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The Orbital-Hub: Low Cost Platform for Human Spaceflight after ISS

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Abstract

The International Space Station ISS demonstrates long-term international cooperation between many partner governments as well as significant engineering and programmatic achievement mostly as a compromise of budget, politics, administration and technological feasibility. A paradigm shift to use the ISS more as an Earth observation platform and to more innovation and risk acceptance can be observed in the development of new markets by shifting responsibilities to private entities and broadening research disciplines, demanding faster access by users and including new launcher and experiment facilitator companies. A review of worldwide activities shows that all spacefaring nations are developing their individual programmes for the time after ISS. All partners are basically still interested in LEO and human spaceflight as discussed by the ISECG. ISS follow-on activities should comprise clear scientific and technological objectives combined with the long term view on space exploration. This includes key competences like robotics, internal and external space structures, module/facility and experiment operations as well as supply systems (e. g. ATV). Giving financial feasibility priority, DLR started to investigate future low cost options by evaluating various LEO infrastructure concepts including opportunities for national realisation and international cooperation. Scientists and users from various disciplines were involved to assess the usability of corresponding options. Proposed payloads were based on their Mir and ISS experience with respect to future scientific fundamental and technological research questions. Together with US and European industry, NASA and ESA astronauts, operation specialists, current ISS users and scientists, DLR conducted an extensive concept study using the DLR Concurrent Engineering Facility (CEF).

The present paper describes the results of these activities with a Phase A design called Orbital-Hub based on a small low cost manned LEO platform including a man-tended free flyer. The first flying H/W components could be realised in the frame of moderate budgets in the next eight years. The Orbital-Hub would guarantee a smooth transition between ISS and further space activities in and beyond LEO and would represent an important step regarding long-term space research, Earth observation respectively monitoring and human space exploration.

Keywords: Post-ISS, Human Spaceflight, Low Earth Orbit, Base Platform, Free Flyer

Acronyms/Abbreviations

AHP:	Analytical Hierarchy Process
ATK:	Alliant Techsystems Inc.
ATV:	Automated Transfer Vehicle
CE:	Concurrent Engineering
CEF:	Concurrent Engineering Facility
CSA:	Canadian Space Agency
DLR:	Deutsches Zentrum für Luft- und Raumfahrt / German Aerospace Center
ECLSS:	Environmental Control & Life Support System
EVA:	Extra Vehicular Activity
H/W	Hardware

IBDM:	International Berthing and Docking Mechanism
IDSS:	International Docking Standard
ISECG:	International Space Coordination Exploration Group
ISPR:	International Standard payload Rack
ISS:	International Space Station
LEO:	Low Earth Orbit
MLI:	Multi Layer Insulation
MPCV:	Multi Purpose Crew Vehicle
OHB:	Orbital- und Hochtechnologie Bremen
SLS:	Space Launch System
wrt:	with respect to

1. Introduction

The International Space Station ISS demonstrates long-term international cooperation between 15 partner governments as well as a significant engineering and programmatic achievement. Regarding possible LEO activities after ISS operation a paradigm shift to higher innovation and risk acceptance can be observed. This holds for the development of new markets by shifting responsibilities to private entities and broadening research disciplines, demanding faster access by users and including new launcher and experiment facilitator companies. U.S. commercial launch providers currently are e. g. SpaceX and Orbital Sciences. U.S. experiment facilitators are e. g. NanoRacks, Kentucky Space and the mediator foundation CASIS. A platform provider with a commercial approach is the US-company Bigelow Aerospace. European experiment facilitators Airbus and OHB also try the commercial approach in Europe.

