

On the Use of Mega-Constellation Services in Space

Executive Summary

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Executive Summary

On the Use of Mega-Constellation Services in Space, funded by ESA's Open Space Innovation Platform (OSIP), investigates how mega-constellations can be used to provide low-Earth orbit (LEO) spacecraft with broadband low-latency services, a novel Concept with potential to disrupt spacecraft design, operation, and performance by allowing spacecraft to access mega-constellations' enormous resources (Tbit/s throughputs) and global coverage at a lower cost than traditional data relay systems and ground station networks (two to fifty times cheaper, that is, a few hundred to a few thousand dollars per month for a daily net capacity from hundredths of Gbit up to almost ten Tbit).

Because they can continuously communicate with space users at high rates (up to hundreds of Mbps) and low latencies (<50 ms), space networks have limitless applications, ranging from improved traditional mission phases (mission analysis and satellite design, assembly integration validation and pre-launch activities, launch and early operation phase, special and end of life operations, etc.) to innovative space robotics, in-orbit servicing, tandem and formation flying missions – applications with strict requirements that are exceptionally hard to satisfy (i.e., latency, position accuracy, capacity, coverage). Risk, one of the main mission and cost drivers, can also be reduced due to increased connectivity.

Space-based broadband services are also uniquely positioned: flexible, high throughput, high reliability, low latency, and low cost 24/7 communications cannot be easily achieved by ground station networks, given their limited installed capacity, tangled scheduling, and station hand-over requirements, as well as increasing installation and maintenance costs and complex logistics. Moreover, given the rapid pace at which new payloads are being deployed and its expected growth in the coming decades, not even the deployment of data relay systems and highly autonomous ground station networks for near-real time high-throughput connectivity may be enough to provide the necessary coverage, capacity, and latency.

To assess the feasibility of space-based broadband services for LEO satellites, a model of the communication system was derived from coverage and physical layer simulations, identifying mega-constellations' space service volumes and the user orbits can be best served by providers. Ku-band satellite-to-satellite communication channels are predominantly line-of-sight and nearly immune to atmospheric effects but have challenging signal dynamics because the fast relative motion between satellites produces 500-to-550 kHz Doppler offsets, kHz/s Doppler rates at the zenith, and 120-to-180 dB of path losses. Additionally, fading, interference, noise, and other impairments further degrade system performance.

Path losses and coverage probability are functions of altitude and inclination. Most users will experience intermittent space-based connectivity, characterised by long accesses interspersed with short losses of contact. However, those below 550 km or at critical inclinations, that is, the constellations' inclinations, will be served uninterrupted for most of their orbit (> 90%), enabling high-capacity applications due to continuous coverage.

To make use of broadband services in such a highly dynamic and lossy channel, several technologies must be packaged into a space-grade lightweight, low power, and compact user terminal: low-noise wideband electronics; multi-channel modems; variable code and modulation; wide-steering ranges; low minimum elevation angles (25-to-40 degrees); and multi-beam beamforming/beam-steering antennas or wide beam antennas (>= 100-degree half-power

beamwidth). While many mature ground and flight multi-constellation multi-satellite terminals on the market were assessed as potential candidates for the Concept, they were small-sat sized (heavy, large, and high power) and lacked space qualification, radiation hardening, and robustness to withstand the launch and space environment, making it clear that there were no common off-the-shelf flight terminals for the Concept and that a custom solution was needed.

As a result, a custom multi-system, multi-orbit, software-defined space user terminal architecture was defined to meet these needs, within the constraints of common-off-the-shelf SDRs, antennas, power amplifiers, and modems, to provide implementers and users with the flexibility to tune the terminal to their applications and service providers. This custom terminal was shown to provide users with Tbit-scale capacity using low-power (10W) passive patch antennas (8-dBi gain) by constant data dripping at low (20 Mbps) data rates and high link margins (3-dB) within a 10x10x15cm footprint and a 1.5 kg maximum mass for the common case.

