69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018.

IAC-18, B3, 9-GTS.2, 2, x43816

The Free Flyer Element of DLR's Orbital-Hub Concept: Designed for Science Opportunities and More

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Abstract

In order to perpetuate the achievements of Human Spaceflight in the context of the International Space Station (ISS), DLR supported by Airbus DS and other external partners, by extensive use of its Concurrent Engineering Facility, has conducted a thorough Post-ISS concept study for a LEO architecture referred to as Orbital-Hub. The Orbital-Hub is based on a small crewed LEO platform including a human-tended Free Flyer, and its design has been centred on financial feasibility and user needs in the frame of human spaceflight. Within this paper the Orbital-Hub's Free Flyer, which consists of a pressurized laboratory area, an external payload or experiment platform and a service compartment, is highlighted with respect to its diverse purposes and applications. Based on a detailed collection of current and forecasted user needs with the help of the science community, the Free Flyer is designed as versatile multi-purpose platform meeting a wide range of requirements for different use cases such as observation, µg applications, exploration, technology demonstration and commercial use. Furthermore, it serves as a key element in the Orbital-Hub concept during assembly and nominal operations.

Keywords: *Post-ISS, Orbital-Hub, Free Flyer, Human spaceflight, climate measurement, micro-g research, exploration, robotic, Concurrent Engineering, International Space Station, Space City*

Acronyms/Abbreviations

CE	Concurrent Engineering
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
EVA	Extravehicular Activity
ISECG	International Space Exploration Coordination Group
ISPR	International Standard Payload Rack
ISS	International Space Station
LEO	Low Earth Orbit
LWIR	Long-Wave Infrared
MLI	Multi-Layer Insulation
MWIR	Mid-Wave Infrared
NASA	National Aeronautics and Space Administration
NIR	Near-Infrared
SWIR	Short-Wave-Infrared
UV	Ultraviolet
VIS	Visible

1 Introduction

The continuation of the ISS program has been confirmed by all partners until at least 2024 with an extension option to 2028. Even though the lifetime of the ISS is theoretically extendable beyond this time-frame, the overlapping question by all users is, if and how the research achievements in low Earth orbit (LEO) will be realised after the risk for further operation of the ISS exceeds the acceptance level. As the existing examples in history show that the transition phase between two crewed orbital platform concepts takes between 10 and 15 years, it is mandatory to now take action for paving the way for a successor platform ensuring a continuous human presence in LEO. This is stated as a goal by multiple nations, e.g. Europe's LEO 2020 roadmap, ISECG roadmap [1] or NASA's ISS transition report [2]. Germany, i.a. providing the astronaut Dr. Alexander Gerst in command of the ISS during his second mission, is a strong supporter of human presence and science in LEO. [3]

Already in 2013 the executive board of the German Aerospace Center (DLR) initiated the Post-ISS project to find answers to how to continue with space research and space technology development in LEO after the ISS utilisation period. It was divided into four main steps:

1) Analysis of current ISS setup to derive lessons learned to be considered for and incorporated into a potential follow-up design, as well as a review of current LEO infrastructure considerations of other nations.
2) Establishment of station concept options based on the former analysis and framework conditions.
3) Listing of possible and desired utilisation intent and experiments by the relevant science community derived from the basic station concept.
4) Fleshing out the initial concept into a comprehensive design with the help of the state-of-the-art Concurrent Engineering (CE) process, based on the results from a utilization workshop.

2 The Orbital-Hub Concept

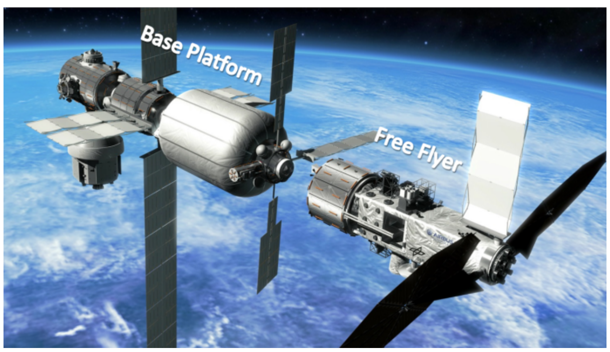

Fig. 1. DLR Orbital-Hub concept.