Spacefaring nations are developing their individual programmes for the coming years, i. e. the time after ISS [2]: NASA shifts LEO operations and utilisation services to competing U.S. commercial companies while focussing on the next preparatory steps of exploration (e.g. SLS, MPCV) of asteroids, the Moon and in the long-term, Mars. Russia plans new human-rated space infrastructures at various optional locations in space (e.g. OKA-T Free Flyer) rather than committing to continue the utilisation of its ISS modules. In the field of human spaceflight, China continues with its Chinese Space Station CSS and prepares its next objective: a human Moon landing. Europe's human spaceflight partners tend to consider new platforms in LEO or cis-lunar space and utilise ISS as long as possible. A necessary transition is expected beyond 2024. Europe itself is interested in continuing research according to its LEO 2020 roadmap in particular wrt human spaceflight as discussed by the ISECG, depending on the funding [2]. In the following a non-binding German proposal for a corresponding concept is described.

2. Objective and Motivation

Clear scientific, technological and commercial objectives combined with the long-term global view on space exploration (habitation, crew training, robotics, experiment operations, supply systems) have to be considered wrt the set-up of an ISS follow-on concept. Therefore, DLR started to investigate future options by evaluating various LEO infrastructure concepts including opportunities for national realisation or international cooperation. DLR scientists from various disciplines assessed the usability of these options and designed strawman payloads based on their Mir and ISS experience wrt future scientific fundamental and technological research questions.

Currently (status mid 2016) all ISS partners agree to utilise the orbital research facility until at least the year 2020. NASA, Roscosmos and CSA announced to support the extension of the ISS until 2024. There is a common understanding that a platform in LEO is crucial for continuous research, technology demonstration, Earth observation and monitoring as well as *for preparing the next steps for going to Moon and Mars*. With a corresponding lean LEO concept, based on today's knowledge and based on all the ISS experience *a significant cost reduction compared to ISS could be achieved*.

A transition to such a new concept without a critical loss of know-how takes up to 10 to 15 years. Therefore, the conceptualisation regarding technical layout, creating a road map and development of a follow on outpost in LEO must be started ***now***.

The DLR concept ORBITAL-HUB (see Fig. 1 and [1]) described in the present paper can be understood as national preparatory work for the establishment of future programmes in the field of human spaceflight and to secure long-term research and astronautical activities in LEO. In summary, the engineering concept study is focussed on the basic question how to continue with space research and space technology development after the ISS utilisation period. Therefore, the following objectives were defined within the present DLR study:

- analysis of the pros and cons of current ISS,
- recommendations based on lessons learned,
- market research of existing technologies,
- analysis of additional user demand, *like a desired man-tended Free Flyer* including additional scientific disciplines and technological research,
- design of infrastructure concepts,
- analysis of the reusability of the current architecture.

The overall goal is to prepare a proposal for a technically feasible, financially affordable, lean and useful future LEO-platform beyond the year 2025. Finally, the future platform might even re-use some of the existing ISS modules and technologies.

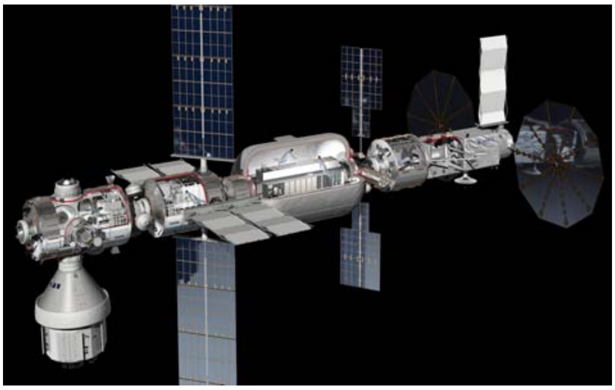

Fig. 1: DLR's Orbital-Hub with docked Free Flyer

3. User Demands for LEO Platform

Requirements from many research disciplines regarding a small future LEO platform had been collected by DLR scientists and engineers [2, 4] and analysed. In a Concurrent Engineering study strawman payloads were defined and analysed for a Base Platform and a strongly required Free Flyer. Both platforms form the Orbital Hub as a possible ISS follow-on human spaceflight research platform in LEO described in section 4 of the present paper. In addition to traditional -µg-research, an extended focus has been set on payloads for future Earth Observation, Atmospheric Physics and Technology Demonstrations for human-rated platforms. The following overview summarises the top-level science driven requirements which are quantified in [3]:

- observe processes in real-time (e.g. materials); on-orbit analysis opportunity to significantly reduce the return of samples,
- low vibration levels (e.g. caused by astronauts or moving structures),
- high and flexible modularity (easy access and exchange of samples or instruments),
- high data transmission rate possibility and storage,
- storage for instruments, spare parts, new hardware, samples,
- long-term utilisation time (e.g. min. 10 years),
- robotic exchange of samples, higher autonomy
- maintenance possibilities, work bench,
- wrt astronauts: short term crew exchange for extended complementary terrestrial research, long-term mission for preparation of exploration activity aspects.

Issues like orbital structure layout and logistics, best location of payloads and secondary demands, e.g. data volume, I/F, Crew and lifetime were included. All of them drive the orbital concept design.

Tab. 1: Results of top level user demands on Post-ISS platform design

	Science User demand for P/L	**Overall System Design**
Base Platform	≤ 8kW average	30kW total
	payload mass: ~ 3.5t (initial) experiment resupply: 1-2t	total mass: ~ 66t
	P/L-equipment in lab: ~ 5 ISPR	available equipment in lab: ~ 24 ISPR
Free Flyer	≤ 10kW average	20kW total
	payload mass: ~ 8.5t (initial) experiment resupply: < 1t/yr	launch mass: ~ 19t (science P/L on launch config.: ~1.5t)
	P/L-equipment in lab: ~ 5 ISPR	available equipment in lab: ~ 12 ISPR

Tab. 1 displays identified top level user demands in comparison with the overall system design. To give a rough idea of the required and available volume for equipment (e.g. scientific P/Ls and other subsystems inside the pressurized parts of the "Orbital Hub") the unit ISPR (International Standard Payload Rack) is applied. This corresponds to a standardised rack used in the ISS with dimensions roughly: 2m × 1m × 0.9m and mass ≤ 800kg (incl. PL), power 3-6 kW. Future equipment, however, will probably have different standard measures (especially in order to be compatible with the IBDM (International Berthing & Docking Mechanism) with Ø = 80 cm).

Once the system and experiment equipment are in orbit, operational costs are intended to be reduced by implementing modularity of all experiment equipment, an improved station wireless network and improved data transfer options. The latter shall allow more direct monitoring and controlling of experiments by the user on ground.

Scientific users also demand accuracy (i.e. pointing) and low impacts caused by the crew or mechanical parts of the platform (i.e. vibration from rotating panels or from exercising crew). The Free Flyer in free and uncrewed mode shows one solution as well as electrical propulsion for orbit keeping on both platforms thus providing stabilities over weeks around the required up to 10^{-6}g.

User wish to have more 'do-it-yourself' options in the lab as one does on Earth. Therefore work benches have been included in the design allowing not only to maintain the platform and the experiment racks but also to provide flexibility for investigators to manufacture or alter H/W if needed. In the following some baseline requirements for the Base Platform as well as for the Free Flyer of the Orbital Hub are shown (for details see [1] and [4]).

Base Platform: Maximum total power requirements (all experiments on in parallel) are high (~ 20 kW). Most experiments, however, have duty cycles between 5 and 50 %, so that suitable experiment time lining should be possible with an average power demand of up to ~ 8 kW. Required data rates and data volumes for scientific payloads are moderate due to the low duty cycles in most cases. Some video links and teleoperations / telepresence from ground are proposed (e.g. in Gravitation Biology and Human Physiology), but they are not excessive and stay within ISS-standards. The up to now proposed (DLR internal) scientific (strawman-) payloads for the Base Platform are mostly derived/extrapolated from present ISS-research. Those payloads do not call for any special novel support from a future LEO space platform and thus represent no significant design driver. Commercial utilization proposals are under consideration by industrial partners like Airbus DS. A broader poll within the scientific community and industry in Germany and Europe could extend the basis of information and is strongly recommended.