Through a compact and passive wide-beam antenna, the terminal can simultaneously illuminate and communicate with multiple satellites in visibility, with two-to-four parallel channels being optimal for common user, shifting the paradigm of inter-satellite links towards a point-to-multipoint paradigm and simplifying acquisition, tracking, and pointing. Ultimately, the proposed terminal is extremely flexible, being suitable for any platform and mission, and its impacts on the hosting platform are incommensurate with the tremendous coverage and capacity it unlocks.

Most importantly, for a reference scenario placing the user in a sun-synchronous orbit at 500-km altitude, a widely used orbital configuration for many applications representing the common case of constant connectivity with mega-constellations, the quality of service that LEO mega-constellations could provide to LEO users, as per the Concept and proposed terminal configurations, is at least one order of magnitude better, both in terms of data latency (< 50 ms) and volume capacity (1-to-10 Tbit), than that offered by established data relay systems in MEO and GEO, on similar user equipment capabilities.

Imposing roughly identical hosting requirements on flight terminals, Ground Stations as a Service (GSaaS) can provide a net daily capacity comparable to the Concept if provided enough contact time (depending on the terminal configuration), but in general require more than one contact per revolution on average, which could be challenging for some orbits and/or ground networks, and cannot provide the same latency because of visibility constraints.

Nevertheless, data relay systems and ground station networks can both augment the Concept, by providing multi-orbit connectivity, bridging potential gaps in coverage for certain user orbits (>750 km altitude, low inclination), while offering diversity. Conversely, the Concept can augment existing systems by increasing coverage where they lack the most: at high latitudes.

Considering publicly available service fares for mega-constellations, data relay systems, and GSaaS, the Concept offers the best cost-benefit trade-off for any capacity. When comparing costs across services, the Concept maintains monthly fees comparable to GSaaS for lower data volumes, with MEO and GEO costing about two-fold and five-fold for the same daily capacity. When increasing volumes, costs increase quickly for GSaaS and space-based data relay systems, being up to twelve-to-fifty times larger than mega-constellations.

Assessing the Concept's value across the identified applications in terms of the number homogeneous concurrent users that could be supported, it was estimated that OneWeb alone could support tens to hundreds of thousands of users, depending on their configuration. While these numbers alone are quite promising, coexistence with ground users is a key question. A

parametric analysis on the maximum number of concurrent users as a function of the available capacity for space users was performed, but an accurate figure is still to be defined based on policies that account for temporal and geographical demand, as well as traffic asymmetry, skewed towards the downlink for ground users, and towards the uplink for space users. It is our belief that 90% of mega-constellation capacity will be exclusively reserved to ground users and, in this case, one can expect 155372, 42244, 11456, and 4296 UTs in the low-end, common case, high-end (36 MHz), and high-end (125 MHz) configurations, more than enough to serve the entire mission populations in existence and then some.

To conclude the study, we analysed current technology gaps and shortcomings, drawing a technology development roadmap for further maturing the Concept into a fully validated and commercially exploitable solution. As a first step, the feasibility assessment conducted must be complemented by more detailed system analyses and simulations to consolidate user and system requirements. The main algorithms for core user terminal functionalities, namely Constellation Scheduler and the Software Defined Modem, must be prototyped, as well as a refinement of the proposed space user terminal architecture. From a service perspective, there are still several commercial and technical aspects that must be investigated, such as radiofrequency licensing, dynamics aware routing, location and mobility management.

Then, a scaled-engineering model of the space user terminal must be designed, tailored, manufactured, and tested in a representative operational environment, considering the accommodation limitations and hosting requirements of potential flight opportunities so that an In-Orbit Demonstration of the Concept can be performed. Considering that service providers have unique requirements, that the terminal must be certified to work within their network in a way compatible with their main customers and homologated, establishing a partnership with at least one of the potential service providers would be key.

After a successful demonstration, the space user terminal shall be industrialised and a business model for commercial exploitation and service provision must be designed. Here, defining the service business model, intellectual property management, and setting up long-term partnerships with mega-constellation service providers to be competitive with ground station networks and data relay systems are the core business building blocks. Securing a pilot customer for product validation, preparing the product for series production with competitive pricing and establishing channels and processes to support the payload integration into the pilot customer's platform are the final steps towards a viable market solution.

