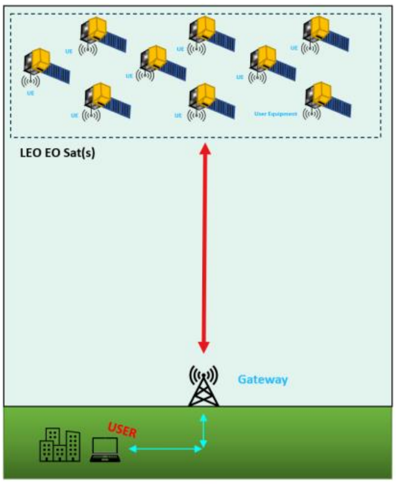
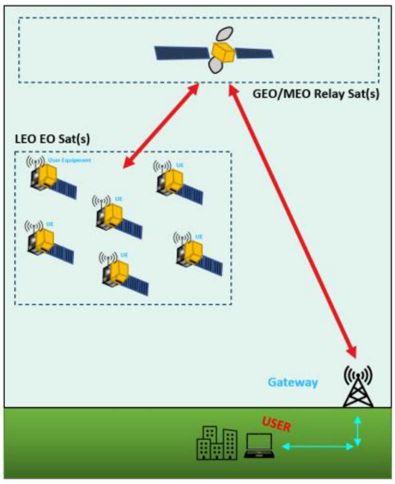
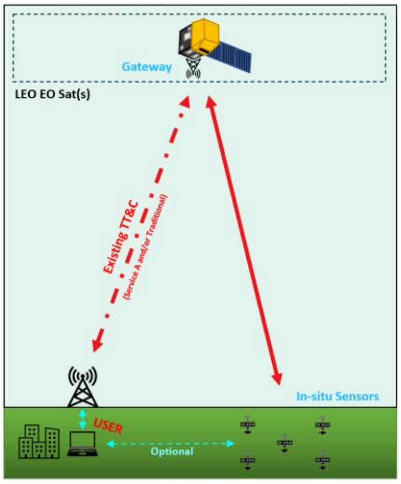
THE INTERNET OF THINGS FOR EARTH OBSERVATION (IoT4EO) PROJECT



Service A-1
(Direct bidirectional low-data-rate TT&C)



Service A-2
(Indirect bidirectional low-data-rate TT&C)



Service B
(Direct bidirectional low-data-rate data collection from In-situ sensors)

Low-data-rate Connectivity Architecture with Earth Observation (EO) Satellites in Low Earth Orbit (LEO)

IoT4EO Service Definition & Preliminary Specification

IoT4EO-SERV-REQ-2024-09-196

APPROVAL

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1 Introduction

1.1 Purpose and Scope

This document defines low-data-rate connectivity services and preliminary requirements identified during the "concepts for the use of IoT in Earth Observation" parallel studies conducted under ESA Contracts "4000139168" [RD-2] and "4000139169" [RD-3] with Airbus Defense and Space (ADS) and OHB Systems respectively. This document is created to serve as a reference for translating and tracing the IoT4EO service requirements to system level. These requirements are defined in **Section 4** and frequently referenced throughout to ensure traceability at each development stage, ensuring a system perspective is maintained.

1.2 Background

The rapid advancement and integration of network technologies on Earth, characterized by near-instant connectivity, offer substantial opportunities to enhance connectivity with Earth Observation (EO) satellites in Low Earth Orbits (LEO), typically between 400 to 800 km in altitude. These satellites complete orbits in approx. 90 to 100 minutes; approximately 15 times a day. However, their visibility with any given ground station (G/S) or gateway is quite limited—about 10% of the orbit period, even in the most favorable orbits.

Leveraging the widespread adoption of cellular and non-cellular Low-Power Wide-Area Network (LPWAN) technologies as part of **Internet of Things (IoT)** could revolutionize Earth Observation satellite connectivity. This concept, referred to as **IoT4EO**, could enable more dynamic satellite tasking, in addition to on-board event detection followed by the near-real-time distribution of information between space and ground nodes. This would not only increase the autonomy of satellite constellations, but also reduce operational costs. The concept could be simple, eliminating the need for complex antenna alignments on spacecraft while, thereby maintaining low yet adequate data rates. For situations requiring higher data rates, the ubiquitous communication system could integrate with more directional, complementary systems. Furthermore, the ongoing proliferation of LPWAN technology on Earth is laying the foundation for the development of ubiquitous networks also in space, by providing a **framework** that has already established important system components, including regulatory policies, physical infrastructure, data management systems, network layers, security, and protocols. It is important to note that IoT4EO intends to **complement** existing communication systems (e.g. high-speed links and traditional TT&C) by enabling cost-efficient and ubiquitous connectivity in LEO. It **is not intended to replace** these systems, given its current early stage of development and data rate limitations.

The need for ubiquitous connectivity with satellites in Low Earth Orbit (LEO) is widely acknowledged. A specific Study Group (SG) was established in 2022 through a collaboration between the European Space Agency (ESA) and other space agencies under the Inter-Agency Operational Advisory Group (IOAG) [RD-1] to explore the multi-dimensional aspects (i.e. technical and business) related to this ambitious goal (see **Appendix C**). This effort extends beyond institutional missions undertaken by these agencies. A primary objective of IoT4EO is to **federate** and facilitate **timely connectivity** between **institutional** and **commercial missions**.

This document synthesizes the findings and outputs from the services identified with OHB System [RD-2] and with ADS [RD-3]. These findings were further refined during IoT4EO Workshops held in February 2023 [RD-4] and will be further discussed in December 2024 [RD-5], which include a multi-disciplinary community of end users and potential service stakeholders. This document, titled "***IoT4EO Service Definition & Preliminary Specification***" outlines the **low-data-rate connectivity services** and **preliminary requirements** to address the needs of customers and users for such services, thereby laying the groundwork for subsequent system definition and requirements development. Understanding requirements translation is important because it clarifies the origin and progression of project requirements, and it ensures these requirements are accurately implemented and can be traced back at every stage of development.

Disclaimer: It is strongly advised that readers familiarize themselves with the system terminology used in this document to ensure a common understanding of the system definition language. Please refer to **Appendix A-2** for this information.

1.3 Applicable Documents

The following list of Applicable Documents are used in the IoT4EO System Requirements Document

ID	DOC-ID	Document reference and Title and version	Link

1.4 Reference Documents

The following list of Reference Documents are used in the IoT4EO System Requirements Document

ID	Document reference and Title and version	Link
RD-1	Interagency Operations Advisory Group	www.ioag.org
RD-2	OHB - Concepts of IoT for Earth Observation – ESA Contract 4000139168	
RD-3	ADS - Concepts of IoT for Earth Observation – ESA Contract 4000139169	
RD-4	IoT4EO Workshop #1 February 2023 - Executive Summary	indico.esa.int/event/438/
RD-5	IoT4EO Workshop #2 December 2024 – Executive Summary (*to be written*)	indico.esa.int/event/513/

1.5 Structure of the Document

The structure of this report aims to cater to multiple communities. It primarily discusses the IoT4EO Vision, which is the development of ubiquitous networks in space through an architecture focused on low-data-rate connectivity, along with its services and service requirements. These elements are clearly defined and consistently referenced throughout the report to ensure traceability at each development stage, ensuring a system perspective is maintained.

Section 2 – IoT4EO Vision

Provides an overview of the vision for the low-data-rate connectivity architecture.

Section 3 – IoT4EO Service Definition & Stakeholders

Provides a brief overview of the service definitions & requirements identified in the "Concepts for the use of IoT in Earth Observation" studies.

Section 4 – IoT4EO Requirements

Provides a collection of all the IoT4EO service requirements, categorized into performance, quality of service (QoS), scalability, security, regulatory, and interoperability requirements, to document the customer/user needs, ensuring their traceability in subsequent stages of the project development.

Section 5 – Appendices

Provides additional information that addresses the technical aspects of low-data-rate connectivity architecture and service, including:

- Appendix A: Acronyms and terminology,
- Appendix B: Use cases, Applications and Stakeholders
- Appendix C: IoT4EO Project
- Appendix D: Summary Table - Services
- Appendix E: Interoperability and Standardization Action Plan
- Appendix F: Scenario Examples with 50+ LPWAN Gateways

2 IoT4EO Vision

2.1 A low-data-rate connectivity architecture

The ongoing proliferation of Internet of Things (IoT) technology on Earth is laying the foundation for the development of ubiquitous networks in space, by providing a **framework** that addresses important system components, including regulatory policies, physical infrastructure, data management systems, network layers, and protocols. Figure 1 describes the possible top-level low-data-rate connectivity between different elements both in space and on ground, with each element representing one or more nodes in the system-of-systems, including non-traditional gateways and Geostationary / Medium Earth Orbits (GEO/MEO) relay assets.

The low-data-rate connectivity architecture with Earth Observation (EO) satellites in Low Earth Orbit (LEO) focuses on developing the space-Earth, Earth-space, and space-space links, using existing terrestrial networks as a foundation to build upon and as a new complementary component. In this context, the engineering of a solution will adopt a **middle-out** approach (as defined in Appendix A.2), focused on engineering within an existing and established system-of-systems to identify and leverage synergies, compatibility, interfaces, and integration opportunities.

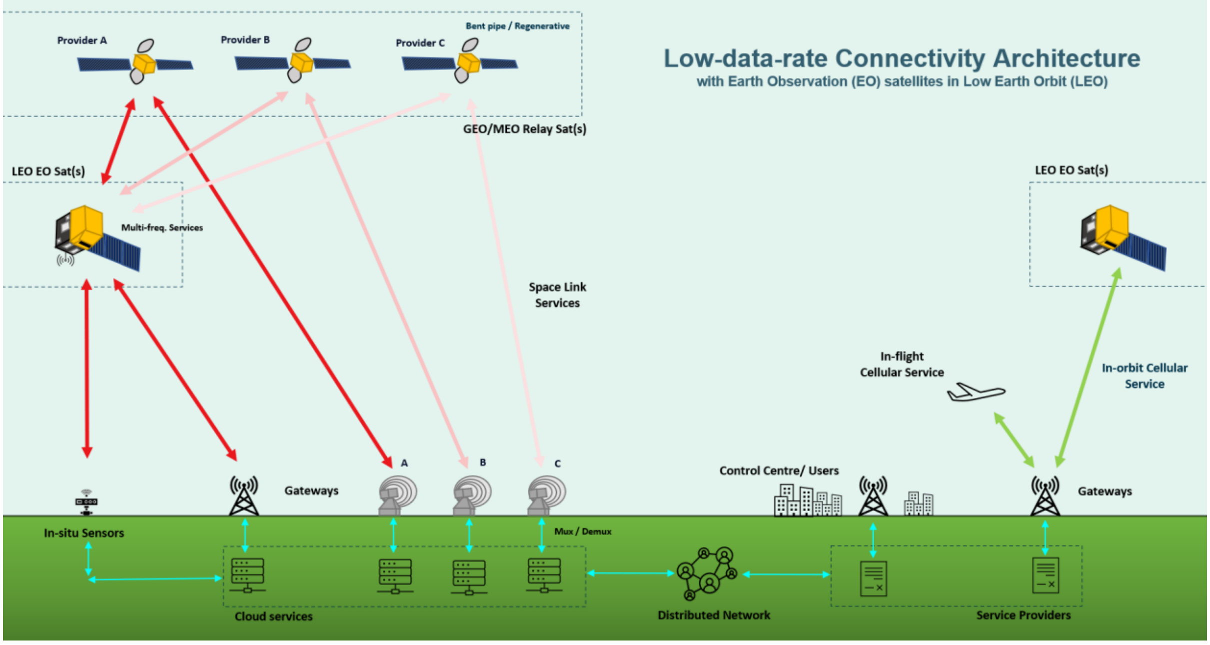

Figure 1 Low-data-rate connectivity architecture with Earth Observation (EO) satellites in Low Earth Orbit (LEO)

It is acknowledged that federating and facilitating global and near-permanent connectivity with EO satellites in LEO, whilst ensuring scalability, availability, and longevity, will require an integrated network infrastructure with services that are **provider-agnostic** (Section 3.5), bi-directional and of low complexity and cost. In this respect, it will be important to standardize enabling parts of the system that facilitate interoperability, and to establish technology roadmaps that support any necessary standardization. However, it is important to recognize that achieving full interoperability with existing terrestrial IoT networks (i.e., Ground-To-Ground, European Aviation Network (EAN)), which typically support a very large user base, is challenging and impractical due to our unique system constraints in LEO and a rather small EO satellite user base. Therefore, we define **interoperability** in the scope of low-data-rate connectivity architecture with EO satellite in LEO as the following:

"The capability of diverse systems, devices, or software applications to communicate effectively, ensuring that they can exchange and interpret shared data accurately across various platforms and environments"

In this context, **ubiquitous connectivity** with LEO satellites is understood as the consistent and widespread availability of connections that are always present or soon to be accessible. This ensures near-constant communication among nodes through various networks, independent of the provider. From a user's perspective, ubiquitous connectivity is the uninterrupted transfer of low-volume data packets across various networks, arriving at the user's desk without requiring any intervention. However, considering the IoT4EO vision's commitment to **provider-agnostic**, bi-directional services are in principle both low in complexity and cost, however, attaining this level of service using standard Telecommand (TC) packets through this link or a standard Ground Station (GS) network might still prove to be exceptionally challenging. The optimal strategy for arriving at a solution involves a system that is both flexible and scalable, guided by Size, Weight, and Power (SWaP) constraints in LEO Spacecraft, and **discrete event messaging**, rather than total continuous connectivity to ensure **low complexity and cost**.

It is also strategic to **leverage** technical **solutions from existing terrestrial services** that are **protocol agnostic** and offer a range of options within Low-Power Wide-Area Network (**LPWAN**) technologies, e.g., LoRaWAN, LTE-M, NB-IoT, Sigfox and even Bluetooth. This approach is particularly useful in scenarios where brief non-connections may occur (e.g. when the network of ground gateways is not extensive enough). These technologies have recently **demonstrated** their capability for low-power and low-data-rate connectivity, including successful applications of LoRa and Bluetooth connectivity **in space**.

While the concept of a low-data-rate connectivity architecture originated from the proliferation of Internet of Things (IoT) technology on Earth, in this "***Service Definition & Preliminary Specification***" document, we purposefully avoid specific IoT terminology in favor of a more general discussion of low-data-rate connectivity. This approach reflects the fact that the technical solutions for these services have often been demonstrated to be protocol agnostic, with a variety of options available within Low-Power Wide-Area Network (**LPWAN**) technologies i.e., LoRaWAN, NB-IoT, and others. Thus, whenever **IoT terminology** appears in this document, please interpret it **in the broadest and most general sense possible**.

2.1.1 IoT4EO Objectives

The IoT4EO vision encompasses the development an **interoperable low-data-rate connectivity** architecture that serves as the foundation for establishing **ubiquitous**, global, and near-permanent connectivity to Earth Observation (EO) satellites in Low Earth Orbit (LEO). This vision is characterized by several key high-level objectives, which are important for requirement traceability and translation, justification of design decisions, anticipation in the verification of the system, and are frequently referenced throughout the project's evolution to maintain a systems perspective. The IoT4EO Vision objectives are as follows:

Objective 1: To establish and develop an interoperable framework for low-data-rate connectivity with Earth Observation (EO) Satellites in Low Earth Orbit (LEO)

- **OBJ 1.1:** To identify the **key elements** of an interoperable IoT4EO **framework** that can expedite its deployment and adoption among EO Satellite End Users (UE) and Service Providers. Prioritization shall focus on the re-use of well-established **commercial elements**, while developing new components or standards to ensure the systems interoperability, ubiquity and provider-agnostic nature.

- **OBJ 1.2:** To ensure that the low-data-rate **connectivity services** are operational, featuring ubiquitous and provider-agnostic capabilities that can scale to support at least **500** Earth Observation (EO) Satellites in Low Earth Orbit (LEO) [1] , alongside a scalable ground infrastructure (i.e., gateways, in-situ sensors).

Objective 2: To enable and operationalize new services, applications, and use cases that add value to satellite operations and facilitate the integration and co-location of satellite and non-satellite measurements

- **OBJ 2.1:** To improve **operational** efficiency and **responsiveness** of Earth Observation (EO) satellites through **dynamic satellite tasking**, quick retrieval of on-board event-detected information, and near-real-time data sharing across global networks by **at least one** *(10^1)* **or two** *(10^2),* **orders of magnitude** compared to traditional telemetry, tracking, and command (TT&C) systems with a single ground station.