Free Flyer: The total mass of all proposed strawman payloads is more than 8000 kg. Probably they cannot be accommodated all together on the initial launch configuration (→ to stay within required single launch mass limit) and must be transported with later resupply flights/launches. The accomodation can be done in docked mode with crew support via the airlock inside the pressurized lab of the Free Flyer plus a robotic arm. If dimensions of the hardware are large (on the order of about 1 meter or more) a procedure for subsequent transportation and placement of potential payloads on the platform after launch should be defined (because the standard airlock has a diameter of ~ 80 cm.). An option could be using unpressurized cargo ships and robotic transfer via 'free space' - requiring eventually a special robotic arm. Power requirements (≤ 10 kW average) can be managed via time lining due to payloads duty cycles of typically 50 % or less. Most required data rates & volumes are standard and comparable with ISS capabilities; some demanding requirements may derive from future Earth observation payloads (e.g. more than a few TByte/day downlink due to very high resolution observations). An update of the current relay satellites and station capabilities is assumed to handle increasing data volume in the range of T-byte. Some of the considered Earth observation and astronomy payloads require dedicated pointing platforms (e.g. the MUSES platform - under construction at Teledyne Brown Engineering, Inc. TBE (USA) for ISS applications). Most experiments have a finite operation-time of about one to several years. Thereafter they should be removed/exchanged. Also a lot of resupply items are needed for some of the experiments during operation. Contrary to the situation on ISS, future material science experiments (assumed to be located in the pressurized lab of the Free Flyer) will be fully automatic and/or monitored on ground in real time with transmission of in-situ diagnostics (video surveillance and tele-science). Crew activities may only be necessary from time to time (typically every 3-6 month) for exchange of experiments and maintenance. The same holds true for Earth observation payloads, which may be relatively short lived or could be of experimental type (contrary to operational), where the crew is needed for exchange of damaged or contaminated instruments (typically every few years). A new application for space platforms may be the test of experimental electric propulsion systems in combination with operational electric propulsion for drag compensation and orbit keeping.

Last but not least the programmatic environment has been addressed. In general user demands conclude that: the ongoing lessons-learnt analysis should be completed to improve the research programmes and processes on Low Earth Orbit (LEO) human rated. After more than ten years of ISS Human spaceflight, the research within ESA and national programmes should change so that scientists do not wait for an equipment and launch window for more than 2 years. Easing access, allowing commercial platform use, defining programme budgets while keeping a thorough selection process for public funded research requires a paradigm shift.

4. Technical Concept

Using the Concurrent Engineering Facility (CEF) of DLR several draft platform concepts have been set up. Four of them were chosen for detailed evaluation using the Analytical Hierarchy Process (AHP) regarding political, social, technical and economic criteria. A lean multi-purpose platform with a dockable free flying platform was evaluated to be the most promising option from a European and German budget point of view (see Fig. 1). The name Orbital-Hub stands for the core element of a modular logistics/distribution centre - the core of a space village idea: on the hub, spacecraft can dock and be serviced, or goods (e.g. propellant or experiments) can be distributed ("hub" as distribution node [3]).

In contrast to the ISS platform, where the complete assembly process to reach its 6-Crew operational readiness was spread over more than 15 years and is partially still ongoing, the simple design of the selected Orbital-Hub concept follows a different approach: to be assembled and equipped using only a handful of launches. For the next generation of LEO platforms, the lessons learnt and experiences gained from ISS [2] allow an assessment of critical minimal functionality required for a scientific astronautical utilisation. The result is a much smaller and simpler platform (see Fig. 2). The presented preliminary technical concept has subsequently been developed in two additional CE studies together with partners from industry [5]. Particular attention has been payed to design the hardware wrt existing flight systems, to reduce development time and cost.

