SSI to ensure that ESA and the Member States will play a key roles in development of SSI technologies, standardisation and governance of the future infrastructure. Economic impact analysis shows an enabling role for SSI technologies in space exploration with a potential to unlock new market opportunities and key capabilities. High commercial interest has been identified in the ground station and operations domain. By providing easy access and services dedicated to terrestrial space data users, this domain has a large potential due to the larger number of already active commercial players and the opportunity to realise short-term benefits. While initial phases and operations are expected to focus mainly on exploration, extension into other economic domains based on private investments may start around 2035. Two commercial profiles are expected to emerge: SSI Network Infrastructure Providers providing end-to-end SSI network solutions, integrating key hardware and software needed to support communication and PNT functionalities. SSI Network Service provider will provide communication and PNT services directly to end users based on the functionality enabled SSI Network Infrastructure providers.

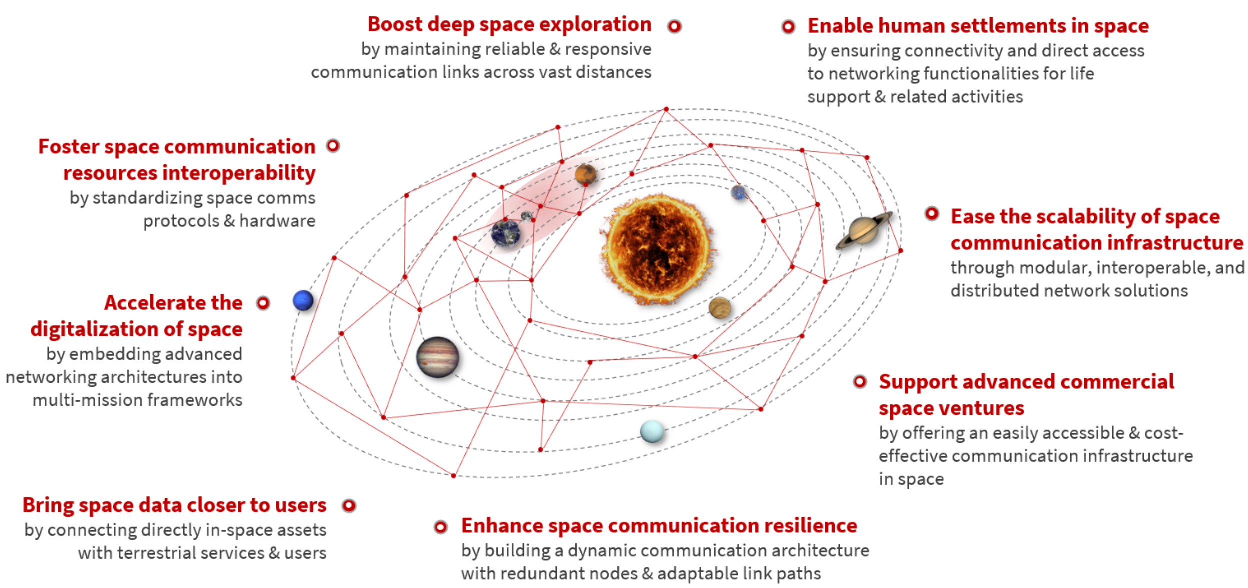

Figure 3: Strategic advantages of the Solar System Internet Infrastructure.

In addition to the strategic and economic analysis, technology readiness in terms of Disruption Tolerant Networking, PNT and beyond LEO optical communications have been assessed and development needs have been identified. A preliminary SSI Roadmap has been defined covering three phases:

- Phase 1: **Foundation and Initial Development (2025-2028)** covering initial infrastructure set-up with the establishment of SSI Reference Facility and initial DTN node deployments on ground. System studies and technology developments will prepare the expansion in Phase 2. Engagement in international standardisation and coordination is essential to ensure interoperability between networks which are being planned and deployed.

- Phase 2: **Expansion and Interoperability (2028-2032)** with the deployment of first space nodes, enhanced throughput and scalable security solutions. Optical compatibility testing provided through the SSI Reference Facility and provision of reference frames and times for operational use. Inter-provider connectivity and automated network management.
- Phase 3: **Full Deployment and Operationalisation (2032-2040)** with nodes at Mars and potentially other planets. Autonomous networking with dynamic routing and opportunistic contacts with neighbour discovery to address scalability.