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[1] Celestrak, a recognized resource in the aerospace sector, provides updated listing satellites. These numbers fluctuate due to ongoing satellite launches and deorbiting events. For precise alignment with real-time data and to ensure accurate comparisons or analyses, stakeholders are advised to consult the latest datasets available (www.celestrak.org)

- **OBJ 2.2:** To strengthen, align and federate **in-situ scientific measurements** with **systematic Earth observation data** to improve calibration and validation processes, enabling higher automation and offering greater reliability and scope in scientific measurements.

Objective 3: To develop standardized technology and regulatory Elements that streamline low-data rate technology integration and ensure interoperability with existing systems

- **OBJ 3.1:** To develop **standardized** technology that ensures interoperability, provider-agnostic services, and scalability, that ensure technical **compatibility** between end-user Earth Observation (EO) systems, existing relay satellite systems, and ground gateways to simplify adoption for various stakeholders.

- **OBJ 3.2:** Identify and align with the existing **regulatory** landscape (e.g., ITU, 3GPP, LoRa Alliance), ensuring compliance with current regulations and actively participating in proposing and applying modifications to existing standards or frameworks where necessary.

- **OBJ 3.3:** To develop, test and validate **technology demonstrators**, including breadboards and flight models, ensuring they meet interoperability, performance, and operational requirements

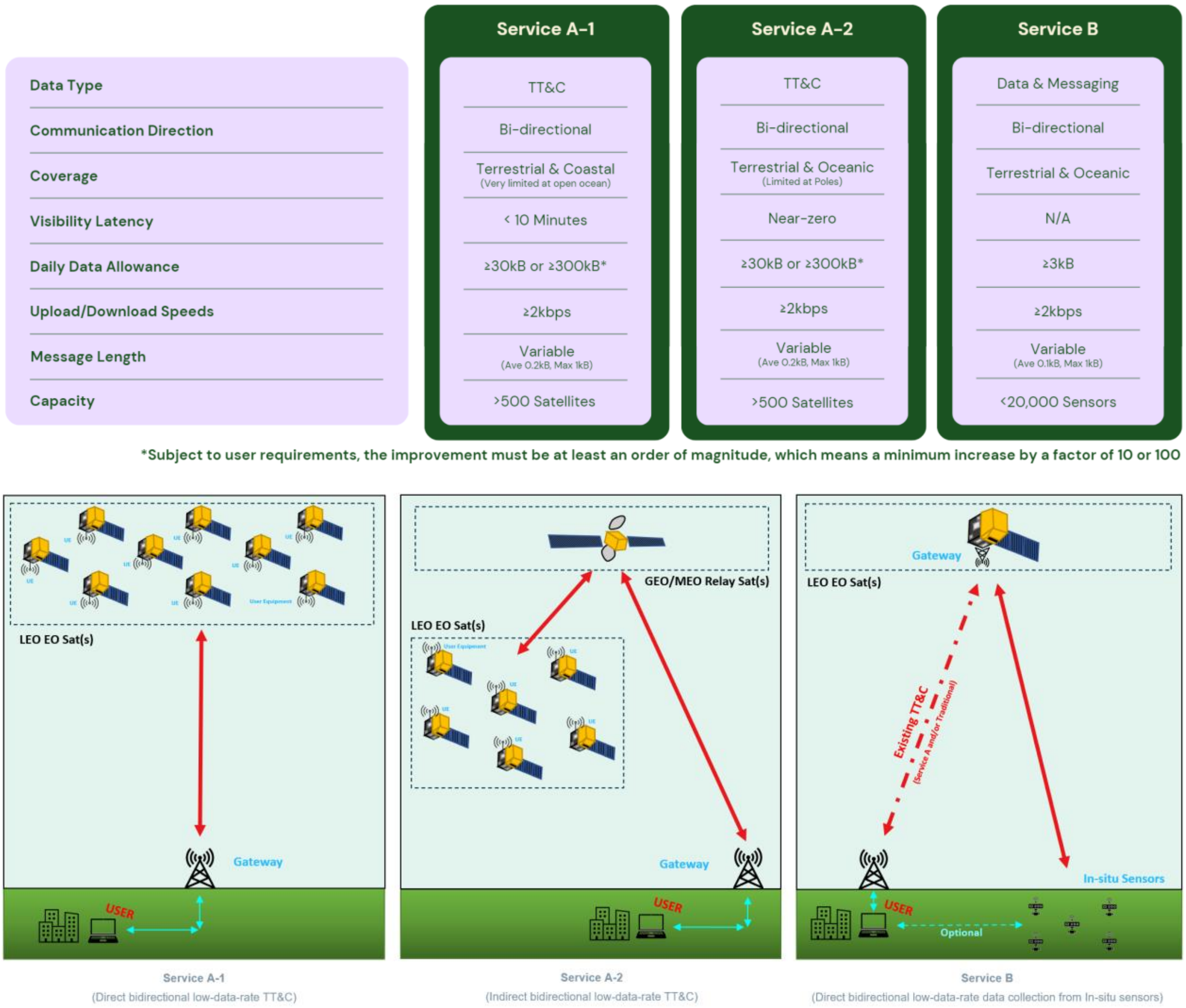
- **OBJ 3.4:** To verify and validate that the **new services**, applications, and use cases meet the needs of end-users and deliver the intended added value in satellite operations and data calibration and validation (CAL/VAL) processes.

The IoT4EO objectives are leveraged as a reference for translating and tracing the service and system requirements. They are defined and referenced frequently to allow traceability at every stage of development, ensuring a system perspective is maintained.

3 IoT4EO Service Definitions & Stakeholders

3.1 General Service Definitions

This section outlines the services identified from the "Concepts for the use of IoT in Earth Observation" parallel studies performed under ESA Contracts [**RD-2**] and [**RD-3**]. This involved an in-depth exploration of use cases and applications (see Table 1) , iterations through an IoT4EO Network architecture and CONOPS for two scenarios: (1) considering re-use of current capabilities, and (2) with more substantial developments, as well as a market survey on LPWAN services, technologies, in-situ sensors, protocols, and security measures. Although a thorough examination of the regulatory framework and preliminary discussions on frequencies and roadmaps were performed, these details are not included in this document because we consider that it should be possible to develop highly integrated equipment with multi-frequency flexibility. The goal of this section is to capture and elucidate **User Requirements** from the **perspective of service provision**, deliberately setting aside technical engineering solutions at this stage.



	Service A-1	Service A-2	Service B
Data Type	TT&C	TT&C	Data & Messaging
Communication Direction	Bi-directional	Bi-directional	Bi-directional
Coverage	Terrestrial & Coastal (Very limited at open ocean)	Terrestrial & Oceanic (Limited at Poles)	Terrestrial & Oceanic
Visibility Latency	< 10 Minutes	Near-zero	N/A
Daily Data Allowance	≥30kB or ≥300kB*	≥30kB or ≥300kB*	≥3kB
Upload/Download Speeds	≥2kbps	≥2kbps	≥2kbps
Message Length	Variable (Ave 0.2kB, Max 1kB)	Variable (Ave 0.2kB, Max 1kB)	Variable (Ave 0.1kB, Max 1kB)
Capacity	>500 Satellites	>500 Satellites	<20,000 Sensors

*Subject to user requirements, the improvement must be at least an order of magnitude, which means a minimum increase by a factor of 10 or 100

Service A-1
(Direct bidirectional low-data-rate TT&C)

Service A-2
(Indirect bidirectional low-data-rate TT&C)

Service B
(Direct bidirectional low-data-rate data collection from In-situ sensors)

Figure 2 A summary of IoT4EO service features (minimum values for each service).

Two core services were identified as solutions addressing Objective 2, covering all use cases and applications summarised in Table 1 and further detailed in Appendix B this document. They are differentiated by their respective data types and operational objectives, which are shaped by the nature of OBJ2.1 and OBJ2.2:

- **Service A** facilitates bidirectional low-data-rate **telemetry, tracking, and command (TT&C)** exchanges between ground-based gateways and EO satellites, divided into two sub-services (Section 3.3):
    - **Service A-1**: Direct bi-directional connectivity via ground gateway
    - **Service A-2:** Indirect bi-directional connectivity via relay MEO/GEO satellites

- **Service B** facilitates bidirectional low-data-rate data collection and messaging exchanges between **in-situ sensors** and EO satellites (Section 3.3)

The subsequent sections provide a detailed definition and description of low-data-rate connectivity services, including service description and architecture, key features, anticipated applications, use cases, and users. Note that the **values provided in Figure 2 are minimums**, which may be challenging to improve due to link budget limitations. However, other system parameters (e.g., daily data allowance) may be **scalable with service cost**. For further details on scalability, refer to Appendix D.

There is a broad spectrum of network technologies that deliver varying performances, from **cellular** technologies (e.g., 5G NR, LTE-M, NB-IoT) that cover long range and mid to high data rates, and **non-cellular** technologies (e.g., LoRa, SigFox) that cover very low data rates and high ranges (e.g., LoRa, SigFox). As previously discussed, this document purposefully avoids specific IoT terminology to facilitate a more flexible system design. Furthermore, to ensure readability and interoperability across various industries and stakeholders, it is important to adopt a common system definition language.

In this document we use the following **LPWAN** terminology to describe the direction of communication:

- **Upload**: LEO EO **User Equipment (UE / node)** to ground **Gateway**. This differs from EO satellite operations, as telemetry is ‘downlinked’ from LEO satellites to a Ground Station (G/S).
- **Download**: Ground **Gateway** to LEO EO **User Equipment (UE / node)**. This differs from EO satellite operations, as a telecommand is ‘uplinked’ from a Ground Station (G/S) to a LEO satellite.

The proposed low-data-rate connectivity architecture, particularly the links between the on-board UE, in-situ sensors, and Gateways, is expected to utilise **discrete event messaging** rather than maintaining continuous connectivity. This is due to a trade-off between need and implementation cost, geometric constraints (i.e. gateway distribution and GEO/MEO coverage over the poles), and a relatively small user base compared to the terrestrial LPWAN market. Moreover, to facilitate discrete event messaging, the use of a "**not-connected**" protocol or one with expanded features (e.g. for **store-and-forward**) is anticipated. This approach is designed to be **protocol-independent**, aiming to achieve a truly interoperable and **provider-agnostic** solution (Section 3.5).

It is assumed that a discrete event message is optimal; however, additional overheads are necessary (e.g., in a bi-directional context, for system synchronization and responsiveness, and for acknowledgment (ACK) back to the source). These overheads, typically 20%, vary based on protocols and should be added to the minimum service values (e.g., daily data allowance) discussed in this document. Appendix D explores scalability options.

Due to these characteristics, '***visibility latency***' (Appendix A) is anticipated to be in the order of seconds to minutes, particularly when User Equipment (UE) is orbiting above open ocean (in the case of Service A-1) and the poles (In the case for Services A-1 and A-2). This is significant when compared to terrestrial network latencies (i.e. msec) with continuous UE-Gateway visibility; however, the requirement for continuous connectivity—and thus the latency—is driven by the needs of the potential users of the services. It might be, that accessing their satellite within a few minutes in the worst case, as opposed to the traditional 90 minutes (1 LEO orbit), might be acceptable. This document aims to explore and elucidate this need.

Preliminary service specifications, along with some justifications, are detailed in **Section 4** of this document.

3.2 Applications & Use Cases

The following mapping of applications and use cases has been simplified, with **Appendix B** providing more detailed explanations. This mapping illustrates that Service-A (TT&C Exchanges) covers 80% of potential use cases.

Table 1 Applications & Use cases mapped to each service type

Ref. ID	Title	Service	Added Value
UC1	TC to EO Satellite	A-1, A-2	TBD – in IoT4EO Survey in [RD-5]
UC2	TM from EO Satellite	A-1, A-2	TBD – in IoT4EO Survey in [RD-5]

Ref. ID	Title	Service	Added Value
UC3	EO Satellite anomaly signal	A-1, A-2	TBD in IoT4EO Survey in [RD-5]
UC4	In-situ data collection	B	TBD in IoT4EO Survey in [RD-5]
UC5	In-situ sensor activation	B	TBD in IoT4EO Survey in [RD-5]
UC6	EO Satellite quick manoeuvres	A-1, A-2	TBD in IoT4EO Survey in [RD-5]
UC7	Broadcast payload operations	A-1, A-2	TBD in IoT4EO Survey in [RD-5]
UC8	Initiate high-speed downlink	A-1, A-2	TBD in IoT4EO Survey in [RD-5]
UC9	Broadcast Information	A-1, A-2	TBD in IoT4EO Survey in [RD-5]
UC10	Constellation autonomy	A-1, A-2	TBD in IoT4EO Survey in [RD-5]

3.3 Service A: Bi-directional low-data-rate TT&C

Service A offers both:

- *direct* (Service A-1) and
- *indirect* (Service A-2)

bidirectional low-data-rate **telemetry and command (TT&C)** exchanges between ground-based Gateways and Earth Observation (EO) satellites in Low Earth Orbit (LEO). The traditional TT&C solutions lack the necessary global coverage and quick responsiveness required for dynamic satellite operations. This is due to their reliance on limited visibility of the LEO satellite from ground.

3.3.1 Service A: Daily Data Allowance and Upload/Download Speeds

The initial assumption that a single Telecommand (TC) packet size of **≈12kBytes** demonstrated to be too demanding for a low-data-rate connectivity architecture that is based on the emerging terrestrial Low Power Wide Area Network (LPWAN) technologies. This is primarily because a ≈12kB/message is incompatible with the most restrictive protocols (e.g., LoRa) due to their payload size limitations and supporting data rates. This limitation does not affect existing services of a similar nature that use traditional telecommunication technologies and protocols (e.g., Addvalue IDRS offers **200kbps** connectivity for indirect communication (Service A-2) via a GEO relay). These services typically offer subscription plans ranging from 100 to 500MB per month per satellite, which equates to approximately **3 to 15 MB per day** per satellite when scaled down. Therefore, for a low-data-rate connectivity service as described in this document, with data rates reduced by 100 times (i.e., **≥2kbps,** due to link budget limitations), and an improvement in current TT&C operations (assuming one exchange per orbit) by *at least one (10^1) or two (10^2) orders of magnitude,* the performance is driven by the need for:

- 10^1 case: A minimum of 10 messages per orbit (TBC) and approximately 150 messages per day (TBC), which results in a minimum cumulative daily data allowance of 30kB (TBC).
- 10^2 case: A minimum of 100 messages per orbit (TBC) and approximately 1500 messages per day (TBC), which results in a minimum cumulative daily data allowance of 300kB (TBC).

In both scenarios outlined above (i.e., 10^1 or 10^2), the average message size of ≥0.2kB (TBC) is compatible with even the most restrictive protocols (e.g., LoRa), which supports message sizes up to 1kB. It is recognized that message length should be variable and flexible to accommodate the end user's needs. As detailed in Section 3.1 and Appendix A.2 and re-emphasized here, additional **overheads are necessary** (e.g., in a bi-directional context, for system synchronization and responsiveness, and for acknowledgment (ACK) back to the source). These overheads, typically 20%, vary based on protocols and should be added to the **minimum service values** (e.g., daily data allowance) discussed in this document. Appendix D explores scalability options

The order of magnitude of improvement requirement is to be confirmed by end users and feasibility evaluated by service providers based on the low-data-rate connectivity architecture described in this document.

≥30kB or ≥300kB Daily Data Allowance*

Send/receive ≥150 or ≥1500 messages/day/satellite (~0.2kB each, on average) with a cumulative total daily data allowance of ≥30kB or ≥300kB.

≥2kbps Upload and Download Speeds

Data upload/download speeds start at 2 kbps, with priority given to higher-speed transmissions for mission-critical operations

Figure 3 Service A Performance Baseline. It shows (left) An image of an LPWAN/IoT Gateway, (top) Daily Data Allowance and (bottom) Upload/Download speeds, both compatible with LoRa-like and NB-IoT-like protocols.

In his document, it was our intention to decouple these service performance requirements from **Service A-1 and A-2**, as both services **share the same objectives**. As discussed earlier, in this document we purposefully avoid specific IoT terminology in favour of a more general discussion of low-data-rate connectivity, which extends to frequency allocation and to a diverse range of options available within LPWAN technologies e.g., LoRaWAN, Bluetooth, NB-IoT, and others.

