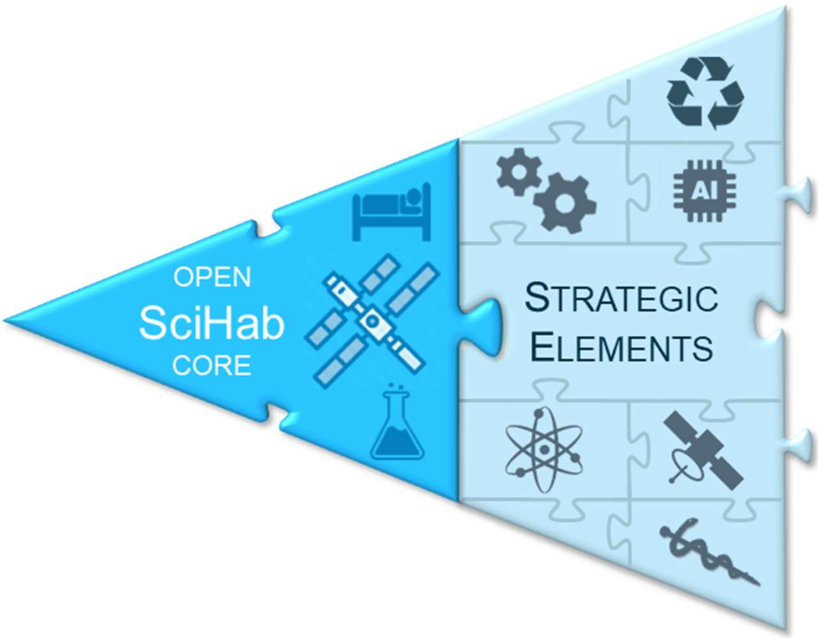
The SciHab concept

a lighthouse for Europe's Post-ISS engagement in Low Earth Orbit

November 2021



This document describes the LEO SciHab concept that was outlined by the ESA LEO strategy virtual team within the frame of ESA's Terrae Novae 2030+ strategy roadmap. It is intended to provide a lighthouse for Europe's post-ISS orientation in LEO, and it is a reference document to the Request for Information (RFI) "*Services for Human Space Exploration - Meeting ESA's future Research and Astronaut Mission Objectives in Low Earth Orbit and beyond*" (ESA-HRE-XI-RFI-0001). It is not intended to define a policy directive, nor to set boundary conditions to the scope of the RFI. All assumptions and conclusions provided in this document may be challenged by the respondents to the RFI.

Executive Summary

Low Earth Orbit Optimise the use of the ISS during its remaining lifetime and prepare human post-ISS activities, including fostering its commercial use and supporting the exploration of Moon and Mars

The “golden” era of ISS utilisation will be coming to an end most likely in the next decade. One of the major challenges for Europe is to retain its capabilities, to remain relevant in the exploration and utilisation of Low Earth Orbit, and to become more competitive amongst other spacefaring nations. Even to maintain a status quo in capabilities, it is not sufficient to continue the past procurement model, level of cooperation, and bartering strategy. An evolution in the kind of cooperation and level of engagement will be necessary, even though the US recently stated that they would like to continue a form of international partnership.

The Low Earth Orbit landscape of the future is, as yet, uncharted. The ISS end-of-life point may be reached in the early 2030s. A combination of new and veteran players and partnerships are currently discussing the continued use of existing platforms alongside developing new platforms. US stakeholders are already planning for a seamless transition to a commercial station before ISS is being decommissioned, therefore avoiding a gap of US presence in LEO.

Europe must also avoid such a gap of LEO capabilities. Therefore, the European stakeholders such as Terrae Novae Participating States and European commercial partners must establish a plan. The first steps are underway which should prepare for concrete decisions at CM25.

The ISS partnership has shown that Europe has grown up in LEO. This means it will have to stand on its own feet from now on. The proposed strategy aims to provide a foundation for this stance, by demonstrating strategic capabilities and agility to ensure that the main European stakeholder requirements, governmental and private, are central to any final scenario. These are:

- continuous fast, simple, and reliable access to world-class micro-g science & technology platform(s) in LEO
- to enable international cooperation, European soft power and leadership in space
- the support of subsequent deep-space destinations like Moon and Mars exploration
- European astronaut flights as a source of identity and inspiration for the citizens of Europe
- proficiency of the European space industry, fostering the engagement of more mid-caps and SMEs from both space and non-space sector
- a developing commercial European LEO economy, preparing for an Earth-LEO-Moon economy

The ambition to meet these challenges is fully aligned with the 5 ESA Priorities that are lined out in ESA's Agenda 2025[1], and which were endorsed by the Member States. Europe is confronted with massive challenges that can only be met by a united front with a bold, comprehensive concept for LEO.

The SciHab concept

Based on these reflections, the "SciHab" (Science and Habitation) concept is proposed as Europe's future keystone element for LEO (Figure 1). The concept is to be studied following CM22, and starting implementation at CM25, to ensure continuity in LEO capabilities. The SciHab concept includes a variety of scenarios and levels of ambition, it should therefore be regarded as a range of possible solutions to Europe's future challenges and ambitions in LEO. It should not be thought of as a classical institutional stand-alone development project but rather a concept based on defined European user-needs which are relevant and useful in the evolving LEO context (both institutional and commercial).

ESA will define user needs, jointly with Terrae Novae Participating States, to shape this element of the strategy together with interested European industry. The common denominator of all potential variations of the SciHab concept is to provide access to a LEO science & habitation platform, with the option to add modular strategic elements that might be of interest for Participating States but also commercial users.