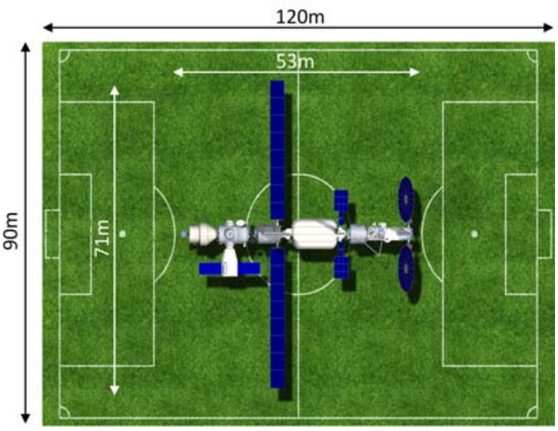

Fig. 2: Overall dimensions of Orbital-Hub with docked Free Flyer in comparison with standard soccer field size.

For a continuous 3-Crew platform plus possible visitors, at least one module for science laboratories, crew accommodation and according environmental control and life support systems is required. For this functionality, the design foresees an expandable habitat (as e.g. developed by Bigelow Aerospace [6] and tested aboard the ISS). The current concept for the Base Platform including internal equipment is shown in Fig. 3. A service module accommodates the necessary systems for attitude, orbit and thermal control and power provision.

The Base Platform shall also be compatible to simultaneously visiting by transport- / crew-vehicles. Therefore, a five-point docking node using the IBDM standard is positioned at one end of the Base Platform. The advantages of a cupola in the sense of direct visual feedback during e.g. teleoperation of robotic arms and its great popularity among astronauts on the ISS lead to the decision to reserve one of these ports for such a viewing platform. Additionally, the docking node houses communication and data systems and allows for possible future extensions.

Up until now, there have been more than 190 EVAs on the ISS [1]. EVAs need a significant amount of the precious crew-time for preparation and conduction and, thus, create additional operation cost [2]. In contrast to the ISS, the Orbital-Hub concept is designed to limit the number of EVAs by placing of items externally with support of robotic manipulation. However, an EVA contingency airlock is foreseen for the Base Platform. To perform routine servicing and equipping of the external platform via robotic manipulation, a payload airlock is included between the pressurised and unpressurised parts of the Free Flyer (see Fig. 5).

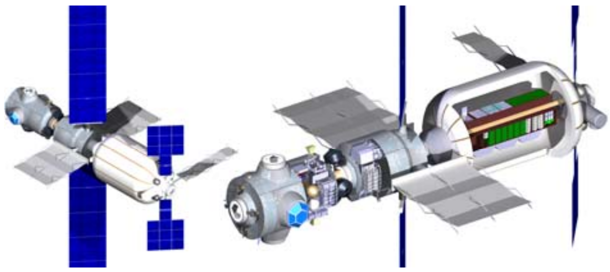

Fig. 3: External (left) and sectional (right) view of Orbital-Hub's Base Platform.

Since the critical user requirements regarding attitude and disturbances are shifted towards the Free Flyer, the Base Platform is free to roll or yaw a certain amount. This allows for a one-axis rotatable solar panel design which does not need additional truss structures as on the ISS. Thereby, the base configuration is free to have the Habitat Module or the Docking Node point into the direction of flight. To avoid regular refuelling for orbit maintenance, the respectively docked crew or cargo vehicle could provide the required thrust to perform the manoeuvres. Electrical thrusters are a promising solution for continuous drag compensation.

In addition to the habitat, a dockable Free Flyer (see Fig. 4) is part of the Orbital-Hub concept in response to the scientific user requirements. It is intended to fly uncrewed in a safe formation to the Base Platform for e.g. three months periods before it automatically docks to the platform for short duration where it can be maintained, reconfigured, stocked up and P/L transferred for return to Earth.