3.3.2 Service A-1: Direct bidirectional low-data-rate TT&C

Service A-1 offers *direct* bidirectional low-data-rate telemetry and command (TT&C) exchanges between ground-based **Gateways** and Earth Observation (EO) satellites in Low Earth Orbit (LEO). This service is designed to enable dynamic satellite tasking and distributed telemetry operations, primarily supporting Earth Observation Satellite Operators who are looking to establish near-permanent communication links with their satellites. The key features of Service A-1 are:

Bi-directional TT&C Exchanges

Supports standard telemetry, tracking, and command (TT&C) data types, and offers both uplink and downlink communications.

Global Terrestrial & Coastal Coverage

Continuous and uninterrupted global coverage over terrestrial and coastal areas, capable of extending to a latitude range of ±90°.

< 10 Minute Visibility Latency

Less than a 10 Minute visibility latency over terrestrial and coastal areas, by leveraging a well-distributed gateway infrastructure.

≥30kB or ≥300kB Daily Data Allowance*

Send/receive ≥150 or ≥1500 messages/day/satellite (~0.2kB each, on average) with a cumulative total daily data allowance of ≥30kB or ≥300kB.

≥2kbps Upload and Download Speeds

Data upload/download speeds start at 2 kbps, with priority given to higher-speed transmissions for mission-critical operations

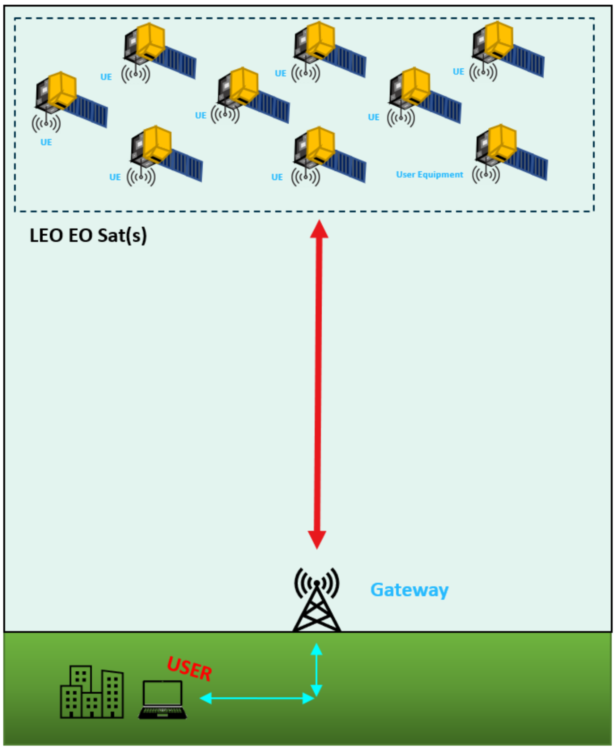


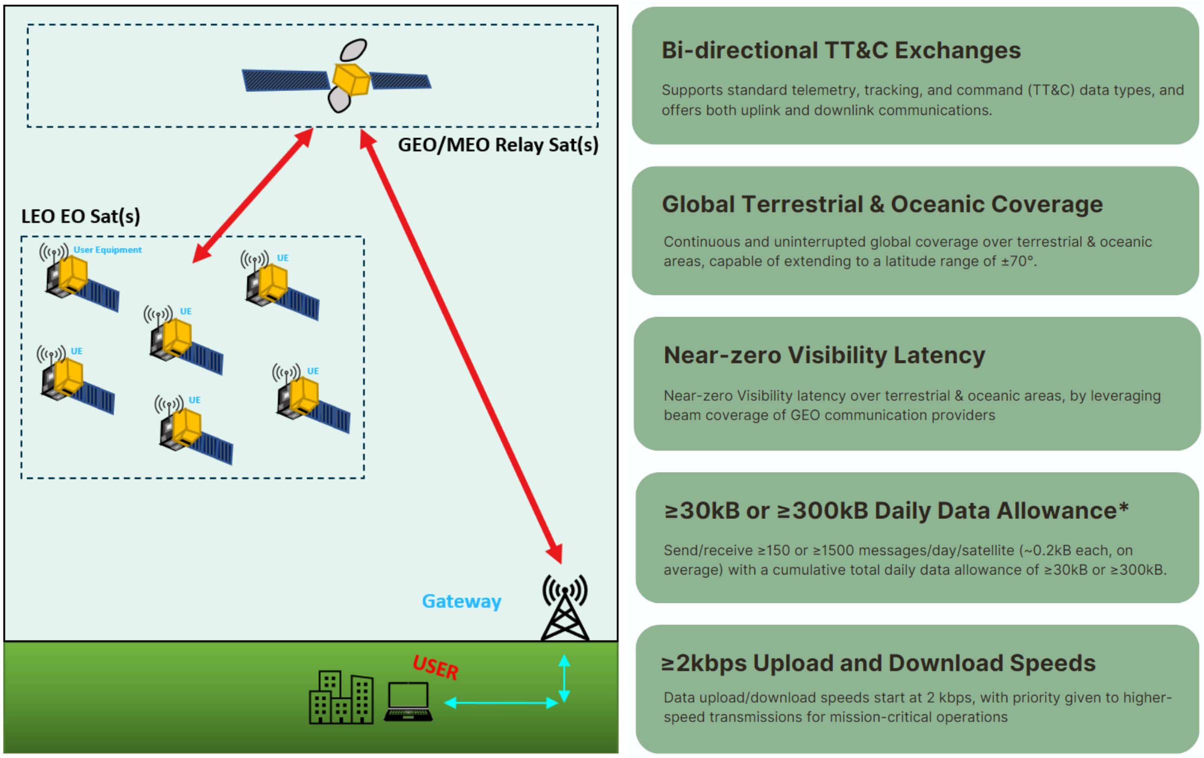
Figure 4 Service A-1: Direct bi-directional low-data-rate TT&C Connectivity Architecture and key features

The strategic deployment and adoption of an extensive and well distributed number of lightweight gateways leveraging LPWAN technologies should enable global coverage (Appendix F 50+ Gateways), covering terrestrial, coastal, polar and oceanic areas in some cases. These Gateways, interconnected through terrestrial networks, could ensure continuous connectivity anytime an Earth observation satellite enters a Gateway's field of view. Despite the lack of open ocean coverage, it benefits from the proximity of Low Earth Orbit (LEO), enabling a direct link that experiences minimal free space loss compared to Service A-2.

3.3.3 Service A-2: Indirect bidirectional low-data-rate TT&C

Service A-2 offers *indirect* bidirectional low-data-rate telemetry and command (TT&C) exchanges between ground-based gateways and Earth Observation (EO) satellites in Low Earth Orbit (LEO), via a Geostationary (GEO) or Medium Earth Orbit (MEO) Relay satellite. This service is designed to enable dynamic satellite tasking and distributed telemetry operations, primarily supporting Earth Observation Satellite Operators who are looking to establish **near-permanent** communication links with their satellites. The key features of Service A-2 are illustrated in Figure 5.

The broad beam coverage of GEO or MEO communication providers, combined with a single or a limited number of lightweight gateways utilizing LPWAN technologies, should enable full global coverage with near-zero visibility latency or near-continuous connectivity over both terrestrial and oceanic areas. Areas beyond ±70-degrees latitude—close to the poles—generally might fall outside the effective coverage area due to the curvature of the Earth and the satellite's fixed equatorial orbit. In comparison to Service A-1, the propagation pathway experiences greater free space loss, however these satellites often compensate by providing high-gain directivity through beamforming, both in the relay satellites and on the ground gateways.



Bi-directional TT&C Exchanges

Supports standard telemetry, tracking, and command (TT&C) data types, and offers both uplink and downlink communications.

Global Terrestrial & Oceanic Coverage

Continuous and uninterrupted global coverage over terrestrial & oceanic areas, capable of extending to a latitude range of ±70°.

Near-zero Visibility Latency

Near-zero Visibility latency over terrestrial & oceanic areas, by leveraging beam coverage of GEO communication providers

≥30kB or ≥300kB Daily Data Allowance*

Send/receive ≥150 or ≥1500 messages/day/satellite (~0.2kB each, on average) with a cumulative total daily data allowance of ≥30kB or ≥300kB.

≥2kbps Upload and Download Speeds

Data upload/download speeds start at 2 kbps, with priority given to higher-speed transmissions for mission-critical operations

Figure 5 Service A-2: Indirect bi-directional low-data-rate TT&C Connectivity Architecture & key features

Overall, Service A-1 and A-2 can provide substantial benefits for Earth Observation, particularly in scenarios requiring rapid response times—from observation request initiation to data delivery—including **human activity**, disaster response and emergencies, which typically have latency requirements of only **a few minutes.**

3.4 Service B: Bi-directional low-data-rate data collection from in-situ sensors

Service B offers bidirectional low-data-rate data and messaging between ground-based in-situ sensors (which are often battery-powered), and Earth Observation (EO) satellites in Low Earth Orbit (LEO). This service is designed to enable co-located (in space and in time) in-situ (ground) and EO satellite measurements to improve calibration and validation (CAL/VAL) processes and may autonomously trigger and enable spontaneous observation requests from the Mission Control Centre (MCC). It primarily supports EO data providers and users who are looking to offer greater responsiveness, facilitate automation in the federation of data, and increase the scope in scientific measurements derived from multiple EO data space and in-situ sources.

3.4.1 Service B: Daily Data Allowance and Upload/Download Speeds

The typical data volume for an in-situ sensor transmitting data via local area network or satellite can vary based on the application, transmission frequency, and data type. Small-scale sensors (e.g., temperature, humidity) typically generate very small data packets, often between **10 - 200 bytes per message**. In contrast, larger data applications (e.g., cameras, advanced environmental sensors) can transmit data volumes ranging from kilobytes to megabytes per session. Despite this, the transmission of large data volumes is not common in standard IoT applications over satellite, primarily due to cost and bandwidth limitations. In current satellite-based IoT systems, particularly those using Low Power Wide Area Network (LPWAN) technologies (e.g., LoRaWAN, NB-IoT, Sigfox), data volumes are purposely kept minimal to manage costs and power consumption effectively.

There is a broad spectrum of network technologies that deliver varying performances, from **cellular** technologies (e.g., 5G NR, LTE-M, NB-IoT) that cover long range and mid to high data rates, and **non-cellular** technologies (e.g., LoRa, SigFox) that cover very low data rates and high ranges (e.g., LoRa, SigFox). In this scenario, **non-cellular LPWAN** technologies (e.g. LoRa, SigFox) establish the baseline for data allowance and upload/download speed performance. Therefore, by leveraging established standard practises from the existing IoT constellation landscape—and without requiring an order of magnitude improvement in operational efficiency and responsiveness (i.e., OBJ2.1)—Service B provisionally offers the possibility of **at least two messages per in-situ sensor(s) per orbit**, which corresponds to about **30 messages per in-situ sensor per day** to Low Earth Orbit (LEO).

The two messages per orbit is **arbitrary** and depends on:

- Application (e.g. Acknowledgement (ACK) requirement),
- Visibility opportunities (e.g. In-situ sensor latitude and orbit)

For more detailed information on this topic, refer to Section 4.3 IOT4EO-PRF-320. Moreover, it is worth noting note that each in-situ sensor (i.e. User Equipment (UE)/Node) might want to connect to multiple LEO EO Satellites (i.e., LEO Gateways). Section 4.4 explores scalability requirements.

This results in a **daily data allowance** of at least 3kB per sensor (TBC), aligning with established IoT standards that typically feature **message sizes of 100 Bytes or more.** However, it is likely that the service would usually be offered in **SERVICE BUNDLES** (e.g., 100 sensors with 0.3 MB, or 1,000 sensors with 3 MB). This document describes it this way to provide granularity down to a single sensor to characterize the link. Initial link budgets, even from battery-based in-situ sensors, indicate that connectivity to LEO EO satellites at **≥2kbps** data rates should be possible.

≥3kB Daily Data Allowance

Send/receive ≥30 messages/day/sensor (~0.1kB each, on average) with a cumulative total daily data allowance of ≥3kB.

≥2kbps Upload and Download Speeds

Data upload/download speeds start at 2 kbps, with priority given to higher-speed transmissions for mission-critical operations

Figure 6 The current performance baseline for service B. It shows (left) An image of an in-situ sensor, (top) Data Allowance and (bottom) Upload/Download speeds, both compatible with LoRa-like and NB-IoT-like protocols.

As for Service A, additional **overheads are necessary** (e.g., in a bi-directional context, for system synchronization and responsiveness, and for acknowledgment (ACK) back to the source). These overheads, typically 20%, vary based on protocols and should be added to the **minimum service values** (e.g., daily data allowance) discussed in this document. Appendix D explores scalability options

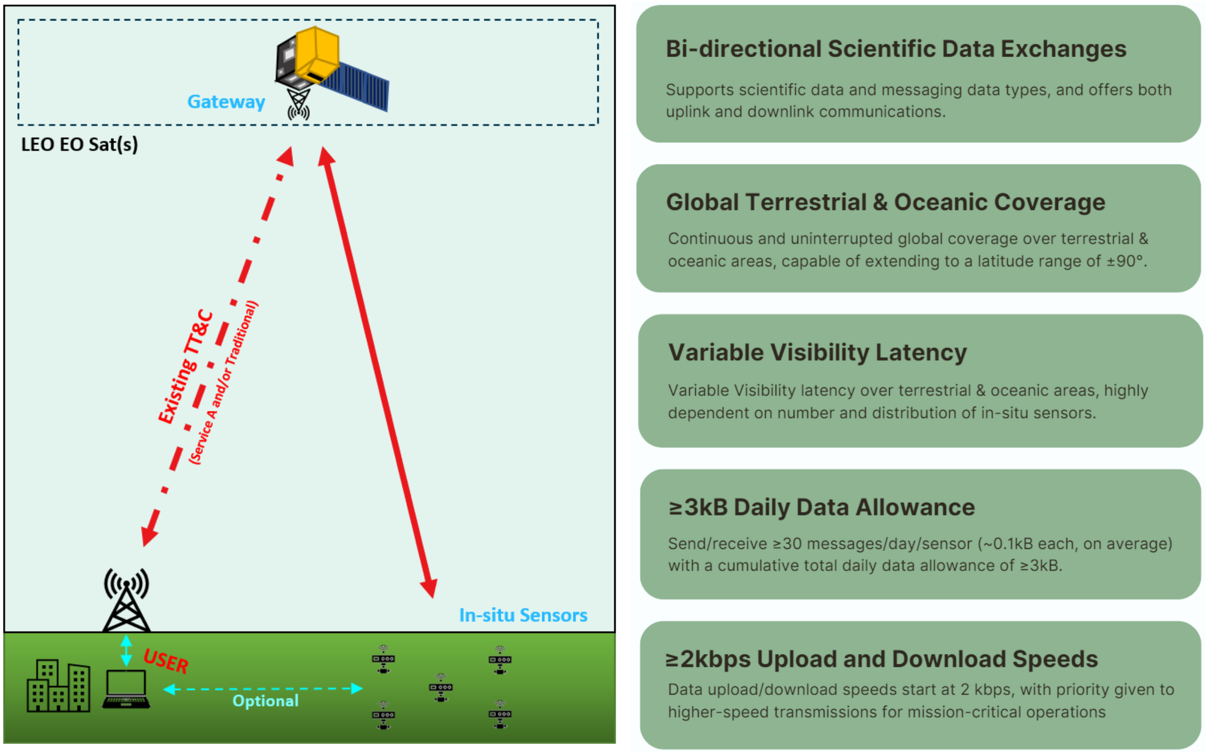
It should be noted that to directly notify an in-situ sensor from an EO Satellite ahead of its ground track—thus preparing it for data collection and transfer, or as part of an alert system for environmental disasters, and to dynamically task the satellite to target the area with the in-situ sensors—this service may need to be used in conjunction with other TT&C services (e.g. Service A-1 and/or A-2, or classical TT&C).