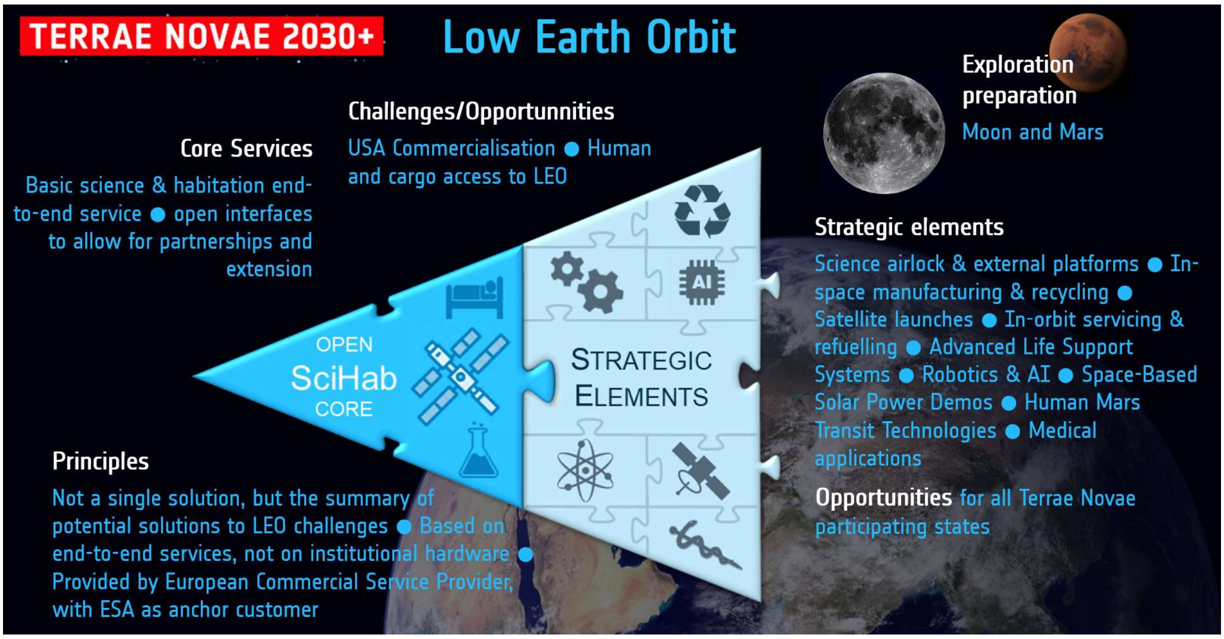


Figure 1: The SciHab concept. Its core service covers basic science and habitation functions, and it can be supplemented by additional strategic elements.

A commercial procurement model is proposed, involving European-led Commercial Service Providers. An important part of the concept is that the procurement shall include end-to-end service requirements including crew and cargo transportation, operations, utilisation

[1] Five ESA Agenda 2025 Priorities: Strengthen ESA–EU relations, Boost green and digital commercialisation, Develop space for safety and security, Address critical programme challenges, and Complete the ESA transformation.

management, payload development, up to crew training elements. While most investments shall be made in Europe, the participation of non-European providers in European-led consortia and industry-to-industry partnerships is strongly encouraged, within limits to be defined, with or without an International Partners framework.

The SciHab concept is therefore compatible with newly proposed commercial and institutional infrastructures such as:

- Axiom space station
- Blue Origin/Sierra Space/Boeing 'Orbital Reef'
- Lockheed Martin/Nanoracks 'StarLab'
- Russian Orbital Service Station 'ROSS'

SciHab is also a complementary LEO companion to the Gateway and eventual lunar surface infrastructure ('Moon base'), enabling long-term research and technology validation in LEO, followed by the Moon and eventually the big leap to Mars. Its construction and preparation for operations are proposed to overlap with ISS operations, so that a gap in LEO services is avoided. The SciHab concept shall sustain long-term presence of humans as well as intermittent un-crewed autonomous robotic operations.

Two decades of ISS operations have shown that cargo and human transport are amongst the key cost drivers of LEO operations. Acquiring all the necessary transportation capabilities therefore needs to be part of any future European LEO concept of operations. In the past, ESA has achieved this through a mixture of own capabilities and a bartering mechanism with NASA. However, with the rise of the US LEO economy and its multitude of players with independent capabilities, the model of a "barter economy in LEO" will evolve. Europe has various options to implement this strategy and maintain its capabilities in LEO including:

1. direct procurement from non-European providers, without significant geo-return, in exchange for human & cargo transport and/or on-orbit services (less preferred solution);
2. identifying and providing sufficiently attractive European barter elements that could be used to offset transportation services and resources that are required to maintain European LEO capabilities;
3. developing a European cargo and human transportation capability to complement a European LEO infrastructure, to serve as an international cooperation element.

For each of these three choices, when decided in time, and if implemented to a sufficient level, the SciHab concept can secure and meet the most important stakeholder requirements for Europe and Terrae Novae Participating States. Its opportunities can attract a multitude of potential cooperation partners, both institutional and commercial.

It is clear from a multitude of European heritage technology projects that Europe is well capable of providing any piece of technology that is required for a LEO platform. The decision

of whether Europe will assume a leadership role in LEO in the decades to come is therefore not a technical one, but a political one.

Combining the SciHab concept with new European transportation capabilities would provide Europe with an opportunity to take up a high level of strategic autonomy and leadership in an otherwise fragmented LEO landscape. However, such a capability implies a very large financial commitment far beyond the current financial envelope of E3P.

Such investment could only be fully economically justified if other – non-ESA – users emerge, especially in the commercial domain. The three relevant markets are:

- Commercial research
- In-orbit manufacturing of high value goods
- Space tourism and other luxury products

It is the goal of the E3P Business in Space Growth Network to nurture the first two markets. US commercial space station providers see all three as promising, but they see space tourism as the key market, which is already a reality.

Finally, the Matosinhos Manifesto[2], a resolution adopted unanimously on 19 November 2021 at ESA's Intermediate Ministerial Meeting in Portugal, puts forward a suggestion to investigate a so-called human space exploration 'inspirator'. The reflection on this idea is ongoing, but the Terrae Novae 2030+ strategy for LEO needs to be robust and deliverable even if such a concept is not implemented.

[2] https://esamultimedia.esa.int/docs/corporate/ESA_C_2021_176_EN.pdf

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1 Destination LEO - from the past to the future

During the last two decades, Low Earth Orbit was explored, or more correctly phrased, utilised by government agencies mainly through a single unique and magnificent cooperation effort, the International Space Station. What started out as a project unlikely to succeed, to build the most complex machine that humanity has ever created, proved to be one of the most successful and finest projects of international cooperation.