The resulting LEO architecture design established during the Post-ISS project was called "Orbital-Hub"[4][5]. It stands for the basis or the core element of a space village idea: On the hub, spacecraft can dock and be serviced, or goods (e.g. propellant or experiments) can be distributed (cf. hub as distribution node of the Internet). The Orbital-Hub is a lean multi-purpose platform (Base Platform) combined with a dockable spacecraft (Free Flyer) as depicted in Fig. 1. It was laid out under the following concept framework conditions:

- Technical-modular concept (separation of astronauts and experiments were driven by user requirements; possibility to exchange single modules when they fail to operate, optional autonomous operation of units (habitat/ temporarily crewed Free Flyer)),
- political-modular concept (countries resp. agencies can participate according to individual budget possibilities and scientific interests),
- design mainly based on available technologies (e.g. Columbus, ATV) with participation of private and commercial partners,
- user requests for availability of multiple disciplines (flexible shared items), and
- reasonable costs for operations (e.g. direct access).

The applied design process was strongly depending on and characterised by the use of concurrent workshops and studies involving an interdisciplinary team including users, domain experts and engineers, as well as experienced astronauts for first-hand experience, to create an optimised, consistent and realistic concept (see also Tab. 1.).

2.1 Base Platform

The Orbital-Hub's Base Platform aims to employ the minimum functionality required for a crewed scientific LEO base (three crew members continuously plus visitors): One module houses science laboratories, the crew accommodation and according environmental control and life support systems (example design: expandable habitat). A service module ensures attitude and orbit control and provides power and thermal control. A five-point docking node (one used by the cupola) allows for crew and cargo transfer and extension opportunities and can comprise communication and data systems or backup subsystems.

Up to the beginning of October this year, there have been 214 EVAs on the ISS. In contrast to the ISS, the Orbital-Hub concept is designed to limit the number of EVAs by avoiding items placed externally to the station. However, an EVA contingency is foreseen on the Base Platform and a payload airlock is included between the pressurised and unpressurised parts of the Free Flyer to service external payloads using a robotic arm. Since the critical requirements regarding attitude and disturbances are shifted towards the Free Flyer, the Base Platform is free to roll or yaw a certain amount. That allows for a one-axis rotatable solar panel design which does not need additional truss structures as used on the ISS. The Base Platform is also 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 will provide the required manoeuvres. Hereby, especially visiting vehicles with electrical thrusters are a promising solution for drag compensation also in interaction with the Free Flyer. [6][7]

2.2 Free Flyer

Fig. 2. Orbital-Hub's Free Flyer.

The dockable Free-Flyer (Fig. 2) is part of the Orbital-Hub concept in response to the scientific user requirements. It is intended to fly uncrewed in a safe formation with the Base Platform for e.g. three months periods until it can be maintained or reconfigured when docked to the base for short duration (approx.. two weeks). At its aft a service module provides attitude and orbit control and also formation flying and independent power and thermal control. Furthermore, it contains a pressurised module for µg-research which can be accessed by the crew when docked to either the Base Platform (e.g. via the docking node or via the expandable habitat module) or directly to a crew vehicle. An external science platform builds the centre of the Free Flyer. It has a berthing structure for any external payload and provides power, data and thermal conditioning.

Most likely the Free Flyer will fly with the 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 Concurrent Engineering design study, which has been conducted in close cooperation with AIRBUS DS, the external science platform is implemented as a rigid rectangular truss structure covered with MLI. The main volume of the payload airlock is located inside this structure and can be reached through a lateral cut-out by the robotic arm. This manipulator is moving along a rail around the structure to place different payloads onto the four sides of the platform with respect to their desired viewing direction.

Furthermore, the Free-Flyer is intended to support the assembly of the Base Platform by being the active part of automated docking, since there is currently no similar vehicle like the decommissioned U.S. Space Shuttle available. The overall dimensions of the Free-Flyer in stowed configuration (retracted photovoltaics and radiator wings) have been optimised to be in line with the launch scenario using a single ARIANE 64. [8][9]

3 Application opportunities

The design of the Orbital-Hub has been driven by the user community from the beginning of the project. Contemporary research needs are hard to predict for the upcoming ten years, since they are often driven by PhD theses and project funding periods of rather three to five years. However, in close collaboration with the most interested user community (material physics, atmospheric physics, human physiology, gravitation biology, radiation biology, astronomy/ astrophysics, plasma physics) a detailed set of requirements has been established.