3.4.2 Service B: Direct bi-directional low-data-rate data collection from in-situ sensors

Service B offers *direct* bidirectional low-data-rate data and messaging between ground-based in-situ sensors and Earth Observation (EO) satellites in Low Earth Orbit (LEO) orbit. This service is tailored for direct data collection and transfer between the ground sensors and the satellite. In this setup, the **satellite** functions as a **Gateway**, communicating with multiple in-situ sensors (i.e., User Equipment (UE)/Nodes) through Service B, and with the Mission Control Centre (MCC) and end-users through Service A-1 and/or A-2, or classical TT&C. Thus, the system terminology adopted here is reversed compared to Service A and more closely resembles the terminology used in the earth observation industry.

- **Upload**: Ground **User Equipment (UE / node)** to LEO EO **Gateway**. This refers to communication from ground-based in-situ sensors (UE) to the LEO EO satellite (Gateway).
- **Download**: LEO EO **Gateway** to ground **User Equipment (UE / node)**. This refers to communication from the LEO EO satellite (Gateway) to ground-based in-situ sensors (UE).

The IoT Constellation landscape is already well-developed, with a variety of providers operating IoT Constellations in LEO Orbit and utilizing Low Power Wide-Area Network (LPWAN) technologies for in-situ and IoT data collection. As done today, in-situ validation of EO measurements systems is already performed with sensors distributed near the satellite ground track, their data is used to calibrate the measurements made by the satellite as it passes overhead. **Rather than competing, this service aims to complement by providing a scalable solution that** can facilitate the automation and federation of co-located in-situ and remote sensing measurements, across spatial and temporal dimensions.



Bi-directional Scientific Data Exchanges

Supports scientific data and messaging data types, and offers both uplink and downlink communications.

Global Terrestrial & Oceanic Coverage

Continuous and uninterrupted global coverage over terrestrial & oceanic areas, capable of extending to a latitude range of ±90°.

Variable Visibility Latency

Variable Visibility latency over terrestrial & oceanic areas, highly dependent on number and distribution of in-situ sensors.

≥3kB Daily Data Allowance

Send/receive ≥30 messages/day/sensor (~0.1kB each, on average) with a cumulative total daily data allowance of ≥3kB.

≥2kbps Upload and Download Speeds

Data upload/download speeds start at 2 kbps, with priority given to higher-speed transmissions for mission-critical operations

Figure 7 Service B: Indirect bi-directional low-data-rate TT&C Connectivity Architecture & key features

This low-data-rate connectivity architecture, supported by the advanced on-board intelligence capabilities, might enable much higher reactivity based on autonomous satellite decisions in real-time to immediately monitor events using data or signals triggered from in-situ sensors. A service of this quick reactivity and nature could bring great value into, for example, the international space charter for disaster response. It should also enable EO data providers and vertically integrated EO companies to deploy in-situ sensors, helping to overcome the common limitations associated with a lack of onboard calibration tools.

Refer to Appendix D for the Service Summary Table, which outlines **scalability** considerations for certain service parameters that may impact service costs. Initial specifications are detailed in Section 4.

3.5 IoT4EO Provider-Agnostic System Architecture

This section, which is further detailed in Appendix E, explores the **interoperability** landscape of a low-data-rate connectivity architecture to identify interventions where standardization can enable an IoT4EO provider-agnostic solution. The objective of having a Provider-Agnostic system is to quickly **build up the scalability** of the envisaged services for 500+ EO satellites in LEO orbit and increasing number of ground Gateways and accessibility to thousands of in-situ sensors. Thus, the inclusion of an *'IoT4EO Provider-Agnostic System Architecture'* in this document aims to stimulate stakeholders, users, and service providers to identify their location in the '*value chain'* of the service provision. This is expected to further define the system later in the development process and support the creation of a standardization and interoperability action plan. Two complementary approaches have been identified:

- **Modification to Existing Standards** → Identify existing standard elements that vary across service providers and suggest modifications to unify them. This task is particularly challenging due to the existing systems across industries and technologies sharing the same standards, where modifications can have a ripple effect. Additionally, the relatively small size of the IoT4EO market means there is limited momentum to implement significant changes.

- **Middle-Out Engineering Approach** → Identify system elements and interfaces that vary across service providers and develop a middleware architecture or standard that enables technology solutions to integrate with existing systems without altering current standards. A focus on middleware development ensures common middleware standards for all providers.

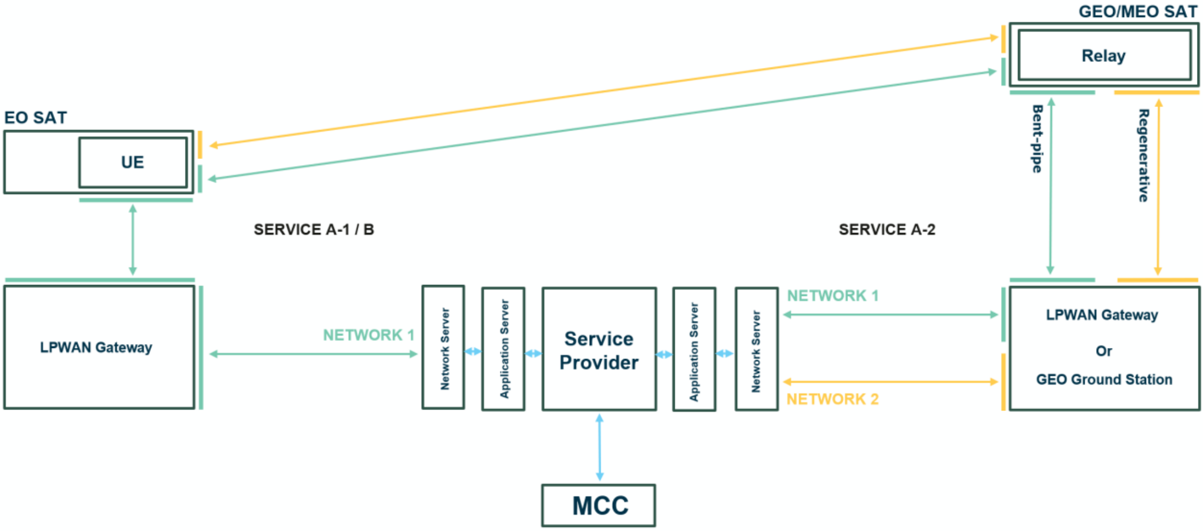


Figure 8 A simplified IoT4EO Provider-Agnostic System Architecture for Service A-1 (left) and A-2 (right)

A more elaborated and detailed Provider-Agnostic System Architecture is provided in Appendix E.1, expanding on Figure 8. Two potential architectures have been identified:

- **Bent-pipe Architecture** in the Relay satellite, featuring common paths (highlighted in green) shared by both Service A-1 (direct space-to-ground) and Service A-2 (via the Relay satellite).
- **Regenerative architecture** in the Relay satellite, where Service A-2 follows a distinct path (shown in yellow) from that of Service A-1 (shown in green).

In either of these system architectures, the user equipment (UE) must be engineered for interoperability across various network frameworks to ensure compatibility with a range of frequencies and protocols (e.g., NB-IoT, LoRaWAN, DVB-S) based on identified solutions. This **middle-out** engineering approach focuses on developing middleware capable of interfacing with both existing and future systems across various service providers and aims to establish **common middleware standards** that promote a **provider-agnostic** solution and stimulate competitiveness and scalability within the service provision.

Service B should also benefit from the scale that could be achieved under a provider-agnostic architecture, which would give access to a larger number of ground in situ-sensors and LEO Gateways. However, scaling up will raise several questions, incl. which stakeholders will manage the LEO Gateways, and what business agreements will be necessary among stakeholders (see section 3.6). These considerations are outside the scope of this document but will undoubtedly play an important role in the future.

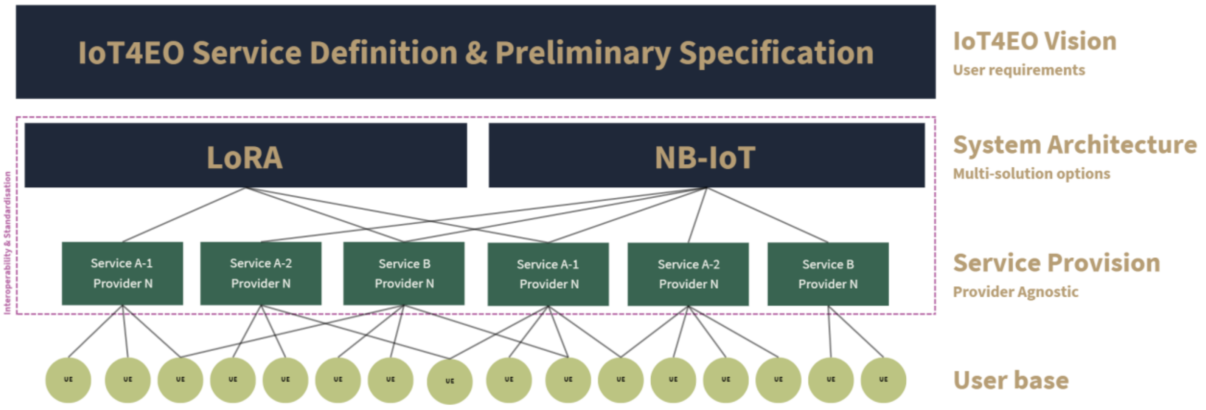


Figure 9 Example of IoT4EO System Architecture Standardization Snapshot. Note: Although two solutions, LoRa and NB-IoT, are mentioned here, this document continues to remain solution agnostic

The System Architecture is complex and will affect multiple stakeholders in the area of User Equipment, Gateways, Regulatory and Network management. Flexible approaches (e.g. use of SW Defined Radio, SDR) in UE equipment will be needed to ensure the scalability towards a Provider-Agnostic architecture.

For further details on interoperability and a provider agnostic architecture, refer to Appendix E.

3.6 Stakeholders

This section explores the potential stakeholders in the low-data-rate connectivity architecture, including those expected to use the service, those who assist in its development and provision, and third parties impacted by it.

Table 2: Potential end users

User	Description
EO Satellite Provider	Manufacturers, from major integrators to smaller firms, that are developing Earth Observation (EO) satellites and integrating new LPWAN equipment to facilitate the use of novel LPWAN services for seamless ground connectivity. These manufacturers must subscribe to LPWAN services and, in some cases, are the same entities as the EO Satellite Operators
EO Satellite Operators	Satellite operators with a Mission Control Center (MCC) that are looking to improve their traditional telemetry, tracking, and command (TT&C) systems (e.g., Improved autonomy, dynamic tasking) by adopting the new, cost-effective, and ubiquitous capabilities provided by LPWAN from Service Providers in Service A-1 and A-2. Service B could be provided through multiple LEO Gateways either by an Earth Observation (EO) Satellite Operator or by a different entity under an agreement with the EO Satellite Operator (TBC).
EO Data Providers	Data providers that seek to coordinate and integrate multi-source EO data measurements, typically from co-located (in time and space) satellite and in-situ measurements, to produce better calibrated and validated (CAL/VAL) products. This integration could also streamline the creation of higher-level products that are readily usable by EO Data Users.
EO Data Users	Data Users, which may include research or operational institutions, that integrate complex EO data products or utilize pre-processed data products provided to them for strategic decision-making

User	Description
In-situ Sensor Users / Operators	Entities that utilize in-situ sensors and integrate User Equipment (UE) compatible with new services that interact with remote sensing Earth Observation (EO) satellites in Low Earth Orbit (LEO). In-situ sensors might be mission specific, where the EO Data Providers might coordinate and manage their subscription to the IoT4EO low-data-rate services. Alternatively, they could be more generic (e.g., ocean buoys) and their operators should integrate User Equipment (UE) with generic services to connect with standard LEO EO satellites.

Table 3 Service provision value chain

Service Providers	Description
Ground Station Operators	Operators of traditional ground stations that handle traditional TT&C services, often from polar latitudes, managing essential communications systems for robust mission support.
LPWAN Gateways Operators	Operators that could manage new low-data-rate services to achieve ubiquitous connectivity with LEO EO satellites, utilizing APIs for system integration and Gateway registration. The Gateway operators for Service A (TT&C) will likely differ from those for Service B (Data), due to distinctions in the physical and topological locations of the gateways—namely, the gateways in Service B are located on the LEO EO satellites.
Network Server Operators	Network and Application server operators that maintain critical infrastructure for network, application, and join servers, providing APIs for data communication and device integration across technologies.
GEO/MEO Relay Operators	Operators that manage GEO satellite systems to facilitate communications between EO satellites and terrestrial Gateways, especially over remote oceanic areas.
In-situ Sensor Operators	Entities that utilize in-situ sensors and integrate User Equipment (UE) compatible with new services that interact with remote sensing Earth Observation (EO) satellites in Low Earth Orbit (LEO). In-situ sensors might be mission specific, where the EO Data Providers might coordinate and manage their subscription to the IoT4EO low-data-rate services. Alternatively, they could be more generic (e.g., ocean buoys) and their operators should integrate User Equipment (UE) with generic services to connect with standard LEO EO satellites.
LPWAN User Equipment Manufacturers	Manufacturers that produce terrestrial or LEO LPWAN User terminals including hardware components and communication protocols tailored to the envisioned low-data-rate services. This equipment must be integrated into EO LEO satellites, terrestrial Gateways, and ground-based in-situ sensors.

Table 4 Third party stakeholders

Service Providers	Description
International Telecommunication Union (ITU)	The ITU Radiocommunication Sector, or ITU-R, coordinates radio-frequency spectrum and satellite orbits worldwide. It sets standards for radio equipment and systems and develops technical guidelines for ensuring radio spectrum frequencies are used safely and efficiently.
National Frequency Administrations	Local entities allocate and manage frequency spectrum, ensuring compliance with both national and international regulations to optimize spectrum use and prevent interference.

The aim is to encourage stakeholders to identify their roles within the *'IoT4EO Provider-Agnostic System Architecture*' introduced in Section 3.5, by mapping their location within the value chain and identifying potential areas for standardization to develop an interoperable middleware solution. For example, LPWAN Gateway Operators could capitalize on the opportunity to develop and distribute ground Gateway infrastructure, offering 'shared' access via a flexible, interoperable interface.

In this scenario, an intervention point for Space Agencies could then be:

- Promote the development of middleware standards that ensure compatibility between User Equipment (UE), Gateways and LPWAN & GEO/MEO Relay Operators' frequencies and protocols.
- Facilitate and support interaction with other commercial Operators of the system. This arrangement should alleviate the burden on potential end users by eliminating the need to manage the development, deployment, and maintenance of existing infrastructure and services.

4 IoT4EO Service Requirements

4.1 Requirements Translation & Traceability

The following section outlines the translation of requirements to clarify the origin and progression of project needs, ensuring they are accurately implemented and traceable at every stage of development:

- **Customer/User Needs**: These are the needs and desires of potential users of the proposed low-data-rate connectivity services e.g., EO Data providers, EO Data users.
- **IoT4EO Vision:** These are the objectives (Section 2) envisioned by the ESA IoT4EO team to provide ubiquitous low-data-rate connectivity to Earth observation satellites in Low Earth Orbit (LEO).
- **Service A & B Requirements**: These requirements elucidate user needs and desires from the perspective of service provision, deliberately setting aside technical engineering requirements at this stage. The service definitions are detailed in Section 3 of the "***IoT4EO Service Definitions and Preliminary Specification***" document. The preliminary specification is covered in Sections 4.2 to 4.8.
- **System Requirements**: These requirements relate to the system and network aspects of the low-data-rate connectivity architecture, derived from all the previously mentioned components. They describe the functional behaviour and technical architecture of the system. They are captured in the ''***System Definition and Preliminary Specification***'' document, which will serve as a source for deriving subsystem requirements. This document has not been written yet and will be developed based on the evolution of the Service Specification.

The following block diagram outlines the thought process and proposed method for translating requirements and ensuring their traceability from the source to the system level. This formed the basis of this document and serves as a starting point for discussion at IoT4EO Workshop 2 [**RD-5**]. This discussion aims to invite feedback from EO Users and potential Service Providers, enabling them to influence the direction and framework of the efforts. It promotes a collaborative approach towards standardizing and validating technology to ensure interoperability, scalability, and easy adoption among various stakeholders.