Generations of scientists from more than 100 nations have benefited from this unique orbital platform that is permanently operated and inhabited for more than two decades now, resulting in many breakthroughs, excellent science, and thousands of publications. It was a hard effort, but we humans have learned to live and work continuously outside the protective sphere of our planet. And millions of young children and adults have been inspired by this common goal in space, by achieving what some said is "impossible". In the time until 2030, a continued strong effort will be placed in the maximum use of ISS. But at the same time, it is clear that the "golden" era of ISS utilisation will at some stage come to an end.

Already today, the situation in LEO is becoming increasingly dynamic with every new development and additional actor entering the stage. It will be hard to forecast beyond 2030, and even harder to predict beyond 2040. International partners such as the US have already started to transition to a post-ISS era. New commercial, as well as several governmental stakeholders are entering the stage with strong investments and initiatives, which will play an important role in the next decades. Consequently, to continue playing a role in space exploration, Europe must set the right sails now, or we will soon lag behind the other actors.

In addition to the established space actors (US, Russia, Europe, Japan, Canada) that aim to continue using LEO platforms, China is rapidly building its own space station, and others are contemplating human-operated LEO platforms (e.g., India). Some nations (e.g., UAE) are entering the scene with an interest in cooperation and partnerships in LEO. Furthermore, various commercial actors have entered the stage with serious intentions to build up orbital infrastructures for human exploration and utilisation of LEO, and as a staging ground for deep space exploration (e.g., SpaceX, Axiom, Sierra Space, Blue Origin, Nanoracks). Undoubtably, a sense of new business opportunities in LEO is rapidly firming up.

This mentality of *"we will build it, and customers will come"* is in line with US space policy changes for their LEO involvement: a shift away from a government-led initiative to procure and operate hardware towards using commercial assets providing end-to-end services. Even though the US explicitly welcome the continuation of the ISS partnership into the age of "commercial LEO", they do not plan for a future government-led platform anymore. In fact, the bidding process for a US commercial LEO platform has already started. Our ability to *Make Space for Europe*[3] will depend on our ability to navigate the challenges of this new LEO landscape.

[3] Agenda 2025 of the ESA Director General (https://download.esa.int/docs/ESA_Agenda_2025_final.pdf)

2 Continued demand in LEO

Recently, NASA's Commercial LEO Destinations project[4] defined its institutional requirements for a future commercial LEO presence. Similarly, the European research community will expect ESA to implement a sizeable portfolio of human-tended long-duration microgravity investigations. Main areas of demand are the still developing field of basic microgravity research in Europe, human physiology research, technology development and the rapidly developing field of in-space manufacturing. Initial estimates of required future institutional capabilities exceed those of the Columbus laboratory, assuming a moderate growth of demand. Already today, the biggest bottleneck for implementing European utilisation activities on ISS is the availability of intravehicular space. Additionally, the infrastructure operator will have to cater to a steadily growing non-institutional / commercial market. At the same time there is a demand for a simpler and faster access to LEO platforms (< 1 year from idea to on-orbit implementation).

Future LEO activities have an important support function for deep space exploration destinations such as the Moon and Mars, by providing a test bed and serving as a staging post. A special emphasis will be given to the closing of knowledge gaps and the provision of logistical support, such as on-orbit refuelling and re-configuration of spacecraft. Critical exploration technology can be tested in the comparatively benign environment of a LEO platform before being implemented at further destinations.

Examples are In-Space Manufacturing, On-Orbit Assembly and Servicing, advanced life support systems, radiation protection, AI & autonomy from ground systems, robotic assistance to humans, space based solar power, electric propulsion, on-orbit servicing and refuelling, and Entry-Descend-Landing (EDL) technologies for Mars, tested in Earth's upper atmosphere. Since the mastering of many of these technologies is on the critical path for any major space exploration actor, tackling these challenges will at the same time provide an opportunity for cooperation.

The expected growing demand for human physiology and other types of research in microgravity will require a sufficient cadence of European astronaut flights to LEO, with an estimated one European long duration mission per year for professional "career" astronauts and possibly an additional shorter duration mission per year for "project" astronauts, in line with the future evolution of the ESA astronaut corps. This is meeting the important prerequisite for European identity and our capability to inspire European citizens, from the young generation to already established scientists, to help them think beyond their current horizons and to include "space" into the solution to the important challenges of tomorrow.

This capability to inspire will continue to rely on regular missions to LEO, due to the expected high effort and thus low cadence of astronaut flights to the Moon and beyond. This will also ensure that European industry and ESA's mission operations teams, e.g., at the European Astronaut Centre, keep their proficiency and capability to safely conduct space missions.

[4] https://procurement.jsc.nasa.gov/CLD/

An important but challenging goal for ESA will be to retain industrial capabilities by creating business cases for European companies (including small & medium enterprises, and non-space players) that eventually do not rely on ESA as the primary anchor customer anymore but will rather be part of a global LEO economy.

3 Proposed European roles & goal setting for LEO

ESA's capability to perform cutting-edge exploration beyond our horizons is based on the principle that, once the forefront of current capabilities has been explored, this area is handed over to actors that operate in the wake behind ESA's exploration initiatives, to cultivate the field that has been ploughed by ESA. This mechanism ensures that after an area has been explored, it can be efficiently utilized, and resources are released to concentrate on new horizons.

Currently, LEO is – in part – such an area. It has extensively been utilised by government agencies through ISS and its predecessor programmes. In the time until 2030, the continued maximum utilisation of ISS and its assets will be a high priority for ESA, to properly finish the "plough" as a return of significant institutional investments. At the same time, for some partners, the long-term process has started to hand over LEO capabilities slowly but steadily towards private actors. Thus, care must be taken to allow for both processes to occur in parallel, to ensure Europe's interests in LEO continue to be met during the handover process, including a reliable and continuous access for European users to a LEO platform.

When evaluating Europe's heritage and capabilities in space transportation, it is important to note a limiting factor: in the past, despite several re-entry technology demonstration projects, Europe has chosen not to have autonomous human access to LEO. Therefore, to acquire such services from international commercial carriers (1 to 2 flights per year plus up- & down-mass for science) will mean a significant expense per year to be spent outside of Europe until this capability is acquired by European industry, if no other 'barter mechanism' will exist. It also means that the most lucrative service, namely space tourism, will remain out of scope for European companies until this capability is available. In this respect, it is interesting to imagine the position that Europe could currently be in, if an autonomous human transport capability would exist.