A pressurised module for µg-research is an essential part of the concept. When docked to the Base Platform (e.g. to the docking node or to the expandable habitat module) or directly to a crew vehicle, the astronauts can access the lab. This enables direct and quick maintenance or replacement of the internal experiments but also for the external payloads before being sent through the included airlock. As the pressurised lab is not intended to be manned during free-flying mode, the ECLSS complexity could be reduced. The air composition and humidity is controlled via the Base Platform or any other visiting vehicle when the Free Flyer is docked. The lab's design is based on the existing Columbus module and, thus, the available knowledge is likely to lead to reduced development time and cost. To perform automated rendezvous and docking manoeuvres with the Base Platform, the lab's in-flight front surface is equipped with multiple sensors taken from the successful ATV, to re-use the associated control concept. The Free Flyer's docking adapter again is the IBDM, which is compatible with the IDSS [7] (first compatible adapter by NASA has been launched on Dragon CRS-09 in July 2016 to be installed on the ISS [8]). Therefore and thanks to its envisaged short development time, the Free Flyer is designed to be ready to dock to the existing ISS for one of its first missions as long as the Orbital Hub's Base Platform is not available.

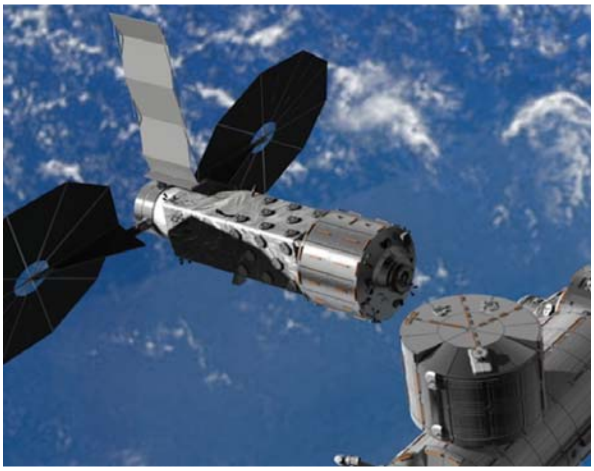

Fig. 4: Fully equipped Orbital-Hub's Free Flyer with deployed photovoltaic and radiator wings.

The external platform is the centre of the Free Flyer. It is equipped with several payload interfaces on each of its sides which provide mechanical berthing, power, data transmission and thermal conditioning. The Free Flyer will orbit with remote sensing instruments pointed nadir but in principle, is free to change attitude for certain periods depending on user requirements. As one result of the Free Flyer's CE study, which has been conducted in close cooperation with Airbus Defence and Space, the external platform is designed as a rigid rectangular truss structure covered with MLI, c.f. Integrated Truss Structure aboard the ISS [9]. To minimize the reserved space inside the pressurised lab, the main volume of the required payload airlock has been moved inside this structure. Once exposed from the airlock, payloads can be reached through a cut-out in the surrounding structure by the robotic arm. This manipulator is moving along a circular rail around the structure to attach different payloads onto the four sides of the platform with respect to their desired pointing direction or additional requirements (see Fig. 5).

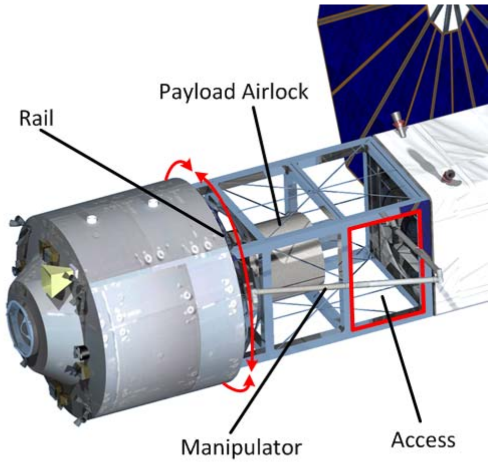

Fig. 5: Free Flyer airlock and robotic manipulator concept for external platform servicing.