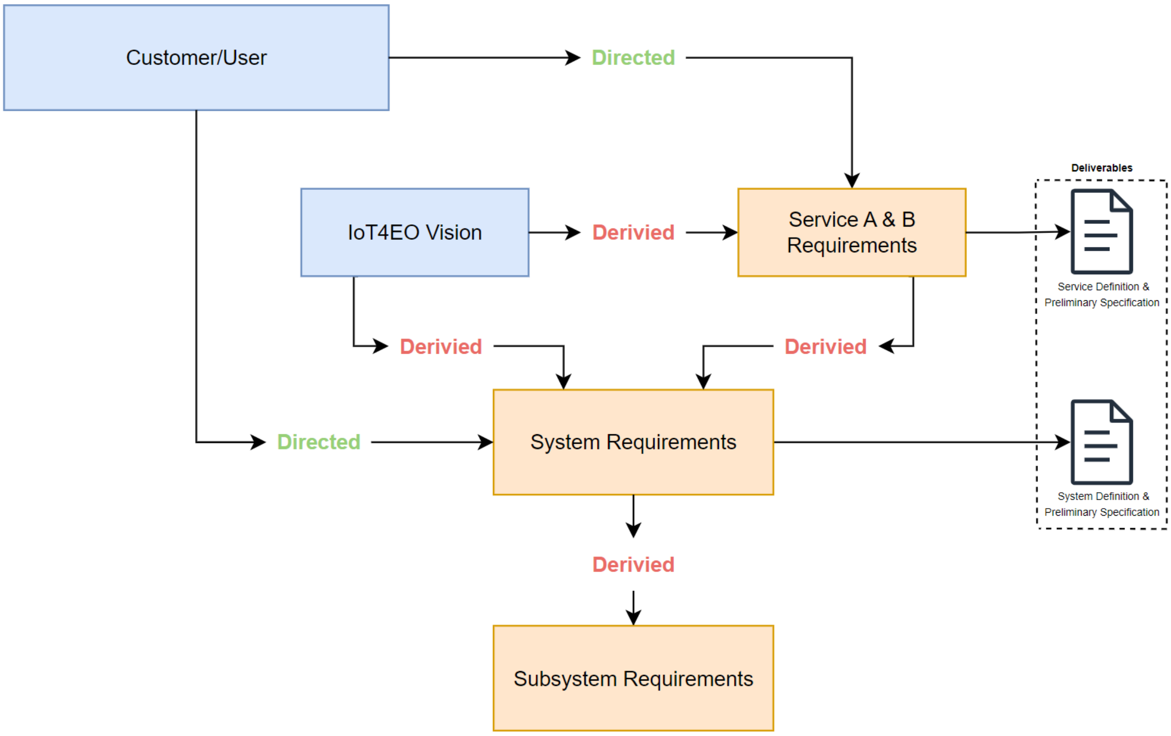


Figure 10 Low-data-rate connectivity architecture Requirements Translation & Traceability block diagram

The following sections detail user needs by translating them into Service Requirements from the perspective of service provision, deliberately setting aside technical engineering requirements at this stage.

4.2 Service Requirements Identification

All requirements in this document are uniquely identified according to the following convention:

- IOT4EO-XXX-nnn

Where:

- IOT4EO represents Low-data-rate Connectivity Architecture
- ‘XXX’ represents the requirements group identifier.
- ‘nnn’ represents the requirement number.

The following requirement group identifiers are defined:

Table 5 Requirement group identifiers

Identifier	Scope of Service Requirement
PRF	Performance Requirements
QOS	Quality of Service (QoS) Requirements
SCL	Scalability Requirements
SEC	Data Security and Privacy Requirements
REG	Legal and Regulatory Requirements
INT	Interoperability Requirements

4.3 Performance Requirements

The performance-defining requirements listed below were identified, where the first digit in the 'nnn' sequence indicates the specific service as identified in this document (i.e., '1nn' for Service A-1, '2nn' for Service A-2, and '3nn' for Service B).

Table 6 Service A-1 (*Direct, via gateway*) - Performance defining requirements

Identifier	Requirement (Service A-1)
IOT4EO-PRF-100	The service (A-1) shall support bi-directional standard telemetry, tracking, and command **(TT&C)** data types to ensure interoperability and effective communication between the Earth Observation satellites and ground Gateways.
IOT4EO-PRF-110	The service (A-1) shall offer **minimum data upload** and **downloads speeds** of at least 2 kbps (TBC) in nominal operation conditions, with higher speeds prioritized for mission-critical business services. **Note:** The speed is limited by the link budget of this system, designed to provide a ubiquitous and cost-effective solution for multiple users simultaneously **Note:** Although the link budget may support higher speeds, the minimum speed is maintained at the same value for both Services A-1 and A-2 to ensure consistency **Note:** The system definition language adopted for Service A-1 and A-2 follows terminology adopted in LPWAN systems, as is defined as follows: • **Upload**: LEO EO User Equipment (UE/node) to ground Gateway. • **Download**: Ground Gateway to LEO EO User Equipment (UE/node).

IOT4EO-PRF-120	The service (A-1) shall provide <10 minutes (TBC) **'visibility' latency** over terrestrial and coastal areas within a latitude range of ±90°(TBC), subject to practical limitations of gateway deployment at the poles. **Note:** This visibility latency is driven by the distribution of terrestrial Gateways and their coverage over terrestrial and coastal regions. A zero visible latency is geometrically impossible in this scenario with land-based Gateways, but feasible if visibility latency is measured only over terrestrial and coastal region coverage. **Note**: A scenario example is provided in Appendix-F with 50+ LPWAN Gateways.
IOT4EO-PRF-130	The service (A-1) shall offer each satellite the ability to send and receive at least 10 or 100 messages (TBC) **per orbit** or a minimum of 150 or 1500 (TBC) **messages per day**. **Note:** The order of magnitude of improvement with respect to one message per orbit is to be confirmed by end users: • 10 messages per orbit, 150 messages per day refer to a 10^1 improvement • 100 messages per orbit, 1500 messages per day refer to a 10^2 improvement
IOT4EO-PRF-140	The service (A-1) shall support variable **message lengths**, with an average size of approximately 0.2kB (TBC), ranging from a minimum of 11 Bytes (TBC) to a maximum of 1kB (TBC). **Note**: A simple acknowledgment (ACK) message should be shorter than messages transmitting more detailed information, where applicable. **Note:** This requirement is identical to IOT4EO-PRF-240 (Service A-2) **Note:** The *minimum* message size of 11 Bytes (TBC) is driven by the most restrictive LPWAN Protocols. It has been assumed that LoRaWAN *minimum* message size is 11 Bytes (TBC). However, this may need to be revisited if the required (TT&C) packets necessitate longer lengths. **Note:** The *maximum* message size of 1kB (TBC) is driven by the most restrictive LPWAN Protocols. It has been assumed that LoRaWAN *maximum* message size is 1kB (TBC). However, this may need to be revisited if the required (TT&C) packets necessitate longer lengths.
IOT4EO-PRF-150	The service (A-1) shall offer each satellite a **minimum cumulative daily data allowance** of 30kB or 300kB (TBC), with options for to increase allowance at an additional cost. **Note:** The order of magnitude of improvement is to be confirmed by end users: • 30kB cumulative daily data allowance refers to a 10^1 improvement • 300kB cumulative daily data allowance refers to a 10^2 improvement **Note:** This requirement does not include protocol overheads. It is acknowledged that additional overheads are necessary (e.g., in a bi-directional context, for system synchronization and responsiveness, and for acknowledgment (ACK) returns). These overheads, typically 20%, vary based on protocols and should be added to the minimum cumulative daily data allowance. **Note**: These daily data allowances were derived based on the message frequency and message length defined in IOT4EO-PRF-130 and IOT4EO-PRF-140, respectively. **Note:** A daily data allowance was assumed to be an effective way to capture this performance requirement; however, a monthly allowance might be more convenient.

	Note: This requirement is identical to IOT4EO-PRF-250 (Service A-2)
IOT4EO-PRF-160	The service (A-1) shall provide continuous and uninterrupted **global coverage** over **terrestrial** and **coastal areas** within a latitude range of ±90°(TBC), subject to practical limitations of Gateway deployment at the poles. **Note**: Open ocean coverage would be highly beneficial, but its feasibility depends on the possibility of placing Gateways on strategically located islands, human-made structures, and/or stable buoys. The ocean accounts for 71% of the Earth's surface.

Table 7 Service A-2 (*Indirect, via relay*) - Performance defining requirements

Identifier	**Requirement (Service A-2)**
IOT4EO-PRF-200	The service (A-2) shall support bi-directional standard telemetry, tracking, and **command (TT&C)** data types to ensure interoperability and effective communication between the Earth Observation satellites and ground Gateways.
IOT4EO-PRF-210	The service (A-2) shall offer **minimum data upload** and **downloads speeds** of at least 2 kbps (TBC) in nominal operation conditions, with higher speeds prioritized for mission-critical business services. **Note:** The speed is limited by the link budget of this system, designed to provide a ubiquitous and cost-effective solution for multiple users simultaneously **Note:** Although the link budget may support higher speeds, the minimum speed is maintained at the same value for both Services A-1 and A-2 to ensure consistency **Note:** The system definition language adopted for Service A-1 and A-2 follows terminology adopted in LPWAN systems, as is defined as follows: • **Upload**: LEO EO User Equipment (UE/node) to ground Gateway. • **Download**: Ground Gateway to LEO EO User Equipment (UE/node).
IOT4EO-PRF-220	The service (A-2) shall provide a 'near-zero' <10 Seconds (TBC) **'visibility' latency** over terrestrial and oceanic areas within a latitude range of ±70°(TBC), and <10 Minutes (TBC) outside a latitude range of ±70°(TBC), subject to effect coverage limitations of a GEO/MEO satellite when in line of sight of an EO Satellite. **Note:** This visibility latency *within* the latitude range of ±70°(TBC) is driven by the GEO Beam coverage over the low and mid-latitudes. The <10 Seconds (TBC) visibility latency was defined arbitrary and open to revision. **Note:** This visibility latency *outside* the latitude range of ±70°(TBC) is driven by the GEO Beam coverage over the poles in relation to the GEO <> LEO EO link. The <10 Minutes (TBC) visibility latency is established based on the following rationale: • In a 90-minute LEO orbit (360°), the worst-case scenario of a 40° gap in visibility over one of the poles would equate to 10 minutes.
IOT4EO-PRF-230	The service (A-2) shall offer each satellite the ability to send and receive at least 10 or 100 messages (TBC) **per orbit** or a **minimum** of 150 or 1500 (TBC) **messages per day**. **Note:** The order of magnitude of improvement is to be confirmed by end users: • 10 messages per orbit, 150 messages per day refer to a 10^1 improvement • 100 messages per orbit, 1500 messages per day refer to a 10^2 improvement

Identifier	Requirement (Service A-2)
IOT4EO-PRF-240	The service (A-2) shall support variable **message lengths**, with an average size of approximately 0.2kB (TBC), ranging from a minimum of 11 bytes (TBC) to a maximum of 1kB (TBC). **Note**: A simple acknowledgment (ACK) message should be shorter than messages transmitting more detailed information, where applicable. **Note:** This requirement is identical to IOT4EO-PRF-140 (Service A-1) **Note:** The *minimum* message size of 11 Bytes (TBC) is driven by the most restrictive LPWAN Protocols. It has been assumed that LoRaWAN *minimum* message size is 11 Bytes (TBC). However, this may need to be revisited if the required (TT&C) packets necessitate longer lengths. **Note:** The *maximum* message size of 1kB (TBC) is driven by the most restrictive LPWAN Protocols. It has been assumed that LoRaWAN *maximum* message size is 1kB (TBC). However, this may need to be revisited if the required (TT&C) packets necessitate longer lengths.
IOT4EO-PRF-250	The service (A-2) shall offer each satellite a **minimum cumulative daily data allowance** of 30kB or 300kB (TBC), with options for to increase allowance at an additional cost. **Note:** The order of magnitude of improvement is to be confirmed by end users: • 30kB cumulative daily data allowance refers to a 10^1 improvement • 300kB cumulative daily data allowance refers to a 10^2 improvement **Note:** This requirement does not include protocol overheads. It is acknowledged that additional overheads are necessary (e.g., in a bi-directional context, for system synchronization and responsiveness, and for acknowledgment (ACK) returns). These overheads, typically 20%, vary based on protocols and should be added to the minimum cumulative daily data allowance. **Note**: These daily data allowances were derived based on the message frequency and message length defined in IOT4EO-PRF-230 and IOT4EO-PRF-240, respectively. **Note:** A daily data allowance was assumed to be an effective way to capture this performance requirement; however, a monthly allowance might be more convenient. **Note:** This requirement is identical to IOT4EO-PRF-150 (Service A-1)
IOT4EO-PRF-260	The service (A-2) shall provide continuous and uninterrupted **global coverage** within a latitude range of ±70°(TBC), subject to effect coverage limitations of a GEO/MEO satellite when in line of sight of an EO Satellite. **Note:** This requirement, unlike in Service A-1, does not differentiate between land and open ocean areas. **Note:** A minimum of three GEO satellites are required to cover the entire Earth within the ±70° latitude range.

Table 8 Service B (*Direct, via in-situ sensors*) - Performance defining requirements

Identifier	**Requirement (Service B)**
IOT4EO-PRF-300	The service (B) shall support bi-directional scientific and messaging data types to ensure interoperability and effective communication between the Earth Observation (EO) Satellites in Low Earth Orbit (LEO) and in-situ sensors on-ground
IOT4EO-PRF-310	The service B shall offer **minimum data upload** and **downloads speeds** of at least 2 kbps (TBC) in nominal operation conditions. **Note**: The speed is limited by the link budget of this system, designed to provide a ubiquitous and cost-effective solution for multiple users simultaneously. However, in principle, the speed is expected to be lower than for Service A-1/A-2, as battery-powered in-situ sensors typically have lower Effective Isotropic Radiated Power (EIRP) compared to Gateways. **Note:** The upload and download speeds do not necessarily have to be identical; they are kept the same for simplicity. **Note:** The system definition language adopted for Service B follows terminology adopted in LPWAN systems, as is defined as follows: • **Upload**: Ground **User Equipment (UE / node)** to LEO EO **Gateway**. • **Download**: LEO EO **Gateway** to ground **User Equipment (UE / node)**.
IOT4EO-PRF-320	The service (B) shall offer each **in-situ sensor** (User Equipment) the ability to send and receive at least 2 messages (TBC) **per orbit** or a minimum of 30 (TBC) **messages per day**. **Note:** It is assumed that within 15 LEO orbits per day, typically only one message per access within a LEO orbit is required, though this varies by application (e.g., a second message might be needed for ACK confirmation). Visibility also depends on the sensor's latitude and the orbit type; for example, a sensor at low latitude in a high-inclination Sun Synchronous Orbit (SSO) may only be visible once per day, while other orbits or higher latitude sensors might offer more frequent opportunities.
IOT4EO-PRF-330	The service (B) shall support variable **message lengths**, with an average size of approximately 0.1 kB (TBC), ranging from a minimum of 11 bytes (TBC) to a maximum of 0.2 kB (TBC). **Note**: A simple acknowledgment (ACK) message should be shorter than messages transmitting more detailed information, where applicable. **Note:** The *minimum* message size of 11 Bytes (TBC) is driven by the most restrictive LPWAN Protocols. It has been assumed that LoRaWAN *minimum* message size is 11 Bytes (TBC). However, this may need to be revisited if the required data packets necessitate longer lengths.
IOT4EO-PRF-340	The service (B) shall offer each in-situ sensor (User Equipment) a **minimum cumulative daily data allowance** of 3kB (TBC) to one LEO Gateway, with options for to increase allowance at an additional cost. **Note:** This requirement does not include protocol overheads. It is acknowledged that additional overheads are necessary (e.g., in a bi-directional context, for system synchronization and responsiveness, and for acknowledgment (ACK) returns). These overheads, typically 20%, vary based on protocols and should be added to the minimum cumulative daily data allowance

Identifier	Requirement (Service B)
	Note: These daily data allowances were derived based on the message frequency and message length defined in IOT4EO-PRF-320 and IOT4EO-PRF-330, respectively. **Note:** A daily data allowance was assumed to be an effective way to capture this performance requirement; however, a monthly allowance might be more convenient.
IOT4EO-PRF-350	The service (B) shall offer in-situ sensor operators **SERVICE BUNDLE** options to accommodate large quantities of in-situ sensors. **Note**: If a minimum cumulative daily data allowance of 3kB (TBC) is allocated to one LEO Gateway, this would result in, for example, 0.3 MB for a bundle of 100 sensors, or 3 MB for a bundle of 1000 sensors. **Note**: It is assumed that an in-situ sensor or sensor bundle has access to all LEO Gateways registered with the IoT4EO LEO Gateway network. See IOT4EO-SCL for more details.
IOT4EO-PRF-360	The service (B) shall provide connectivity to multiple LEO Gateways (e.g., several LEO EO satellites operated by the same company), allowing one in-situ sensor or a bundle of in-situ sensors to access many LEO Gateways within that service. **Note:** In Service B, the terms "LEO EO Satellite" and "LEO Gateway" are used interchangeably because the LEO EO Satellite functions as a LPWAN gateway. **Note:** EO Satellite operators might wish to offer Service B themselves given that they either operate multiple satellites or have an agreement with an entity that offers Service B. Alternatively, the service could be offered by equipment manufacturers who supply IoT hosted payloads to various satellite integrators. Other arrangements are also feasible.
IOT4EO-PRF-370	The service (B) shall provide continuous and uninterrupted **global coverage** over terrestrial and oceanic areas within a latitude range of ±90°(TBC), subject to practical limitations of sensor deployment at the poles.