Figure 2 shows (in blue boxes) the main strategic roles and interests of Europe in LEO, focusing on being an enabler for science, technology, and the economy by ensuring access to a human-operated LEO platform. International cooperation will continue to play an important role, both as an enabler for other goals, and as a goal by itself that is an important asset of soft-power and intergovernmental stability. One of ESA's major assets is that it is capable of implementing ambitious projects that are beyond the scope of a single Member State, allowing them to remain competitive amongst other spacefaring nations. Furthermore, possibly most important in the long run, as laid out in ESA's Agenda 2025, it is ESA's role to foster a European Identity and inspiration of citizens by defining a common "higher" exploration goal, and by demonstrating European capabilities as well as leadership in space operations.

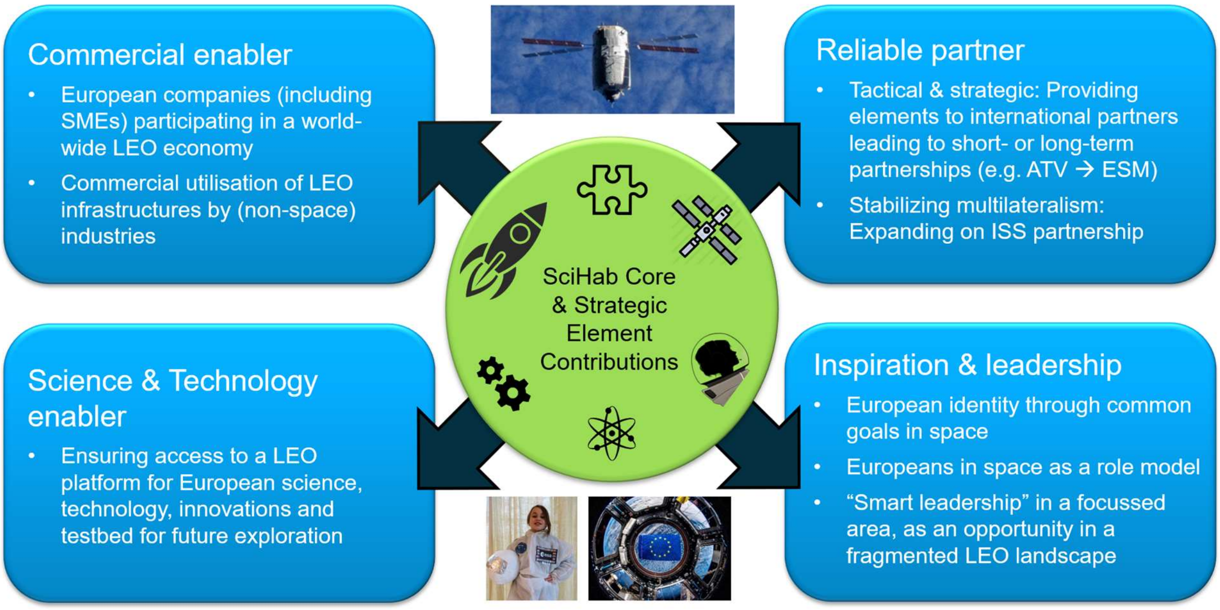

Figure 2: European Strategic Roles & Goals in Low Earth Orbit (blue boxes). The green circle indicates areas for Europe's potential contributions to enable these roles through the SciHab concept including its strategic elements.

4 Possible engagement levels for Europe in LEO

Three general levels of engagement can be identified for Europe (Figure 3), of which several have the potential to meet Europe's major strategic goals, as summarised in Figure 2. The levels in Figure 3 are derived "bottom up", not constrained by top-down budgets, and are shown in an order of increasing commitment, starting from a reference of zero investment in LEO (Level 0), which will serve as an analysis of stakeholder capabilities that are at stake in this decision process.

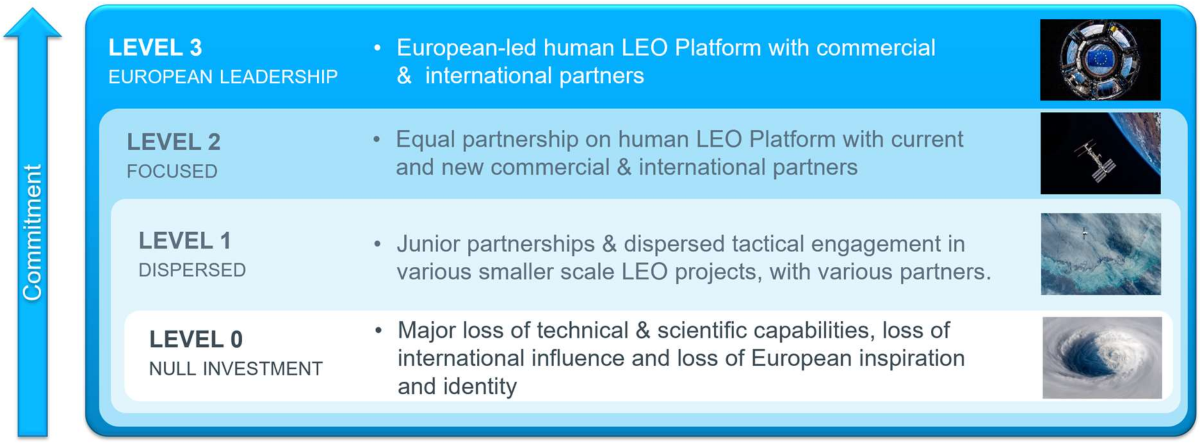

Figure 3: Engagement levels for Making Space for Europe in Low Earth Orbit

5 The Open SciHab concept and its Strategic Elements

The "Open SciHab" concept (Figure 4) is proposed as Europe's future keystone element for LEO. Its core consists of a "next generation advanced laboratory & habitation module" (or a set of modules), that are provided by European companies as a service, covering basic research and living functions:

"*Sci*" = generic intra- and extravehicular science space that can accommodate experiment hardware of various sizes and purposes, including the provision of resources (e.g., power, data, cooling, gases, venting, vacuum, stowage). Capabilities should at least be on par or exceed those currently available on Columbus.