4.2.2 Solar System Internet Pathfinder Concurrent Design Activity

Early 2025 an initial study in ESTEC's Concurrent Design Facility (CDF) looked into the definition of the payload suite in terms of optical communications, Disruption Tolerant Networking and Deep Space PNT for a potential cis-lunar SSI Pathfinder mission with the following mission statement:

> *The SSI Pathfinder will be the world-first mission to demonstrate reliable routine operations of a cis-lunar optical trunk link and the first ESA mission to use Disruption Tolerant Networking operationally. It will demonstrate technologies for Deep Space PNT and prepare the provision of Lunar Reference Time and Reference Frames.*

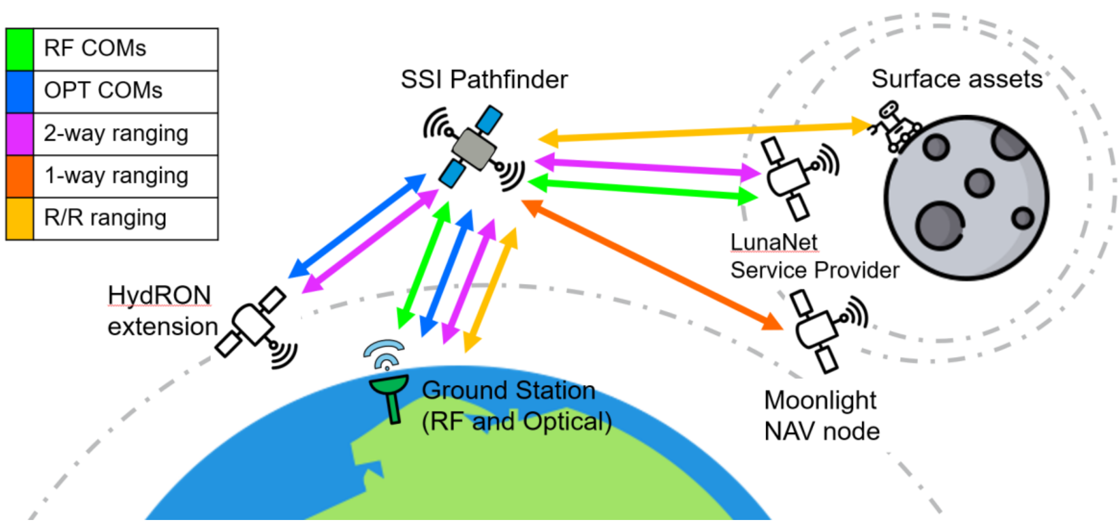

Figure 4:Initial SSI Pathfinder mission design with RF and optical links and ranging including passive retroreflectors (R/R).

The SSI Pathfinder CDF study concluded with an initial payload design which would enable ~5 Gbps data downlink back to an optical ground station on Earth or to a geo-stationary extension of the HydRON network. The full DTN protocol suite could be supported using state-of-the-art Data Processing Units enabling the SSI Pathfinder to act as a user and a provider of LunaNet networked communication services.

SSI Pathfinder could be equipped with a navigation payload suite that would include 1) a Moonlight navigation receiver, 2) a precise timing system (including at least one stable atomic clock), 3) sensors to support autonomous ODTS (star trackers, etc.), and 4) a laser retroreflector, and 5) laser ranger payload to perform ranging with respect to reflectors on the lunar surface. This payload would enable demonstrations and performance extrapolations for deep space PNT. Furthermore, the SSI Pathfinder would be able to provide an independent validation baseline based on ranging with Lunar Retroreflectors, Moonlight LCNS, HydRON and Earth stations. Finally, these additional baselines (especially the baseline between SSI Pathfinder and lunar surface retroreflectors) could enable an improvement of the realization of the existing lunar reference frames and their transformation to Earth equivalents. Two implementation options have been considered. The payload suite or parts of it could be flown as hosted payloads with other missions, in which case 3-4 years would be needed before launch. The other option is to realise the SSI Pathfinder as a dedicated SmallSat mission, which would take 4-5 years until launch assuming use of a standard platform with some eventual customisations.

5. Conclusions

The European Space Agency (ESA) is committed towards realizing the vision of a Solar System Internet. By leveraging on technologies such as Disruption Tolerant Networking (DTN), combined RF and optical communication, and Positioning, Navigation, and Timing (PNT), ESA aims to establish the foundation of a robust and interoperable infrastructure that will enhance space communication and across the Solar System.

Building on existing infrastructure and aligning with current activities at ESA related to communication and PNT, the Solar System Internet will be realised gradually. The goal is to create a system of systems encompassing existing infrastructure and assets, the different planned constellations for providing communication and PNT service and complementing those with the dedicated SSI concept. This is not limited to institutional actors or ESA itself. Interoperability is at the core of the SSI concept and does include other space agencies and commercial entities where viable business cases exist. Furthermore, the ASSIGN activity and the Solar System Internet Pathfinder mission concept highlight ESA's proactive approach to technology development and standardization. By collaborating with international partners and contributing to global standards, ESA ensures interoperability and maximizes the potential of the Solar System Internet.

Overall, ESA's steps towards the Solar System Internet represent paradigm shift to space communication and navigation, paving the way for future exploration and commercial opportunities. The continued investment in these technologies will enable ESA and its member states to play a leading role in the development and governance of this critical infrastructure.

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