The subsequent Section 4.4 discusses scalability requirements, while Section 4.5 focuses on interoperability requirements. These sections cover how a single LEO EO Satellite, acting as a Gateway, can connect to numerous in-situ sensors acting as User Equipment (UE), and the necessity to enable access for multiple in-situ sensors to multiple LEO Gateways

4.4 Scalability Requirements

The following requirements were identified as common across all services

Table 9 Scalability requirements

Identifier	Scalability Requirement
IOT4EO-SCL-010	The service (A-1) shall accommodate **simultaneous connectivity** for up to 500 (TBC) Earth Observation (EO) satellites in Low Earth Orbit (LEO). **Note:** This assumption is based on the current number of LEO Earth Observation (EO) satellites as reported by celestrak.org.
IOT4EO-SCL-020	The service (A-2) shall accommodate **simultaneous connectivity** for up to 500 (TBC) Earth Observation (EO) satellites in Low Earth Orbit (LEO).

Identifier	Scalability Requirement
	Note: This assumption is based on the current number of EO LEO satellites as reported by celestrak.org. **Note:** An end user may subscribe to both Services A-1 and A-2. There is no requirement (TBC) for simultaneous use of both services.
IOT4EO-SCL-030	The service (B) shall accommodate simultaneous connectivity from a LEO Gateway for up to 20,000 (TBC) in-situ sensors distributed over the ground visibility area. **Note:** This assumption is based on field of view of ±80 degrees from the in-situ sensor for a minimum elevation of 10 degrees, resulting in approximately 14 million km² of area coverage from a LEO EO satellite at 800 km altitude. This area is on the scale of large-scale geographic regions and should support the largest multi-national scale projects: • Small Scale Projects (10 – 50 sensors) (TBC) • Medium Scale Projects (50 – 200 sensors) (TBC) • Large Scale Projects (200 – 1000 sensors) (TBC) • Multi-National Projects (1000 – 20,000 sensors) (TBC) **Note**: 14 million km² represents <3% of the Earth's surface (510 million km²) - with 10,000 sensors, this would result in one sensor per 1,400 km², or cells measuring 37 x 37 km. Alternatively, distributing 10,000 sensors in cells of 10 x 10 km would cover an area of 1 million km².
IOT4EO-SCL-040	The service (B) shall offer **each in-situ sensor** with the potential for simultaneous connectivity to at least 50 (TBC) different LEO Gateways **Note:** The whole system is expected to support 500+ LEO EO satellites, but it is assumed that only 10% of these will be visible at any given time from a specific in-situ ground location **Note**: A service B provider can offer access to multiple LEO Gateways, which could apply to multi-satellite operators or entities providing the service across multiple satellites
IOT4EO-SCL-050	The services shall be designed for scalability to support an **increasing number** of Earth Observation (EO) **satellites** in Low Earth Orbit (LEO) without degradation in performance, capable of expanding to handle up to 150% (TBC) more satellite connections within the next ten years, subject to the projected growth of the commercial EO landscape.
IOT4EO-SCL-060	The services shall be designed for **compatibility** within a **provider-agnostic framework**, supporting various data transmission methods and satellite communication as they become available **Note:** It is assumed that some system elements technically depend on specific providers, whereas others do not; business agreements should facilitate provider-agnostic operations wherever possible. **Note**: While the potential need for an entity to coordinate between service providers is outside the scope of this document, it is an important issue that should be addressed.
IOT4EO-SCL-070	The services shall support a **scalable architecture** that allows for the dynamic adjustment of the number of gateways based on operational demands and capacity requirements.
IOT4EO-SCL-080	The **service protocols** and **infrastructure** shall be designed to operate independently of specific frequencies to accommodate potential bandwidth **expansions.**

Identifier	Scalability Requirement
	Note: Authorization from the ITU may be required to expand the frequency band for some protocols.

4.5 Interoperability Requirements

The following requirements were identified as common across all services

Table 10 Interoperability requirements

Identifier	Interoperability Requirement
IOT4EO-INT-010	The service shall comply to a set of agreed **international standards** and **protocols** that promote interoperability across different service providers, reducing technical and operational barriers.
IOT4EO-INT-020	The service shall establish a **governance framework** that includes periodic review and updating of interoperability standards to align with evolving technologies and regulatory environments
IOT4EO-INT-030	The service shall support **cross-platform** communication **capabilities** to facilitate data exchange and operational coordination between diverse systems and technologies, in support of a provider and technology agnostic solution
IOT4EO-INT-040	The service shall **provide well-documented APIs** (Application Programming Interface) that support the easy integration with third-party services and systems, facilitating a ubiquitous flow of information across various platforms and technologies, especially between terrestrial LPWAN systems and satellite systems, whenever applicable **Note**: Sharing information between service providers and User Equipment (UE) can be beneficial. For example, the well-determined orbits of Low Earth Orbit (LEO) satellites can facilitate the optimization of gateway usage or in-situ sensors in planning.
IOT4EO-INT-050	The service architecture shall be **modular** and **interfaceable**, designed for easy adaptation and ubiquitous integration of new technologies or modifications to existing components, ensuring uninterrupted overall service functionality
IOT4EO-INT-060	The services shall provide a well-documented **Interface Control Document (ICD)** along with detailed API specifications, including software and hardware requirements for users, to facilitate optimal service interaction
IOT4EO-INT-070	The services shall undergo **regular compatibility testing** with existing and newly introduced systems to ensure continuous interoperability and address any emerging compatibility issues.
IOT4EO-INT-080	The service (A) shall streamline the **interface** for the **Mission Control Centre (MCC**) by adding an extra degree of freedom through the low-data-rate connectivity infrastructure, thus reducing the barrier to adoption.
IOT4EO-INT-090	The service (B) shall streamline the **interface** for **in-situ sensor operators** and **EO Data Providers** by adding an extra degree of freedom through the low-data-rate connectivity infrastructure, thus reducing the barrier to adoption. **Note:** This interface is not limited to the LPWAN Architecture. Information exchange can also occur through terrestrial networks (e.g., sharing orbital parameters) which may help optimize critical battery resources in in-situ sensors.

4.6 Quality of Service (QoS) Requirements

The following requirements were identified as common across all services

Table 11 Quality of Service (QoS) Requirements

Identifier	QoS Requirement
IOT4EO-QOS-010	The service shall provide a **minimum** of 99.5% (TBC) **uptime** across all covered areas, excluding scheduled maintenance windows, to provide **reliable service** to customers & users as part of the Service Level Agreement (SLA).
IOT4EO-QOS-020	The service shall provide a minimum of 99.9% (TBC) uptime across all covered areas for **mission-critical business services**, excluding scheduled maintenance windows, to provide reliable service to customers & users as part of the Service Level Agreement (SLA).
IOT4EO-QOS-030	In the event of partial system **degradation**, the service shall continue to operate at a **reduced capacity** of no less than 75% (TBC) of normal operating levels, ensuring minimal impact on service performance and availability.
IOT4EO-QOS-040	The service shall implement a **disaster recovery plan** that includes data backup and system recovery processes that can be activated within 24 hours of a catastrophic failure.
IOT4EO-QOS-050	The service shall employ **redundancy** for all critical system components to ensure **uninterrupted service** and data availability in case of hardware or software failure.
IOT4EO-QOS-060	The service provider shall offer 24/7 **customer support** with multiple channels available (e.g., phone, email, chat) to ensure that customer inquiries are addressed within 24 hours.
IOT4EO-QOS-070	The service shall define **regular maintenance** periods and the protocol for notifying clients. Emergency maintenance procedures shall also be clearly outlined.
IOT4EO-QOS-080	The service shall maintain a high level of **data accuracy**, with error rates specified and measures in place to correct any inaccuracies in data transmission.

4.7 Data Security and Privacy Requirements

The following requirements were identified as common across all services

Table 12 Data Security and Privacy requirements

Identifier	Data Security and Privacy Requirement
IOT4EO-SEC-010	The service shall use **end-to-end encryption** for all data transmitted between satellites, gateways and in-situ sensors to ensure that data cannot be intercepted or deciphered by unauthorized parties
IOT4EO-SEC-020	The service shall implement **robust access control** mechanisms to ensure that only authorized personnel can access sensitive data and operational capabilities.
IOT4EO-SEC-030	The service must have resilient network infrastructure capable of withstanding various types of **cyber-attacks** and ensuring continuous operation even under duress.
IOT4EO-SEC-040	The service shall have a well-defined **incident response plan** that includes procedures for dealing with data breaches, including notification protocols as per compliance requirements
IOT4EO-SEC-050	The service shall undergo regular **security audits** to identify and mitigate vulnerabilities, ensuring compliance with the latest security standards and practices
IOT4EO-SEC-060	The service shall comply with applicable regional and international **data protection** regulations (e.g., GDPR, HIPAA)

4.8 Legal and Regulatory Requirements

The following requirements were identified as common across all services

Table 13 Legal and Regulatory requirements

Identifier	Requirement
IOT4EO-REG-010	The service shall comply with international **regulations** (i.e., **ITU**) and national space operation guidelines where applicable
IOT4EO-REG-020	The service shall comply with **environmental regulations** related to satellite launch and operation, including debris management and end-of-life disposal, in accordance with international and national environmental standards.
IOT4EO-REG-030	The service shall comply to **data sovereignty laws** requiring that data collected and transmitted by satellites is stored and processed in the jurisdiction in which it was collected, or as legally required by applicable national laws. **Note:** The concept of data roaming from a LEO orbit needs clarification; however, it is beyond the scope of this document at this stage. This issue might be addressed through commercial agreements between service providers in the future.

5 APPENDIX

5.1 Supplementary Material & Information

The following Appendix provides supplementary materials and detailed data supporting the analyses and conclusions presented in this report. These additional resources are intended to expand understanding and provide transparency into the methodologies used.

Appendix A Glossary

A.1 List of Acronyms

The following acronyms and abbreviations are used in this document

Table 14 List of Acronyms

Acronym	Definition
3GPP	3rd Generation Partnership Project
API	Application Programming Interface
CONOPS	Concept of Operations
EO	Earth Observation
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GEO	Geosynchronous Earth Orbit
GNSS	Global Navigation Satellite System
G/S	Ground Station
IDRS	Inter-satellite Data Relay Service
IoT	Internet of Things
IoT4EO	Internet of Things for Earth Observation
IOAG	Interagency Operations Advisory Group
ITU	International Telecommunication Union
LEO	Low Earth Orbit
LORAWAN	LOng Range Wide Area Network
LPWAN	Low Power Wide Area Network
LTE-M	Long-Term Evolution - Machine Type Communication
MCC	Mission Control Centre
MEO	Medium Earth Orbit
NB-IoT	Narrowband Internet of Things
RD	Reference Document
RF	Radio Frequency
SLA	Service Level Agreement
SG	Study Group
SWaP	Size, Weight, and Power
TC	Telecommand
TT&C	Telemetry, Tracking and Command

A.2 List of System Terminology

The following terminology and definitions are used in this document

Table 15 List of System Terminology

Term	Description
Low-data-rate connectivity	This term encompasses a communication architecture characterized by **low-power** and **low-data-rate** technologies. It highlights that the technical solutions for this are protocol-agnostic, offering a range of options within **Low Power Wide Area Network (LPWAN)** technologies. This document deliberately steers clear of specific IoT terminology in favour of a more general discussion of low-data-rate connectivity
Service	A service is the provision of functionality or work performed by one party for the benefit of another. Services are intangible and do not confer ownership of any physical assets. In this context, the term 'service' is employed to identify and clarify user requirements from a service provision perspective, intentionally omitting technical engineering solutions at this point.
IoT4EO Vision	A descriptor that is designed to capture the overarching vision and objectives for combining terrestrial LPWAN/IoT technologies with Earth Observation (EO) satellites in Low Earth Orbit (LEO). Its aim is to clarify and contextualize the vision, define the project's scope, and facilitate communication by serving as a reference for all involved parties, from team members to external stakeholders
Interoperability	This is the ability of different systems, devices, applications, or products to connect, communicate, and operate together effectively without special effort on the part of the user. In the context of the IoT4EO Vision, achieving full interoperability with existing terrestrial LPWAN/IoT networks is not feasible. Therefore, a modified definition is proposed for this project to maintain its focus: *“The capability of diverse systems, devices, or software applications to communicate effectively, ensuring that they can exchange and interpret shared data accurately across various platforms and environments”*
Gateway	A Low Power Wide Area Network (LPWAN) Gateway is a hub that connects LPWAN-enabled devices (which are typically designed to operate with low power consumption over long distances) to a central network. Gateways serve as the intermediary bridge between the User Equipment (UE) and the broader network infrastructure, relaying data to and from the internet or other centralized services and translating between different protocols as necessary. **Note:** In the IoT4EO low-data-rate architecture, the location of the gateway is dictated by the LPWAN terminology used. Specifically: • In Service A, the gateway is located on the ground and spread across terrestrial landscapes. It functions similarly to a traditional ground station (in Service A for TT&C), utilizing LPWAN technologies. • In Service B, the gateway is located on an Earth Observation satellite and requires connection to the MCC via alternative methods (e.g., Service A-1, A-2, or classical TT&C).
User Equipment	The User equipment (UE) refers to any device or module that interacts directly with the LPWAN infrastructure to send or receive data. The user equipment is configured to communicate efficiently with a network's Gateway. In this context, the IoT4EO Project identifies User Equipment (UE) as the subsystem installed on an Earth Observation satellite, designed to communicate with a terrestrial Gateway through Service A-1 or A-2. In Service B, the User Equipment (UE) refers to the subsystem installed and integrated with an in-situ sensor, designed to communication with a LEO Gateway.
Node	A node is either a redistribution point (e.g. in LEO, MEO or GEO Relay satellites) or a communication endpoint (e.g. in the EO satellite, in an in-situ sensor). A node makes use of LPWAN and/or non-LPWAN communication links to communicate with other nodes. A node is an abstraction of different elements (interface to host, transmitter/receiver electronics, and protocols), without considering their location or physical aspects
IoT Constellation	A reference to the existing constellations of small satellites that are leveraging LPWAN/NB-IoT and similar technologies to offer low-data-rate connectivity on ground. This connectivity addressing the accelerating number of IoT sensors being integrated into various aspects of society (e.g., vehicles, buildings, homes, etc..)
Ubiquitous	Ubiquitous refers to something that is present, appearing, or found everywhere. In the context of connectivity with Low Earth Orbit (LEO) satellites, 'ubiquitous' describes the consistent and widespread availability of connections that are always or soon to be accessible, ensuring near-constant communication across various network nodes, independent of the service provider. **Note:** Although some services might be limited by geographical constraints, ubiquitous connectivity generally applies to the coverage area.
System of Systems	A descriptor that captures a holistic view encompassing all systems, services, technologies, terrestrial and space assets, stakeholders, providers, and users. It acknowledges that the low-data-rate connectivity architecture leverages existing terrestrial network systems as a foundation to build on and a complementary

Term	Description
	element. Consequently, the engineering of a solution adopts a **middle-out** approach, concentrating on developing within an established system-of-systems framework to identify and leverage synergies, compatibility, interfaces, and integration opportunities.
Message	A message refers to a 'packet of data' transmitted between devices over a network using communication protocols that are specifically optimized for the application's requirements. These messages are structured in a standardized format and may include sensor readings, control commands, status updates, or any other information necessary for effective communication between devices (e.g., Acknowledgements). Due to the nature of Low Power Wide Area Networks (LPWAN), messages are often designed to be as small as possible to conserve bandwidth and power, which is important for the long battery life and extended range required by these networks.
Provider-Agnostic	Provider-agnostic refers to systems, software, or processes designed to operate independently of any specific service provider's technologies or platforms.
Middle-out approach	The middle-out engineering approach is a methodology where the design and development process start from an intermediate level of abstraction or system complexity, rather than from the top-down or bottom-up extremes. In middle-out engineering, developers and engineers focus on the most critical components or layers of a system first—those that are fundamentally driven by the functionality, interfaces, performance, and constraints of the interacting systems. This focus ensures that core elements align seamlessly with both higher-level architectures and lower-level details, optimizing integration and system performance.
Store and forward	Store and forward communication is a type of data transmission technique where messages are temporarily held at an intermediate point before being sent on to their final destination
Mission Control Centre	A Mission Control Centre (MCC) is a facility responsible for managing and monitoring space missions, from launch to mission completion. It is responsible for payload planning, sending commands (tele commanding), and receiving telemetry data to monitor the health and status of spacecraft
Telemetry, Tracking and Command	Telemetry, Tracking, and Command (TT&C) is a technology used in space missions to monitor and control satellites. Telemetry involves the transmission of data from a satellite to a ground station, providing vital information about the satellite's health and functioning. Tracking involves determining the satellite's position and trajectory to ensure it remains on the correct path. Command refers to the sending of instructions from the ground station to the satellite to perform specific operations or correct any anomalies. Together, TT&C functions are critical for the successful operation of satellites and other spacecraft.