"*Hab*" = basic habitation functions to sustain the long-term presence of humans (environmental control and life support, communications, sleep stations, galley, toilet, exercise devices, stowage), as well as human-tended robotic operations.

The term "*Open*" refers to the open architecture that allows for software and hardware extensions by various providers at any stage in the project lifetime, as well as openness of the concept for international and commercial cooperation by being modular and extendable. This also allows to change out ageing hardware in time, therefore preventing a "built-in" operational age limit.

The SciHab concept is based on a solid foundation of experience from European heritage projects such as Columbus, I-HAB and ESPRIT. An important innovation of this concept is its modularity on various scales. Due to the "open" infrastructure, stakeholders (including Member States with smaller contributions to the E3P programme, as well as international partners) that are subscribing to the SciHab core service will have the opportunity to add functional "*Strategic Elements*".

These could be more advanced research and technology capabilities that stakeholders can choose depending on their individual priorities and strategy (shown as individual puzzle pieces in Figure 4). Examples for "Strategic Elements" are:

- Science airlock and external platforms
- In-Space manufacturing & recycling
- On-Orbit assembly, servicing and refuelling
- Advanced life support systems
- Radiation protection
- AI & autonomy from ground systems
- Intra-vehicular and extra-vehicular robotic assistance to humans
- Space based solar power demonstrators
- Electric propulsion

- Medical applications
- Human Mars Transit Technologies
- Entry-Descend-Landing (EDL) technologies for other planets such as Mars, tested in Earth's upper atmosphere.

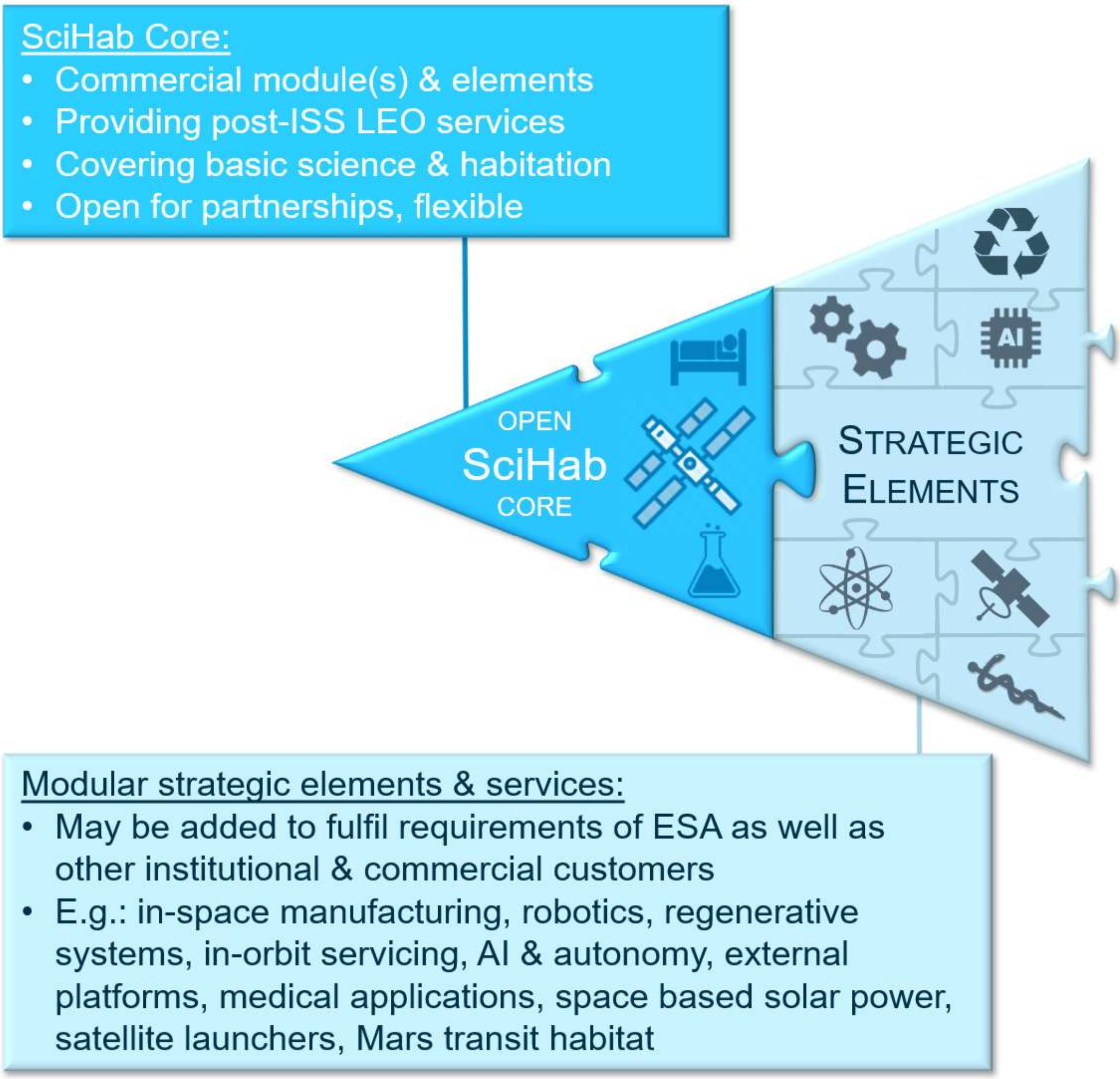

Figure 4: The "Open SciHab" concept: The deep blue triangle depicts the SciHab core laboratory and habitation module(s) provided as a commercial service. The light blue puzzle pieces show a selection of potential functional strategic elements to be added at various steps.

The strategic elements could be added in various ways, e.g., as a sub-systems or modules, either from the beginning or at a later stage of the project, as stakeholder-owned hardware or as a commercial service. Similarly, the SciHab core, i.e., basic science and habitation capabilities, will not necessarily have to be implemented as a single module by the commercial provider. Instead, it could be implemented on orbit through a stepwise delivery of various modules and elements. Some strategic elements might even be implemented on ISS before transitioning to the SciHab concept.