Technology Development Roadmap

Considering that on one hand the Concept aims to provide a service to space users, and on the other hand that the infrastructure to provide such services is at its highest maturity level and some of the considered constellations in advanced state of deployment and approaching full operational capabilities, the Concept technology maturation is focused mostly on the space user terminal, and its development can be divided into three main lines, namely:

- a Hardware line: focused on the development of a space user terminal hardware unit;
- a Software line: focused on the development of the core logic for the space user terminal;
- a Service line: focused on the end-to-end system and service, including licensing and business development aspects, required for a commercial exploitation of the Concept.

In this context, and considering the activities conducted and the promising results achieved within the scope of this project, the Concept's current Technology Readiness Level is estimated to be between TRL 1 and TRL 2 (with some TRL 3 milestones preliminary analysed), given that its technology application has been formulated and will be supported by a peer-reviewed paper currently in preparation, its feasibility has been partially proven through analysis and high-level simulations, and a preliminary application and cost analysis has identified its potential wide target market and competitiveness compared to other narrow- and wide-band communication solutions for space users, both ground- and space-based.

However, it is evident that the Concept technology is at an early stage and there are still several milestones yet to be achieved in order to bring the TRL to the maturity level needed for a wide adoption and commercial exploitation. These milestones have been identified, mapped to the above development lines, and grouped into four main maturation phases, aiming to raise the TRL by two at each phase.

The defined maturation phases follow ESA's Advanced Research in Telecommunication Systems (ARTES) Competitiveness and Growth (C&G) Development Phases, namely:

- a definition phase, where the requirements, specifications and baseline are established;
- a technology phase, with a focus on early in-orbit testing of a prototype;
- a product phase, with the goal of qualifying an engineering model and industrialisation;
- a demonstration phase, all around the operational validation of a proto-flight model.

Such phases, should allow the proposed technology maturation roadmap, summarised in Figure 1, to be easily pitched to many of the Agency's programmes and initiatives, increasing the chances for a rapid development and prompt time to market.

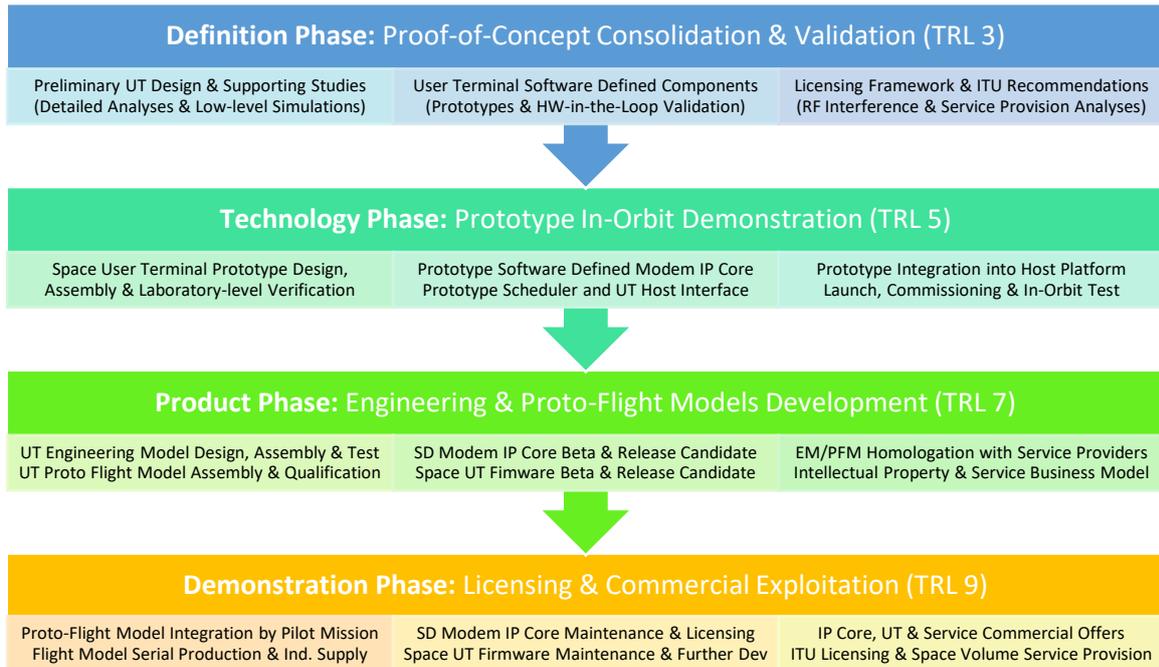


Figure 1 – High-level Technology Maturation Roadmap (left HW dev. line, middle SW dev. line, right Service dev. line)