In analogy to the Base Platform, the Free Flyer requires a service module for attitude and orbit control, for propulsion and independent power and thermal control. In contrast, the Free Flyer's service module is not supposed to be man-tended and, thus, does not need to be pressurised. As a consequence, it has been designed using the same truss approach as the external platform. By this, the mechanical design for stiffness and launch load transfer through the overall structure has been facilitated.

The photovoltaics area has been sized wrt the derived Free Flyer's power demand during science mode of 20 kW. Conservative solar array wings would have led to a fully-deployed overall span-width of approx. 60m, which, due to an increased vibration-level, would have a negative influence on the quality of µg research. Therefore, a circular solar-array design has been selected. This solar-wing type is currently getting more and more attention, as its sophisticated folding mechanism allows for big photovoltaic areas while still obtaining a small packing-volume, light mass and medium span-width. The currently pictured design (see Fig. 4) is based on the existing MegaFlex / UltraFlex solar arrays by Orbital ATK, which are successfully used by several LEO and interplanetary missions [10].

As described above, the Free Flyer has strict pointing requirements during science mode and consequently, the solar wings are rotatable around two axes to follow the sun's alpha and beta angle continuously. This has been accomplished using a common rotary ring in the rear part of the Free Flyer, where also the thermal radiator wing is mounted to.

The overall dimensions of the Free Flyer in stowed configuration (retracted photovoltaics and radiator wings) are optimised for to be in line with the envisaged single-launch scenario using Ariane 6-4 (see Fig. 6).

Fig. 6: Free Flyer in stowed configuration inside the expected Ariane 6-4 fairing.

The build-up of the Base Platform will be performed later, when the different Platform elements (Habitat, Service Module, Docking Node) - launched in separate parts - are assembled with the help of the Free Flyer in orbit. The overall system design (masses, power etc.) is summarized in Tab. 1.

5. Conclusions

The feedback from many scientists and experts has shown continuous high interest in using the Low Earth Orbit on a multi-purpose mini-platform. As explained in [2] a space laboratory is unique and not replaceable. Research in space complements terrestrial opportunities. Scientists also highlighted the fact that Europe/Germany has achieved a technological system competence by developing, constructing and operating research facilities in space. From all the different analysed scenarios the option with the highest interest and flexibility is the modular Orbital-Hub described in the present paper. It represents the highest degree of maturity based on current technologies, operational / logistical systems, current commercial developments and financial aspects. The modular Orbital-Hub is a realistic opportunity, however, only with a significant involvement of Europe and international (commercial) partners. Alternatively, parts of the concept could be implemented separately, e.g. the Free Flyer only or Base Platform parts as a contribution to an upcoming modular station.

Concept study results suggest further consideration of the following items for potential German key contributions:

- Astronautic and robotic science operation in LEO
- Ongoing requirements definition with national/international science user community
- Know-how regarding automated service modules
- Robotic technology options for internal and external use
- Advanced low thrust propulsion; electric low thrust engine as promising technology for drag compensation for LEO architectures
- Clear technical and programmatic interface definition

During the accommodation design of the interior of the Expandable Habitat module, all rigid parts have been attached to the central core structure. With this approach, the balance between rack accessibility and volume still has to be proven. Independent of this proposal, a follow-on study including interested and dedicated partners and new market players is strongly recommended.

In general, it is expected for future LEO architectures to be smaller, more modular and more flexible than the current ISS. *Complementing payloads such as Earth observation, technology demonstration, commercial applications as well as opportunities for preparation of human planetary exploration will add to the conventional scientific utilisation*. The interest of the user community in a research laboratory and an observation platform in LEO serves as a basis for the architecture's design which is open for future commercial involvement.

The first flying hardware components could be realised in the frame of moderate budgets in the next eight years. The Orbital-Hub would guarantee a smooth transition between ISS and future human space activities in LEO and would represent an important step regarding long-term human space exploration beyond LEO.

Acknowledgements

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