Added small-scale functionalities can, over time, be combined and evolved into larger ones, forming innovative "science firsts" or even game-changing elements. For example, an advanced closed-loop life support system or a demonstrator for a Human Mars Transit Habitation Module would allow for the integrated testing and demonstration of all elements that are required for a habitat that can carry humans on the long journey to Mars. An intermediate step could be the transfer of such an evolved SciHab element from LEO to the Gateway, where it can be used and tested in a deep space environment.

On the other side of the spectrum, an On-Orbit-Factory could be implemented making use of In-Space Manufacturing technologies and increased human-robotic synergies. An On-Orbit-Servicing and refuelling element could provide support for other LEO operations and beyond. A test and demonstrator element for Space-Based Solar Power Generation could ensure that Europe remains at the forefront of green technology development. Depending on the choice and scale of these added functionalities, various levels of European leadership and innovation can be achieved. These range from simply covering basic research and habitation functionalities, to a "smart" leadership in a carefully chosen focussed area that enables a high profile of benefits, or European leadership in a wide area of newly developing on-orbit and exploration technologies.

A detailed list of potential strategic element contributions that could be of interest to the Member States and to international partners can be found in Table 2. The Table captures the various strategic contributions identified in the context of the Terrae Novae LEO Strategy, and is fully in line with the roadmaps developed by the International Space Exploration Coordination Group (ISECG)[5].

An important lesson learned from two decades of ISS operations is that, in addition to providing technical and scientific resources, a human LEO platform has the potential to provide an enormous educational and inspirational return on investment. Therefore, the concept of SciHab as an educational platform for the citizens of Europe shall be considered from the start. In the age of social media, which is offering a direct communication conduit from the heart of on-orbit operations right to the smartphone displays of European citizens, new concepts should be explored, such as public live streams of on-orbit experiments, as well as increased live interaction during video events and educational programmes.

6 Interactions with international partners

SciHab is intended to be a cooperation element. I.e., it can be part of a wider orbit infrastructure that is able to provide certain resources or functionalities of an orbital platform. The precise nature of this framework will only be able to be defined when the future LEO platform possibilities are known. The initial SciHab concept should thus be compatible with ISS but also with newly proposed commercial and institutional infrastructures (e.g., proposed by Axiom, Sierra Space Corporation, Blue Origin, Nanoracks, or by international partner agencies), allowing for maximum flexibility along its development phase, to retain the option for a smart reaction to changes in the LEO landscape. At the same time, commercial providers

[5] https://www.globalspaceexploration.org/

are invited to propose certain configurations that they see as beneficial in the frame of the RFI.

The overall scenario in which the SciHab concept operates will eventually be determined by the partnerships that are chosen once stable cooperation elements can be identified in the LEO landscape. Europe could contribute a multitude of elements to such an on-orbit partnership, such as to i) provide access to the SciHab core facilities ii) provide access to its extension interfaces and resources for additional functional elements, and iii) provide additional functional elements. The commercial provider of SciHab may also provide such services directly to its partnering entities. For example, access to the habitation module of SciHab could be rented out to a commercial partner for activities in space tourism when capabilities are abundant, e.g., by hosting commercial spaceflight participants in between European science missions.

Partnerships with commercial entities obviously come with a new type of dependency. Europe will not only have to rely on familiar governmental agency partners, but it might also have to rely on non-European companies on its critical path, which can be an added risk to the successful completion of European space missions.

One of the main dependencies will concern human access to space. First signs of such a change in partnership nature can be observed in NASA's transition from using the institutional Russian Soyuz human transport system to US commercial crew transport providers such as SpaceX or Boeing. European astronauts flying on Soyuz were fully integrated spacecraft pilots and equally qualified operators with their Russian colleagues. In contrast, European astronauts flying on SpaceX vehicles are so far regarded as passengers without many responsibilities, and with reduced access to technical as well as operational information, based on US technology transfer restrictions (ITAR) and company security policies. These restrictions are clearly leading to a reduction in operational proficiency of European astronauts, which will impact the readiness of the European astronaut corps for future missions.

7 Innovative Procurement

A European commercial approach is proposed for the implementation of the SciHab concept, based on the purchase of end-to-end services from a European Commercial Service Provider.

The proposed transition from a classical procurement approach, where hardware is defined, owned and operated by ESA, towards the procurement of commercial end-to-end services will require the careful definition of high-level requirements for the services to be purchased, and the release of some level of control towards the service providers.

To complement the SciHab core, to achieve the concept's full scope, additional modular strategic elements could either be built and operated by partners in the classical way, or they could be procured as services from commercial providers. This represents a new opportunity for European SMEs and Terrae Novae Participating States with smaller contributions to engage in the new LEO landscape and European on-orbit infrastructure.

8 Potential on-orbit configurations of SciHab

Four potential on-orbit configurations of SciHab are presented here as examples in anticipation of current and future developments in the LEO environment. However, potential solutions from industry should not be limited to these configurations, but could entail a combination of them, or even a distributed configuration that is spread across several platforms.

All configurations will require a transport system, or a tug, to deliver SciHab elements to their precise orbit destination and to perform the docking to its host infrastructure. Compatibility with a European launch system should be ensured, along with the possibility of using other launch systems. Additionally, all configurations will have to consider how the infrastructure will be operated and utilized over a period of at least one decade.

A. Cooperation with the commercial Axiom Station - potentially through temporary SciHab implementation on ISS.

Axiom Station is expected to gradually build up in the coming years, located on a forward docking port of ISS. After reaching a critical on-orbit capability, and before the end-of-life of ISS, Axiom's plans are to undock its new station from ISS to operate independently. The SciHab concept could be implemented with ESA being the anchor customer of a European Commercial Service Provider that is cooperating with Axiom. SciHab hardware could be hosted on Axiom Station during its build-up phase, and then separate with it from ISS eventually. Several technical implementations are conceivable and should be considered by the commercial provider, including the re-location and re-use of Columbus as part of SciHab before undocking from ISS. As an operational concept, SciHab could generate its own resources, or it could purchase/trade resources from its host station. A possible trading element could be to allow the European commercial provider to host commercial spaceflight participants in SciHab when surplus capabilities exist.