Table 16 List of Service Terminology

Term	Description
Data type	The term data type refers to a classification that specifies the type of data that a variable or object can hold in programming and data management. Data types are important as they define the operations that can be performed on the data and the way it is stored.
Coverage	The geographical area covered by a network service provider where users can access its communication services. This is also known as network coverage.
Continuous Connectivity	The permanent and uninterrupted communication opportunity between two nodes across a network, allowing a user to send or receive data at any time without delays or availability constraints. It refers to the absence of 'unavailability' on sending and receiving data over a network.
Visibility Latency	The time delay between connectivity windows, termed 'visibility latency,' arises from the geometric constraints of satellite orbits and the distribution of terrestrial gateways and in-situ sensors. This latency specifically refers to the average time the **ground network remains out of sight from the EO LEO satellite**, necessitating a wait until the satellite's ground track re-enters its field of view. For example, a LEO satellite over an open ocean experiences delays in connecting as it moves out of the terrestrial gateway's field of view. **Note:** The term "visibility latency" is not applicable in scenarios of continuous connectivity, which assumes uninterrupted data transmission capability from one node to another across a network.
Latency	The time delay from the transmission of a message at one node to its reception at another node across a network. This definition assumes continuous connectivity, allowing for uninterrupted data transfer.
Daily Data Allowance	This refers to the maximum amount of data, typically measured in Bytes, that a user is permitted to transfer—both upload and download combined—within a specified time frame (e.g. per day if it is calculated daily) under a particular service plan.
Upload speed	Service A: This refers to rate at which data is transmitted from on-board user equipment (UE) on the satellite to a network Gateway located on the ground Service B: This is the rate at which data is transmitted from in-situ sensors on the ground to a network Gateway located on-board the satellite

Term	Description
Download speed	Service A: This refers to rate at which data is transmitted from a network Gateway on the ground to an on-board user equipment (UE) located on the satellite. Service B: This is the rate at which data is transmitted by a network Gateway on-board the satellite to in-situ sensors located on the ground
Capacity	This refers to the maximum amount of data that can be transmitted over a communication channel or system in a given amount of time. It affects the overall performance and scalability of the network, influencing user experience by determining how many simultaneous connections the system can support.

Appendix B Applications, Use cases, and Stakeholders

B.1 Reference Use Cases

The following list of Reference Use Cases Documents are used in this Service Definition and Preliminary Requirements Document. These were identified as potential applications by customers and users.

Table 17 The full list of anticipated applications of a low-data-rate connectivity with Earth Observations and their estimated added value

Ref. ID	Application	Description	Added Value
UC1	Distribution of Telecommands to EO Satellites	A set of telecommands is sent by an operations centre and transmitted via IoT nodes (and ground links) to the EO receiving satellite.	TBD – Outcome of IoT4EO Survey
UC2	Distribution of Telemetry	An EO satellite transmits telemetry (e.g., coordinates of detected events) via IoT nodes (and ground links) to the receiving operations centre	TBD – Outcome of IoT4EO Survey
UC3	Satellite autonomously calling home in case of on-board anomalies.	Instead of the flight operations constantly pinging the spacecraft for its health status via prescheduled ground station passes, the Satellites could initiate the contact to mission operations in case of unforeseen issues enabling a faster response time to anomalies and increase autonomy	TBD – Outcome of IoT4EO Survey
UC4	Collecting data from in-situ EO ground sensor or beacon.	An IoT node in space receives information from an in-situ EO ground sensor via an IoT link. Assuming further on-board intelligence, this might imply immediate and autonomous activation of new measurements by the EO sat or the availability of new ground-truth data to complement on-board calibration	TBD – Outcome of IoT4EO Survey
UC5	Triggering in-situ EO ground sensors	An in-situ EO ground sensor is triggered to perform a collocated observation (e.g., for vicarious calibration) or measurement via an IoT link when the EO satellite is flying by.	TBD – Outcome of IoT4EO Survey
UC6	Support to quick manoeuvres in the context of space debris avoidance	As the number of LEO satellites grows, the necessity for rapid responses to potential collision risks increases. However, the added value of IoT in this context may be limited, since orbital dynamics are predictable and critical orbital changes are typically better managed through traditional Tracking, Telemetry, and Command (TT&C) systems.	TBD – Outcome of IoT4EO Survey
UC7	Broadcasting of payload operations between EO sats	An IoT node as part of the payload of a spacecraft broadcasts relevant information to companion satellites.	TBD – Outcome of IoT4EO Survey
UC8	Optical ground station downlink of opportunity	A ground (gateway) or relay IP node informs (only minutes ahead) the EO satellite that an optical ground station in the coming path of the EO sat will have clear skies for the dedicated (non-IP) high data rate optical downlink to be used.	TBD – Outcome of IoT4EO Survey
UC9	Broadcasting and triggering other sats to acquire new observations in specific area.	EO sat with systematic acquisitions identifies an alarm case with on-board DSP/AI and informs (directly via LPWAN Gateways or via IoT network) another EO sat (e.g., in a New Space constellation) to take action and task new observations (e.g. to zoom in a specific area).	TBD – Outcome of IoT4EO Survey
UC10	Support to on-board autonomy in constellations	In addition to other above cases, constellations can benefit in terms of autonomy (e.g., less ground stations in non-cooperative countries) and tasking for emergency cases. This needs further elaboration.	TBD – Outcome of IoT4EO Survey

Appendix C IOT4EO Project

C.1 Overview

As previously discussed in Section 2.1, the ongoing proliferation of Internet of Things (IoT) technology on Earth is laying the foundation for the development of ubiquitous networks in space, by providing a **framework** that is already establishing important system components, including regulatory policies, physical infrastructure, data management systems, network layers, and protocols. It was on this foundation that the "*Concepts for the Use of IoT in Earth Observation*" studies were funded and conducted under two ESA Contracts with OHB [RD-2] and ADS [RD-3]. The purpose of these studies is to explore the synergies, opportunities, and feasibility of integrating low-data-rate connectivity with Earth Observation (EO) in Low Earth Orbit (LEO). In addition, a specific Study Group (SG) was established in 2022 through a collaboration between the European Space Agency (ESA) and other space agencies under the Inter-Agency Operational Advisory Group (IOAG) [RD-1] to explore the multi-dimensional aspects (i.e., technical and business) related to this ambitious goal.

The ongoing ESA studies, currently progressing through Task 3, are structured as follows:

- Task 1 EO Use Cases, Requirements, and Market Survey.
- Task 2 Concept of Operation (ConOps) and Architecture Definition.
- Task 3 Detailed Architectural Design.
- Task 4 Technology/Standardization roadmap and IOAG Draft Report.

Two public workshops are planned over the course of these studies, with the following objectives and outcome:

- **Workshop 1** was held at ESA-ESTEC on 16-17 February 2023, with the focus on integrating multiple disciplines and communities to participate in the process of learning, interest formation/positioning, coalition building, and strategic planning. The workshop details and executive summary can be found on the Indico website here, and in [**RD-4**].
- **Workshop 2** will be held at ESA-ESTEC on 2-3 December 2024, with the focus on consolidating the Service A and Service B described in this document and gather feedback from potential users and service providers on the proposed approach, unify the community under a cohesive strategy, and determine the next steps. The workshop preparation details can be found here, and in [**RD-5**].

C.2 Project statement

The following statement was drafted during the "*Concepts for the Use of IoT in Earth Observation*" studies. Its purpose was to clarify and contextualize the IoT4EO Vision, define the project's scope, and facilitate communication by serving as a reference for all involved parties, from team members to external stakeholders:

*The integration of low-data-rate connectivity with Earth Observation (EO) satellites in Low Earth Orbit (LEO) has the potential to revolutionize satellite operations by improving **responsiveness** by an **order of magnitude** to facilitate dynamic satellite tasking, on-board event detection with near-real-time distribution of information between ground and space nodes. Moreover, it will strengthen and align in-situ scientific measurements with systematic Earth observation data to improve calibration and validation processes, offering greater reliability and scope in scientific measurements. The IoT4EO project exists to connect the idea with its implementation, through standardization and validation of technology that ensures interoperability, scalability, and ease of adoption across multiple stakeholders into an operational environment with cost-effective ubiquitous connectivity for EO LEO satellites.*

C.3 Project Objectives

The following objectives were listed in the Statement of Work (SoW) for the "*Concepts for the Use of IoT in Earth Observation*" studies [RD-2], [RD-3]and are reiterated here for convenience.

Table 18 IoT4EO Statement of Work (SoW) objectives

User	Description
OBJ1	To identify Earth Observation (EO) use cases, their mapping to data rates, and review of the initial set of requirements in the Appendices of the SoW for these EO use cases
OBJ2	To perform a world-wide market survey and review for IoT in terms of available services, security, network architecture, regulatory framework and implemented standards, including preliminary analysis of expected data rates and identification of gaps and critical areas for further trade-off and system simulations
OBJ3	To establish of a ConOps for the System of System, including the definition of all actors, interfaces, protocols including security and services, in general and also with respect to representative EO use cases
OBJ4	To establish the system architecture(s) required to implement the envisaged ConOps and its IoT network, and detailed analysis of critical issues supported by relevant simulations and updated link budgets
OBJ5	To develop a roadmap for regulatory and technology and further standardization
OBJ6	To generate a public IoT-SG DRAFT document, and supporting the Agency in discussions with international partners in the frame of IOAG and-or other fora (e.g. workshops with institutional and commercial stakeholders)

Appendix D IoT4EO Service Summary

D.1 Summary table

This appendix summarizes three low-data-rate connectivity services identified in the "*Concepts for the use of IoT in Earth Observation*" studies under ESA Contracts [RD-2] and [RD-3]. It includes scalability considerations for service parameters that could affect costs.

	Service A-1		Service A-2		Service B	
	Minimum	**Scalability**	**Minimum**	**Scalability**	**Minimum**	**Scalability**
Data Type	TT&C Messages	-	TT&C Messages	-	Data & Messages	-
Direction	Bidirectional	-	Bidirectional	-	Bidirectional	-
Coverage	Terrestrial & Coastal (Very Limited open ocean coverage)	Gateway distribution (Minimum Elevation Angle)	Terrestrial & Ocean (Limited polar region coverage)	Minimum 3 GEO Relays (MEO to address pole coverage)	Terrestrial & Ocean (Limited in-situ sensor battery)	Sensor distribution (More EO LEO Satellites)
Visibility Latency	≤ 10 Minutes (Limited by ocean coverage)	Gateway distribution (Minimum Elevation Angle)	Near-zero (Limited by pole coverage)	Minimum 3 GEO Relays (MEO to address pole coverage)	N/A (Limited by latitude, orbit, app)	No. LEO EO Satellites No. In-situ Sensors
Upload Speed	≥ 2kbps	Limited by Link Budget	≥ 2kbps	Limited by Link Budget (possible with add. service cost)	≥ 2kbps	Limited by Link Budget
Download Speed	≥ 2kbps	Limited by Link Budget	≥ 2kbps	Limited by Link Budget (possible with add. service cost)	≥ 2kbps	Limited by Link Budget
Daily Data Allowance	≥ 30kB (150 Messages per day)	Increase allowance (at an additional service cost)	≥ 30kB (150 Messages per day)	Increase allowance (at an additional service cost)	≥ 3kB (30 Messages per day)	Increase allowance (with bundle options & service cost)
Message Length	Variable (Ave. 0.2kB)	Protocol dependant (Max 1kB)	Variable (Ave. 0.2kB)	Protocol dependant (Max 1kB)	Variable (Ave. 0.1kB)	Protocol dependant (Max 1kB)
Capacity	≥ 500 Satellites	Gateways & Satellites (Additional ITU BW if needed)	≥ 500 Satellites	Gateways & Satellites (Additional ITU BW if needed)	≥ 50 Sensors (/satellite)	≤ 20,000 Sensors (/satellite) ≥ 50 LEO Gateways (/sensor)

Appendix E Interoperability and Standardization Action Plan

E.1 IoT4EO Provider-Agnostic System Architecture

As previously discussed in Section 3.5, this Appendix expands on the interoperability landscape of a low-data-rate connectivity architecture to identify interventions where standardization can enable an IoT4EO provider-agnostic solution. The inclusion of an 'IoT4EO Provider-Agnostic System Architecture' in this document aims to stimulate stakeholders, users, and service providers to identify their location in the 'value chain' of the service provision. This is expected to further define the system later in the development process and support the creation of a standardization and interoperability action plan.