Definition Phase: Proof-of-Concept Consolidation & Validation

The main goal of this phase is to complement the feasibility assessment conducted in this study, with a more sophisticated proof-of-concept, that formally validates the value proposition, while establishing maturation lines and early builds for core hardware and software components.

For this purpose, more detailed system analyses and simulations shall be performed, including more accurate models that validate and/or override many of the assumptions and simplifications made so far, to consolidate user and system requirements. Also, the development of the main algorithms for some of the core user terminal functionalities shall be engineered and started. Moreover, frequency licensing aspects shall be addressed in parallel to the regulation process under discussion, in order to de-risk any further technology developments in the subsequent phases.

Following the development lines previously described, this phase targets a TRL 3 for the overall Concept, by maturing the technology readiness on three main fronts, hardware, software, and service, described hereafter. It is estimated that this phase could take one to two years, depending on the available resources to conduct some of the activities in parallel.

Technology Phase: Prototype In-Orbit Demonstration

This maturation phase main purpose shall be to demonstrate the Concept and characterise its capabilities, by means of an in-orbit test of a Prototype of the space user terminal, to be developed during this phase.

For this purpose, and based on the proof-of-concept studies, hardware breadboards and preliminary software components developed in the previous phase, a scaled-engineering model of the space user terminal needs to be designed, manufactured, and a tested both at factory as

well as in a representative operational environment, ideally in-orbit should a suitable flight opportunity be made available to host the user terminal as a secondary payload (preferred over a dedicated or embedded mission due to elevated costs and intrinsic risks). This shall not only verify the feasibility of the Concept, but also allow to gather valuable insights of the attained performance and challenges faced, which shall be taken as lessons learned for the following maturation phases.

This phase targets a TRL 5 for the overall Concept, promoted at this stage to Prototype, and its development can be split in three main aspects: hardware, software, and service maturation, described in the following subsections. It is estimated that this phase could take two to three years, depending on the flight opportunity schedule and readiness level attained for the core components in the previous maturation phase.

Product Phase: Engineering/Proto-Flight Models Development

The main goal of this phase shall be to industrialise the space user terminal and develop the business model, so to bring the overall communications product ready for the market.

The starting point is of course the Prototype/scaled engineering model developed for the IOD in the previous phase, which should be upgraded to a fully featured and verified engineering model and eventually already a fully qualified proto-flight model, transition its software components to a release lifecycle, and define the terminal homologation, licensing, and service models.

This phase targets a TRL 7 for the overall Concept/Prototype, upgraded at this stage to a Product, by maturing the technology readiness on its hardware, software, and service, as in the previous phases. It is estimated that this phase could take one to two years, depending on the maturity level attained in the previous phase.

Demonstration Phase: Licensing and Commercial Exploitation

In this final maturation phase, the **main objective shall be the operational validation of the proto-flight model**, accumulating as much flight heritage as possible, all while setting up a **series production of the terminal paired with a competitive commercial offering**.

To achieve such objectives, one of the **key milestones** to achieve early in the phase (or before it), shall be **securing a suitable pilot customer to validate the user terminal in an operational environment**. Parallel to the support of hardware integration activities, software components shall initiate a maintenance and feature release train lifecycle, while implementing and refining commercial offers according to market evolution.

This phase targets a TRL 9 for the overall Product, upgraded at this stage to a Solution, by maturing the technology readiness on its hardware, software, and service, as in previous phases. It is estimated that this phase could take around two years, depending on the PFM integration readiness attained in the previous phase, as well as the availability of a pilot customer, its assembly, integration and testing timeline, and its launch and early operations schedule.

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