Within this compilation strawman payloads have been identified, which allowed a clear definition of system and subsystem requirements for the platform design and in general for future needs in LEO utilisation. One part of the study was to distil information about detailed infrastructure properties such as: dimensions, volume, mass, mass of exchangeable hardware, regular mass download/ upload, power need per rack/ per single experiment, µg-level, temperature stability, storage conditions, data rate/ volume/ cycle, cooling, heating, venting, modularity, inserts, need for ISPR, position, ideal/ acceptable orbit, attitude accuracy, vibration, EVA demand, level of automation, operational time, life time, crew/ test subject, installation support, access, contamination, cost, facility/ experiment maintenance, interfaces mechanical/ power/ data/ fluid and more.

Besides the most prominent demand for future research in LEO, being a direct and fast access to the respective space laboratory, some additional recommendations have been collected:

- Separation of µg sensitive or vibration sensitive disciplines as e.g. material science or observation from crewed part of the platform,
- more flexibility/ scope of action for astronauts on board,
- centralised ground segment and direct communication between scientists and astronauts moderated by Capcom/ Eurocom,
- separated areas with different safety levels on board, and
- improved inventory logistics.

The unique combination of a crewed base and a decoupleable payload platform creates an optimised setup for environmental and operational conditions for the payloads. The platform aims at appealing to both scientific as well as commercial users. The proposed platform facilitates long-term experiment or observation programs to ensure planning reliability, frequent exchange and flight opportunities for the users' payloads and clear interfaces/ resources with respect to data, power and environmental control.

Tab. 1. Fact summary of Orbital-Hub concept

	Base Platform	Free Fyler
total launch mass	65.3 t	18.7 t
total mean power	30 kW	20 kW
payload capacities		
available volume (ISPR equivalent)	4 to 5	5 plus ext. platform
available power	8 kW	10 kW
downlink rate	300 Mbps plus 1.8 to 2.7 Gbps via relay	300 Mbps plus 1.8 to 2.7 Gbps via relay
estimated cost (FY18)		
development & initial assembly in orbit costs	3165 M€	726 M€
yearly operations cost including (crew)/ cargo transport	1069 M€	248 M€

While the payloads inside the crewed platform are foreseen to focus on human physiology, the Free Flyer is designed as multi-purpose payload platform, which provides:

- Experiment or observation programs over a longer period of time,
- microgravity (up to 10^{-6} g),
- space environment,
- regular access for payloads and experiment hardware,
- access to resources (e.g., crew time, performance),
- wide range of equipment internally and externally, covering many research disciplines,
- advertising through "Research in Space",
- high amounts of data either through real-time communication or large memory (platform or relay satellites),
- volume and mass of scientific facilities are limited, but based on the user requirements implemented, and
- use of multi-user systems.

In the following sections the selected strawman payloads which have been accommodated on the Free Flyer to demonstrate the broad bandwidth of application opportunities are shortly described.

3.1 Observatory

Since the Free Flyer would orbit Earth about every 93 minutes and provide coverage of 85% of the Earth's surface and 95% of the world's populated landmass every 1-3 days, one logical application of the Free Flyer is observing our planet. Also perspectives outwards to the stars including our Sun are given. In the following some example payloads in this context are listed.

3.1.1 Earth Observation

On its orbit the Free Flyer is a perfect platform complementing dedicated satellites designed for Earth observation: The lower orbit altitude allows for higher resolution, the variation in local time in comparison to a Sun-synchronous orbit covers a wide range of weather situations and has better equatorial coverage, last but not least due to resupply missions towards the Free Flyer and the opportunity of human interaction there is an exchange capability of components or instruments to foster their further development, testing and calibration against each other.

The following three applications have been considered as examples of Earth observation payloads [10]:

- General purpose optical Earth observation platform: Two telescopes: UV-VIS-NIR-SWIR and MWIR-LWIR (0.2-14.4 µm; 2° and 20° field of view; 1300 km swath; mass: 1500 kg, 1 kW power, >3.3 TByte/day data downlink),
- Atmospheric Physics: Passive spectrometer UV-VIS-NIR-SWIR; 1x1 km² resolution; 400 km swath; measurement of trace gases in Mesosphere (mass: 250 kg, 0.5 kW power, 216-2160 GByte/day data). And a lidar observatory using a nadir cassegrain telescope with an aperture of 1 m or more receiving backscattered laser-light for active measurement of atmospheric trace elements (mass: 400 kg, 3.5 kW power, 43 GByte/day data), and
- Pointing platform MUSES derivatives (Multi-User System for Earth Sensing) providing precision pointing and pointing knowledge and data processing (mass: 600 kg, 1 kW power, 200 GByte/day data).