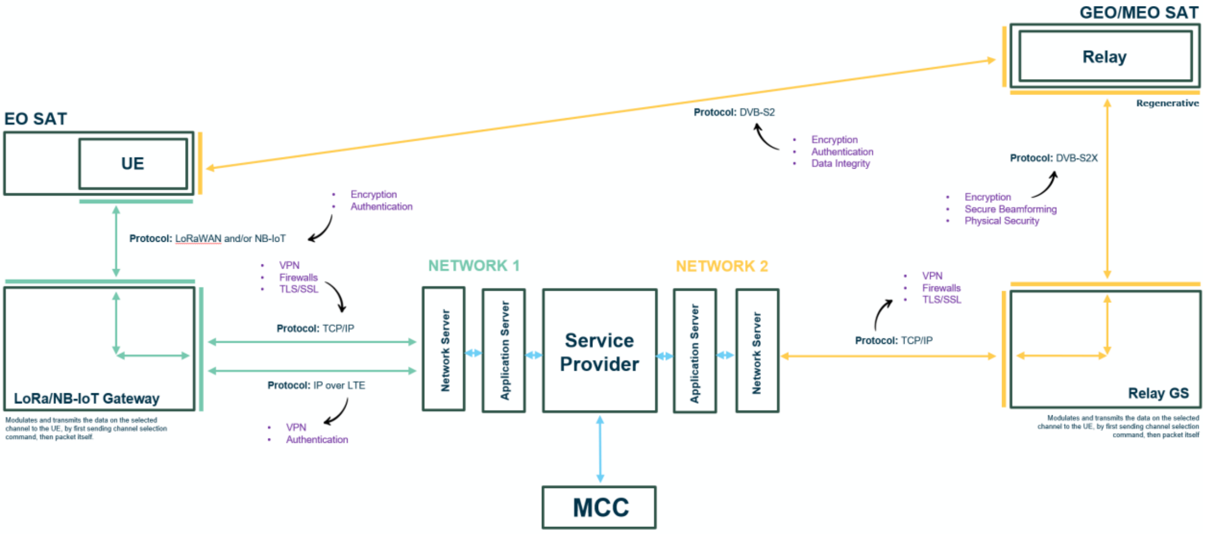


Figure 11 IoT4EO Provider-Agnostic System Architecture (Regenerative)

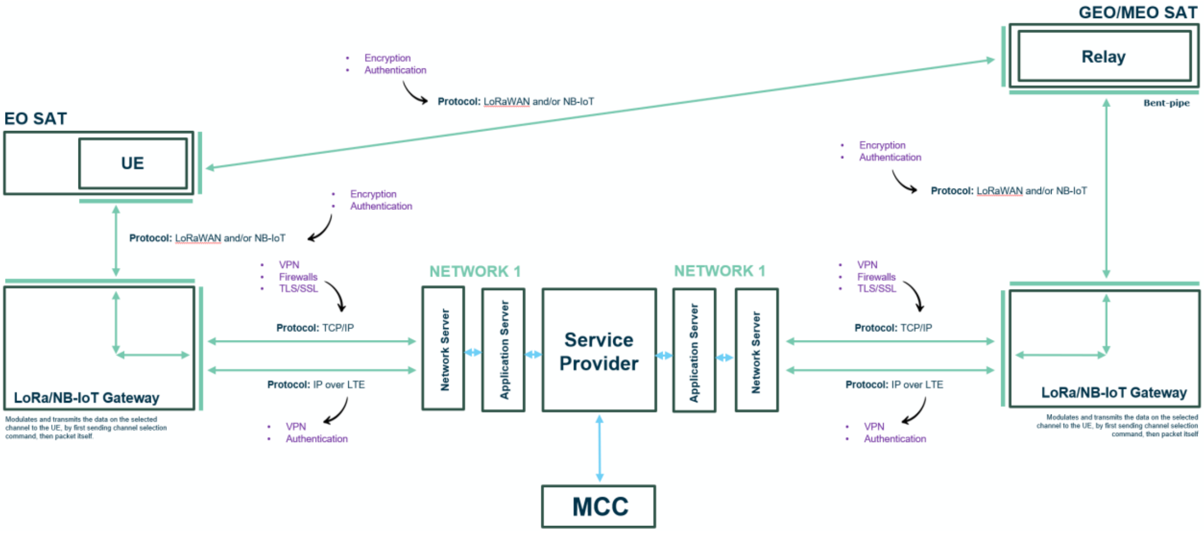


Figure 12 IoT4EO Provider-Agnostic System Architecture (Bent-pipe)

In these provider-agnostic system architectures, two key differentiating features have been identified that affect the solution and future standardization efforts, particularly regarding the functionality of the GEO/MEO Relay:

- **Bent-pipe Architecture** in the Relay satellite, featuring common paths (highlighted in green) shared by both Service A-1 (direct space-to-ground) and Service A-2 (via the Relay satellite).
- **Regenerative architecture** in the Relay satellite, where Service A-2 follows a distinct path (shown in yellow) from that of Service A-1 (shown in green).

The success of the Service A value chain heavily depends on the willingness of stakeholders to participate and the adoption rate among existing service providers. Currently, it is anticipated that the Mission Control Centre (MCC) (i.e., Earth Observation Satellite Operator) will interface solely with the service provider. This arrangement alleviates their need to interface with application and network servers or to handle the development, deployment, and maintenance of gateways. All they need to do is to purchase the User Equipment (UE) for their satellite and subscribe to the service. The service providers manage everything else.

There are several key characteristics that appear to define the IoT4EO Provider-Agnostic System Architecture. These include network topology, which distinguishes between two types of possible networks:

- **Network 1 (Bent-Pipe):** This connectivity framework would utilize only LPWAN (e.g. NB-IoT, LoRaWAN) protocols to facilitate communications between ground and space segments. It leverages existing TCP/IP and IP over LTE protocols between the Mission Control Centre (MCC) and ground gateways. This approach would result in a reduced dependency on numerous stakeholders due to minimal technical differences between Services A-1 and A-2, especially when the User Equipment (UE) uses both services to guarantee widespread access

- **Network 2 (Regenerative):** This connectivity framework would utilize both LPWAN and DVB-S protocols, depending on the solutions implemented at the GEO/MEO Relay satellites. In a regenerative solution, which involves demodulation and re-modulation of the signal in the Relay satellite, compatibility with the service provider’s established network protocols is necessary for facilitating communication through the entire chain. While a regenerative solution offers increased flexibility for the Relay provider, it could also lead to variable paths, interfaces, coordination and greater number of dependencies when utilizing both Service A-1 and A-2.

This ultimately affects whether the solution needs to interoperate with existing 'traditional' GEO Relay infrastructure, such as interfacing with additional protocols like DVB-S for sending and receiving through their network. Conversely, a bent-pipe system does not require demodulation of the LPWAN protocol, thereby reducing complexity from the LPWAN perspective. Cooperation from service providers is needed.

E.2 Standardization Action Plan

The purpose of this Appendix is to encourage stakeholders identified in Section 3.6, along with users and service providers, to identify their location and role within the 'value chain' of service provision. This shall assist ESA in standardizing system components towards an interoperable solution. This section presents our preliminary strategy for developing an action plan focused on interoperability and standardization.

The two "*Concepts for the use of IoT in Earth Observation*" studies under ESA Contracts [RD-2] and [RD-3] have preliminary identified two potential solutions that use LPWAN technologies: LoRa and NB-IoT. The highlighted dotted box indicates areas where intervention is likely needed to facilitate interoperability through standardization and middle-out engineering.

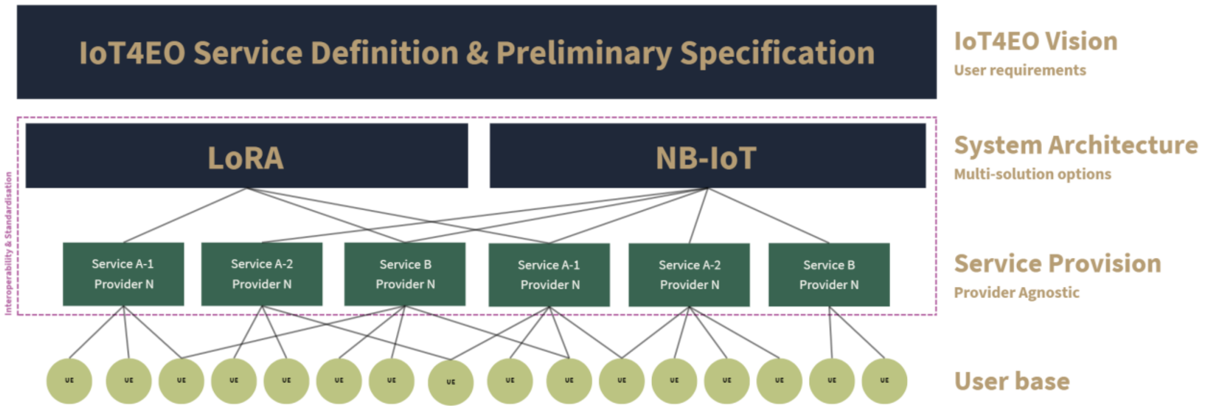


Figure 13 Example of IoT4EO System Architecture Standardization Snapshot. Note: Although two solutions, LoRa and NB-IoT, are mentioned here, this document continues to remain solution agnostic

To create a provider-agnostic environment, a review all Service Provider solutions and system architectures is needed to identify common elements, then further categorize them into components with standardization potential. Note two types of standardization impacts:

1. Service Performance Improvement
2. Enabling Multi-service Interoperability

In this context, the IoT4EO Vision focuses on identifying areas that enable multi-service interoperability since performance improvements should be driven by the service providers themselves to stimulate competition and drive down deployment and operational costs. Creating an environment that supports provider-agnostic solutions is a prerequisite. Key technical assumptions include:

- A User Equipment (UE) is sufficiently versatile (e.g. Software Defined Radio (SDR) technology) to support compatibility with multiple solutions from multiple Service Providers.
- A User Equipment (UE) may subscribe to more than one service of the same type (e.g., A-1 for a subset of Gateways, and another A-1 for an additional subset) or of different types (e.g., A-2 to expand coverage, or B to connect with in-situ sectors). These services may operate concurrently (e.g., A-1 and B) or exclusively (e.g., A-2 only when A-1 is unavailable) with multiple subscriptions.

The Provider-Agnostic architecture outlined in Appendix E.1, which is also be applied to Service B, consists of various system components that also include User Equipment, Gateways, and Regulatory and Network aspects. Several questions could emerge about the stakeholders' readiness to embrace these Services:

- Is it safe, for instance, to route TT&C messages through public networks and Gateways?
- Does the added cost of these Services justify the value provided by their ubiquitous capabilities?

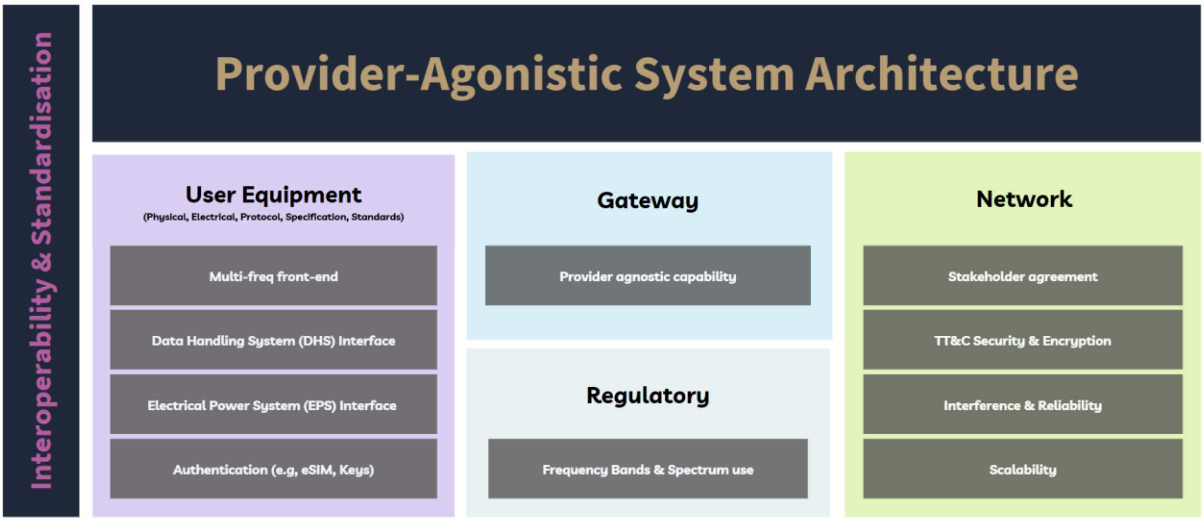


Figure 14 Initial attempt to identify system elements that would require standardization to enable a provider-agnostic solution

Appendix F Scenario examples

F.1 LoRaWAN

The following scenario offers an example of a Low Power Wide Area Network (LPWAN) low-data-rate connectivity architecture utilizing LoRa technology to achieve global coverage and minimize visibility latency, with the potential to improve operational efficiency and responsiveness for Earth Observation (EO) satellites by an order of magnitude. The assumed altitude for LEO satellites is 600 km. A clear trade-off needs to be considered to balance coverage and cost, involving the number of Gateways and the Minimum Elevation Angle (MEA) per Gateway. The following analysis is provided by ADS [AD-3].

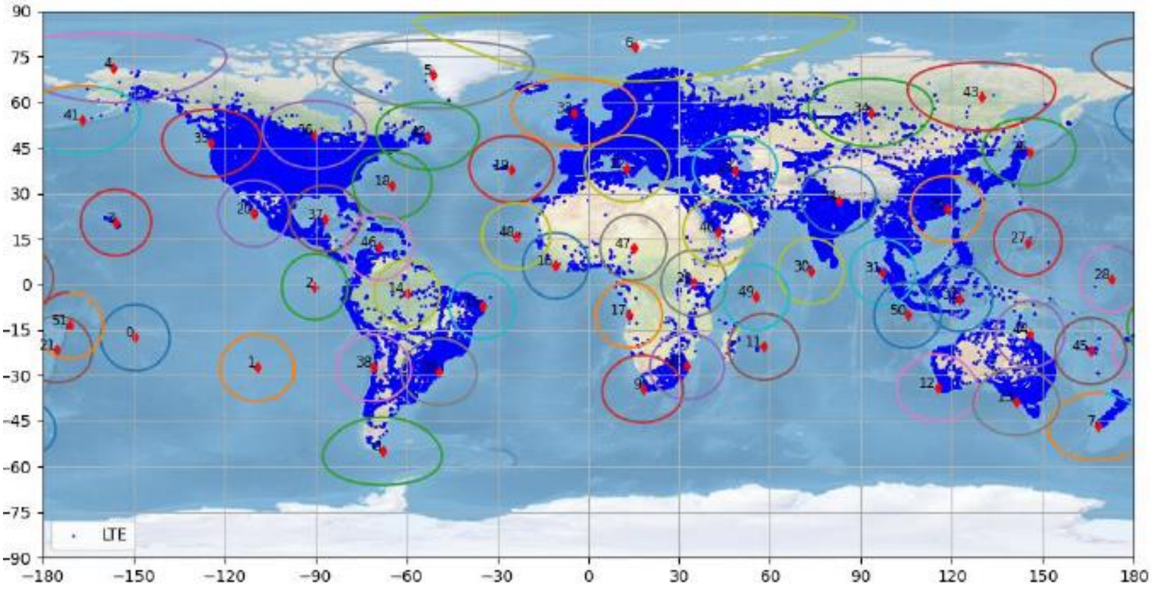


Figure 15 Potential coverage of 50+ LPWAN Gateways with a Minimum Elevation Angle (MEA) of 20 degrees. In this scenario, 40% / 75% global coverage is achieved, with a near-zero / 10 min average visibility latency.

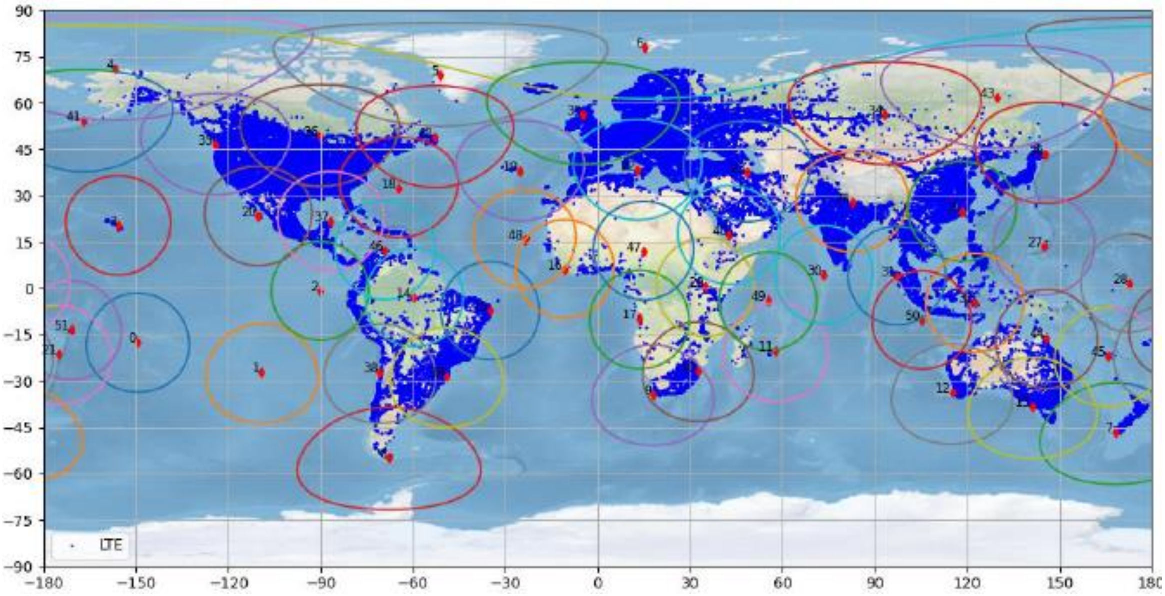


Figure 16 Potential coverage of 50+ LPWAN Gateways with a Minimum Elevation Angle (MEA) of 10 degrees. In this scenario, 66% / 85% global coverage is achieved, with a near-zero / 10 min average visibility latency.

Source: Fig.31 Technical Note provided by ADS under ESA Contract [RD-3]