B. Cooperation with the commercial Orbital Reef / StarLab Stations (or similar), potentially with an added contribution of a resource module as well as functions like attitude and orbit control.

Various US companies develop plans for operating their own independent LEO platforms. Amongst these, Orbital Reef is one of the most advanced concepts, based on its inflatable LIFE modules, node structures, and human transportation. Similar to configuration "A", ESA could act as the anchor customer of a European Commercial Service Provider that is cooperating with the operators of Orbital Reef or StarLab. The commercial provider could attach SciHab to one of these platforms and operate it from there. As a trading element, SciHab could potentially provide resources and functions to the entire station, such as attitude control through a resource module, or transport elements.

C. SciHab on ISS in combination with an ISS life extension.

In case of a delay in the establishment of the currently planned US commercial LEO services, it is conceivable that ISS partners decide for a significant extension of life of ISS beyond the early 2030s. This could be achieved by replacing ageing key functionalities of the Russian Segment such as propulsion and attitude control, similar to what has been achieved in the recent past by replacing ISS solar arrays, external batteries and internal equipment. In such a scenario, SciHab could be implemented on ISS making use of existing European assets such as Columbus and Bartolomeo, allowing Europe to operate on ISS significantly beyond 2030. As an additional functionality, SciHab could provide propulsion and attitude control capabilities, or other resources to the renewed ISS. This might allow Europe to offer a new barter element to the ISS partnership, potentially including attractive new technologies such as on-orbit refuelling.

D. Cooperation on a future institutional space station in an international setting.

Several space-nations have expressed their plans to support institutional capabilities in LEO in the mid to long-term future, on which commercial operators might also play a role. While no concrete plans for such a cooperation exist currently, mostly due to the early definition stages of potential partner platforms, there is a potential for a future international cooperation with Europe in a significant role, similar to the current ISS partnership. A variety of cooperation opportunities can be envisaged, some of which might create challenges with export control regulations that will have to be carefully evaluated.

In all these configurations, commercial contributions from European Commercial Service Providers could be to provide an end-to-end service through the operation of the SciHab Core, as well as by providing additional strategic elements.

Table 1: Matrix showing which European LEO engagement levels are supported by the various SciHab configurations.

	Level 1 Junior Partnership	Level 2 Equal Partnership	Level 3 European Leadership
No SciHab concept	X		
SciHab configuration A		X	
SciHab configuration B		X	
SciHab configuration C		X	
SciHab configuration D		X	X

Depending on the scope of the European contribution, and depending on the implementation of various strategic elements, a Level 2 engagement could be achieved by the SciHab

configurations A, B, C, and D (Table 1), leading to a junior or even equal partnership as outlined in Figure 3. Level 1 could be achieved without implementing the SciHab concept, either by paying for services to non-European providers, or by providing resources such as attitude control to a commercial operator, e.g., with a CLTV derivative, to barter for limited access to commercial research facilities. Such a minimal engagement level, however, would reduce and cement Europe's role in LEO to that of a junior partner for decades to come. It would also result in the loss of significant operations expertise that has been gained through the ISS program.

On the other end of the spectrum, configuration D would be suitable to enable a Level 3 engagement, especially when combined with European leadership elements and the strategic autonomy of a European transportation system for cargo and humans.

Table 2: SciHab Strategic Elements and Modular Functionality contributions, taking into account Terrae Novae strategic goals, Member States interests, as well as supporting ISECG road maps.

SciHab strategic elements	Description
Intravehicular science instrumentation and technology demonstrators	There are widespread capabilities amongst ESA Member States and European commercial entities to develop relevant science instrumentation and technology demonstrators. This category represents a particular opportunity for Member States with mid-sized to small budgets to contribute to a future LEO platform. Potential for various "science & technology firsts".
External Platform & Science Airlock	Extravehicular platforms and science airlocks are important for increased scientific capabilities and technology demonstrations. They provide the most flexible way to operate various-sized payloads which require / benefit from the outer space environment (e.g. materials exposure, exobiology, remote sensing). Based on past operational experience, it is important to foresee a complete end-to-end logistics for these payloads, thus including unpressurised and pressurised cargo logistics with the availability of airlocks. Due to the fundamental importance of access to external payloads, it is advisable to implement this functionality not as an optional strategic element, but to include it in the requirements for the SciHab core functionality. There is European heritage (e.g., Bartolomeo, IBDM, Cupola) of many of the required technical capabilities.
Artificial Intelligence (AI) & Robotics	Maximum output of a LEO orbital platform will be achieved by a synergy between human and robotic capabilities. AI and Robotics technologies will be required to achieve further

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	exploration goals. Some of the AI applications in space missions are autonomous location tracking, navigation and map-building, simultaneous localisation and mapping (SLAM) technology, fault detection, trend analysis, isolation and recovery methods, image processing, object identification and feature detection, task planning and scheduling. Robots can help the space exploration process through planetary rovers, manipulators, actuators, sensors, end-effectors, all of which are potentially interacting with a human crew. AI and Machine Learning are expected to facilitate the integration of human and robotic assets in support of space science and exploration, also enabling a greater autonomy for the crew. Intravehicular robotic systems can support utilization during times when crew is on board, by performing routine or repetitive tasks with high precision. Additionally, they can be designed to support limited utilization during times when no crew is on board. There is confirmed European interest (ExPeRT studies) in many of the required technical capabilities. Potential for various "firsts", game-changing technology development and critical enablers for deep space exploration.
Regenerative Environmental Control and Life Support Systems & Food Production	Advanced, maximally closed, life support systems, based on traditional technologies as well as novel approaches are amongst the most important elements for future human space exploration. Various sub-module systems exist, ranging from plant production equipment and/or other elements such as microbial oxygen & waste processing systems. The LEO environment is a critical testbed for such advanced infrastructures. Part of any advanced ECLSS system will be to close the Carbon cycle. Resources to be delivered from Earth to Lunar and possible Martian environments will be very limited. Consequently, nutrition / space food production will be required to enable sustainable space exploration during multi-year missions. An incremental approach to test the necessary raw materials production and subsequent food conversion shall ideally be implemented in a LEO environment first.