3.1.2 Astronomy

Other observation payloads are looking towards deep space (anti-nadir) mapping background radiation like e.g. a sky polarisation observatory to survey the microwave background (mass: 500 kg, internal closed loop cryocooler, 0.8 kW power, 200 GByte/day data). Observing Sun could be either solved by pointing the whole Free Flyer towards Sun for dedicated periods or using a pointing platform to do so: Solar observatory example (mass: 300 kg, 0.8 kW power, 200 GByte/day data).

3.2 Micro-g Research

The main key feature of the ISS is the absence of gravity. The Free Flyer would be an evolution in this field, as it is also accessible by humans but smaller and in the un-crewed phase free of vibration disturbances. Therefore the µg quality is expected to be at a level of $1x10^{-6}$ g during non-accelerated periods (no manoeuvres). With its electric propulsion system the Free Flyer is designed to compensate drag forces continuously. The following applications have been proposed by the µg community:

3.2.1 Material Science

Researchers want to learn more about solidification processes as well as more accurate measurement data of the obtained thermo-physical properties of alloy melts. The determination of growth rate and structure of the solidification front, the liquid and already solidified areas separated from each other, the interaction of ceramic particles with a solidification front and the growth of drops in immiscible, metallic melting are other objectives that will be explored in the future. These are often falsified by gravity in laboratories on Earth. The design assumption of more plant autonomy, less astronaut interaction and more modularity allows generally more samples and in-situ experiments also for research subjects for soft matter and granular media:

- Multi-user and multi-purpose facility for high temperature materials science research (MUMS):
  - size equivalent up to 5 ISPRs,
  - µg quality continuously better than 10^{-4} g (up to 10^{-6} g),
  - low vibrations,
  - possibility for upgrade and replacement,
  - power: 3 kW (average) / 6.5 kW (peak),
  - data reception:> 10 MByte/day,
  - data transmission:> 100 GByte/day,
  - storage space for instruments, spare parts, new drawers, samples,
  - sample return,
  - lifetime> 10 years,
  - modular construction (rack, sample chamber, experiment-specific use),
  - on-board sample analysis (e.g., X-ray radiography and tomography),
  - robotic exchange / transfer / storage, and
  - parallel operation of all instruments.

3.2.2 Gravitation Biology & Human Physiology

One important subject of the gravitation biology is the elucidation of the signal transduction of gravity/ weightlessness within animal or human cells that are not "professionally" involved in the perception of gravity (e.g., cells of the immune system).

The field of human physiology currently occupies one of the largest research areas on ISS. A near-Earth research platform will continue to make an important contribution to the coming 20 years of research into human processes in weightlessness - time lapse experiments - in comparison to the earthly processes. These include: understanding muscle loss, osteoporosis, back problems, circulatory and orientation problems as well as changes in the immune system. Current core research experiments include: Eye pressure, cardio-pulmonary circulation, and muscle and bone loss. The understanding and the appropriate countermeasures are also a prerequisite for the desired crewed exploration beyond LEO.

During the Orbital-Hub study both research areas were planned to be part of the Base Platform, because especially they benefit from human presence or the crew is subject of the research. And because they require common equipment such as a glove box or freezers or reference centrifuges which would also induce additional vibrations into the whole spacecraft, which is contradicting e.g. the material science requirements. But still parts of the experiments could be implemented also on the Free Flyer and e.g. conducted only during crewed/ docked phases.

3.3 Exploration / Astrobiology

Besides direct Earth-bound research also astrobiology has been addressed by the user community as one example of physical exploration topics.

For the astrobiology as part of the exploration topic using "in situ" research on EXPOSE-like platform and plume simulator for later exploration missions to Mars and ice moons is of importance (also for technology demonstration). Under simulated Mars, icy-moon or space conditions instrument tests in connection with radiation experiments and coupled with defined sample analysis (bio signatures/ mineral-research) shall be conducted. The goal is the proof of stability of chemical, mineral samples and bio signatures under simulated Mars and real space conditions "in situ" (in space). For that the following payloads have been foreseen for the Free Flyer:

- Plume simulator: Instrument test and sample analysis (bio signatures) under simulated icy-moon conditions (H_2O-injector etc.) plus Raman spectrometer (mass: 150 kg, 0.3 kW power, small data rate)
- EXPOSE derivative: Micro-ecosystems under space conditions using sunlight and different spectrometers (mass: 150 kg, 0.3 kW power, small data rate)

3.4 Technology Demonstration

Both the Base Platform and the Free Flyer should offer the opportunity for more novel technologies including operational aspects, tests and demonstration either for use in (human) space exploration (especially for long-term missions) or technology testing for occasional users e.g. the space industry to test new space products. The latter is of special interest, when demanding requirements e.g. high power consumption, high volume requirements or sample exchange/ return capabilities are given, which cannot be fulfilled with a normal satellite mission.