SciHab strategic elements	Description
	There is European heritage (e.g., MELISSA, ISS Life Support Rack) of many of the required technical capabilities, but a significant technology gap exists. Potential for various "firsts", game-changing technology development and critical enablers for deep space exploration.
In-Space Manufacturing	In-Space robotic technologies are rapidly maturing, they are being developed by all major space actors. New capabilities for In-Space Manufacturing and Assembly (ISMA) will generate on-orbit services improving the orbital infrastructure and creating in turn very promising business opportunities in terms of market volume. The establishment of a European in-space manufacturing capacity in LEO is necessary for building this new space infrastructure and to capture a fair part of this market that could be otherwise monopolised by Non-European companies. There is limited European heritage (e.g. 3D-Metal Printer) of many of the required technical capabilities, and current in-space manufacturing initiatives by ESA are under way to further increase these capabilities. Potential for various "firsts", game-changing technology development and critical enablers for deep space exploration.
Servicing & Refuelling Capability	The safe and sustainable operation of any orbital outpost require the mastering of servicing and refuelling capabilities. Within the broad On-Orbit Servicing (OOS) domain, a robotic refuelling capability is attractive, because it would allow to keep orbital platforms alive and working that would otherwise have to be deactivated due to fuel depletion; refuelling capabilities are also envisaged to enhance usability of small LEO launchers. The design of On-Orbit Refuelling (OOR) systems is intrinsically multi-disciplinary as structural interfaces, fluidic, relative dynamics and procedural aspects must be simultaneously considered and harmonised. There is limited European heritage (e.g., ATV, ESPRIT) relevant for such infrastructure element. Potential for various "firsts" and critical enablers for deep space exploration.

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Electric Propulsion	New propulsion technologies will be essential for future deep space exploration, as well as for commercial operational services in LEO and around the Moon. Electrical propulsion technology has strongly advanced in the last decade, increasing in efficiency and thrust level. New technologies will strongly benefit from the possibility of research and demonstration payloads on a future LEO platform.
Remote Medical Applications	Crew safety and mission success face several challenges in deep space, including physiological adaptations to microgravity, radiation exposure, accidental exposure to extreme temperatures and vacuum, and psycho-social reactions to spaceflight. Most importantly, the lack of on-board resources limits medical procedures to a low level, even if they are abundant on Earth. Long-duration deep space missions will require further technological breakthroughs in tele-operations and autonomous technology. Earth-based monitoring will no longer be real-time, requiring telemedicine capabilities to advance with artificial intelligence as crews travel deeper into space. Their implementation in LEO will serve as a testbed as well as improve the quality of healthcare delivery on Earth. There is European heritage (e.g., tele-operated echography, TEMPUS instrument) of many of the required technical capabilities. Potential for various “firsts” and critical enablers for deep space exploration.
Demonstrator for Space-Based Solar Power	Space Based Solar Power (SBSP) is the concept of collecting solar power in outer space and distributing it to Earth. Potential advantages of collecting solar energy in space include a higher collection rate and a longer collection period due to the lack of a diffusing atmosphere, and the possibility of placing a solar collector in an orbiting location where there is no night. Space-based solar power systems convert sunlight to microwaves outside the atmosphere, avoiding these losses and the downtime due to the Earth's rotation, but at added cost due to the expense of launching material into orbit. Despite the added cost, SBSP could be of great advantage as a flexible, grid-independent power supply for Earth-based

SciHab strategic elements	Description
	disaster responses, and is considered a form of sustainable or green energy. SBSP also has the potential to play an important role in planetary exploration of Moon & Mars. There is presently no European heritage for such required technical capabilities. International partners such as NASA have stated their intent to implement such a function, thus cooperation opportunities exist.
Demonstrator for a Human Mars Transit Habitation Module (HMM)	The implementation of such a module on a LEO platform would be an innovative approach to gain the required knowledge and technical capability to send a crew to Mars. A demonstrator module could accommodate an isolated crew for an extended simulation of several months duration to test technology, operations and human factors for a Mars transit. The Module should have the possibility to connect to a subset of resources from a platform that it is attached to, while being autonomous for key aspects like life support, communications, technical autonomy, etc. The module communications would be run with a simulated time delay representative of transit to Mars. A similar initiative (named "ISS4Mars") of a demonstrator of a full voyage to Mars making use of the ISS, is currently studied; possible synergies could be investigated. There is limited European heritage (e.g., ATV, ESM, CLTV) of many of the required technical capabilities.
Staging Post for Deep Space	SciHab could host a dedicated infrastructure with several docking ports that allows components / modules to be "parked" in orbit while additional required components are prepared. It will provide resources such as power, thermal, data, refuelling, and outfitting options. The infrastructure might even have a pressurised internal volume that allows access to the docked components when required for outfitting / servicing tasks, but it does not require long-term human presence. To ensure maximum versatility, docking adapters for all common docking systems will be present (potentially parked on an external pallet). There is limited European heritage (e.g., ATV, ESM, CLTV) of many of the required technical capabilities. Potential for various "firsts" and critical enablers for deep space exploration.

SciHab strategic elements	Description
Factory Module / Platform & In-Space Assembly	Scaling up from the above-mentioned In-Space Manufacturing demonstrators, a "factory module" could provide multiple users with a testbed to demonstrate production technologies, providing the required resources either in a pressurised environment or in open space. With flexible design, additional factory modules could be launched that are dedicated to single customers for their end-to-end manufacturing process. There is presently no European heritage for such large-scale technical capabilities. Potential for various "firsts" and game-changing technology development.
Free-flyer Elements	Small free flying infrastructures could be conceived that operate independent from SciHab for a certain period of time to make use of a clean micro-g environment, after which they return to the larger infrastructure for servicing or the refill of resources. However, redundant European capabilities for a generic free-flyer platform are projected to exist with Space Rider, who is targeting to provide a robotic environment with a very high quality of micro-g, albeit for much shorter missions than what is possible on a LEO platform. A potential payload for a free-flyer that is based on a LEO platform could be a telescope for Earth or space observation. There are significant European contributions (e.g., Hubble, James Webb Space Telescope) of many of the required technical capabilities, but an end-to-end capability has not been demonstrated.