3.4.1 Electric propulsion test platform

Function and long-term tests of electric thrusters in free space supplement the ground-based tests in vacuum chambers and allow more real conditions without interference from the chamber walls and the limited pumping power of the vacuum pumps (thruster experiment mass: 800 kg, 6 kW power, small data rate, attitude/ orbit influence)

3.4.2 Additive/ Subtractive Manufacturing

Additive Manufacturing includes i.a. 3-D printer, e.g. metal powder bed printer (eventually in conjunction with gel-like liquid) and fusion of thin layers successively by laser irradiation (laser-sintering) or powder jet plus laser. Subtractive Manufacturing includes milling or laser cutting. These technologies are already well advanced on the ground, but under µg conditions they still pose new challenges. A successful implementation could offer a bigger independence of the crew in terms of resupply options on board. The production of spare parts/ tools made of metal and other materials is especially attractive for human long-term missions with limited replenishment from Earth (mass: 2x150 kg, power 1.5 kW + 0.5 kW, low data rate).

3.4.3 Technology demonstration for occasional users

For technology demonstration standardised supply interfaces on the external science platform of the Free Flyer are foreseen to test technologies in free space with the goal of short-term and easy access for experimenters and especially the space industry. Conceivable applications are:

- Development/ operation of novel lightweight solar panels or solar dynamic systems (mirror),
- test and operation of communication and navigation technologies (lasers, antennas, etc.),
- test of radiation shields,
- fuel storage/ transfer in orbit, and
- assembly/ deployment of large (lightweight) structures.

3.5 Station Servicing

Additionally to its application options for experiments and payloads, the Free Flyer is designed to function as an active element for station assembly and servicing. Due to its refuelling capability it could take over orbit maintenance tasks for the ISS or other LEO infrastructures. It could substitute former Space Shuttle activities, such as assembly of new modules like Orbital-Hub or re-arrangement of modules which can be detached from the ISS. Finally it can assure a safe disposal of itself and/ or further modules at their end of life. In principle the Free Flyer could also operate at other destinations e.g. Moon vicinity or Lagrange points depending on the transfer or launcher capability.

4 Conclusions

Complementing payloads such as Earth observation, technology demonstration 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 also open for future commercial involvement. A space laboratory is unique and not replaceable by terrestrial means.

In this paper the design of the Orbital-Hub scenario respectively the Free Flyer is described implementing the use of strawman payloads and the evaluation of the most promising answer to the specific user demands post ISS. An infrastructure like the Orbital-Hub would guarantee a smooth transition between ISS and future human space activities in LEO with a broader field of application opportunities. Secondarily, it would continue the capabilities which were achieved by humankind also regarding long-term human space exploration beyond LEO.

Acknowledgements

Besides the authors of this paper, a special thank belongs to all others of the Post-ISS study team, especially to those who were involved in the CE study "Post-ISS Nutzlasten" and the CE study "Post-ISS Scenario-II", i.e. Ralf Anken, Waldemar Bauer, Andy Braukhane, Meenakshi Deshmukh, Philipp Fischer, Gerhard Grunwald, Marcus Hallmann, Steffen Jäkel, Heinz Josef-Kaaf, Bernd Kaifler, Klaus Landzettel, Bryan Lovrinovic, Antonio Martelo, Lisa Martín Pérez, Andreas Meyer, Thomas Müller, Günther Reitz, Jörn Rittweger, Klaus Ruf, Dieter Sabath, Kaname Sasaki, Sander Slijkhuis, Sonja Steinbach, Tobias Storch, Maciej Sznajder, Jean-Pierre de Vera, Vincent Vrakking, Marko Waßmann and Elisabet Wejmo. The same gratitude counts for the involved institutions that allowed the team members to contribute their effort especially the DLR R&D board for funding this study.

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