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Development of Space Mission Integrated Operations Scenarios

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Abstract

Integrated Operations Scenarios (IOS) describe nominal operations planned for a space mission. Operational scenarios are key to an operations concept, as they help identify issues and drivers on the operations system. This paper covers the tools, processes, and inputs that feed into an IOS product, and how IOS iterations during a mission lifecycle can buy down operational risks. A case used for this paper is nominal operations for an initial crewed Artemis mission that includes cross-program sequence of tasks required to accomplish end to end functions from launch through transit, on-orbit operations, to safely return to Earth. An IOS product serves as a reference for discussions during requirements development, task and risk analyses, concept of operations development, and as foundation to prepare space mission flight plans.

Keywords: integrated operations scenarios, flight plan, timeline, Artemis

Acronyms/Abbreviations
CLPS: Commercial Lunar Payload Services
ConOps: Concept of Operations
EHP: Extravehicular Activity and Human Surface Mobility Program
EVA: Extravehicular Activity
FD: Flight Day
FOR: Flight Operations Readiness
HLS: Human Landing System
HSI: Human Systems Integration
IAC: Integrated Analysis Cycle
IOS: Integrated Operations Scenarios
ISS: International Space Station
LM: Logistics Module
LTV: Lunar Terrain Vehicle
MPCV: Multi-Purpose Crew Vehicle
NRHO: Near Rectilinear Halo Orbit
SLS: Space Launch System
SME: Subject Matter Expert
xEMU: Exploration Extravehicular Mobility Unit
xEVA: Exploration Extravehicular Activity

1. Introduction

An Integrated Operations Scenarios (IOS) product exhibits operations planned for a space mission. It can cover nominal and contingency operations for how systems work together to complete a mission. This paper covers nominal operations for a crewed mission, where the system is composed of hardware, software, and human in a given environment.

Operational scenarios are key to an operations concept, as they help identify issues and drivers on the operations system. IOS should include operations for crew and system scenarios. Crew scenarios show how the crew interacts with the flight system and ground personnel. System scenarios show how systems of systems work together [1]. Overall, the scenarios are a combination of the integration of human systems working together to complete the mission. Furthermore, the IOS was recognized as a Human Systems Integration (HSI) product in the NASA/SP-20210010952 NASA HSI Handbook [2].

1.1 IOS Flow Diagram

A flow diagram (Fig. 1) was developed to explain the interactions of the IOS product with mission concept and architecture functions, requirements development, technology development, overview timelines, resources needed, generic rules and constraints, command, control, communication, and training plan for crew and ground. This diagram communicates the needs for developing a Flight Plan for the upcoming Artemis missions.

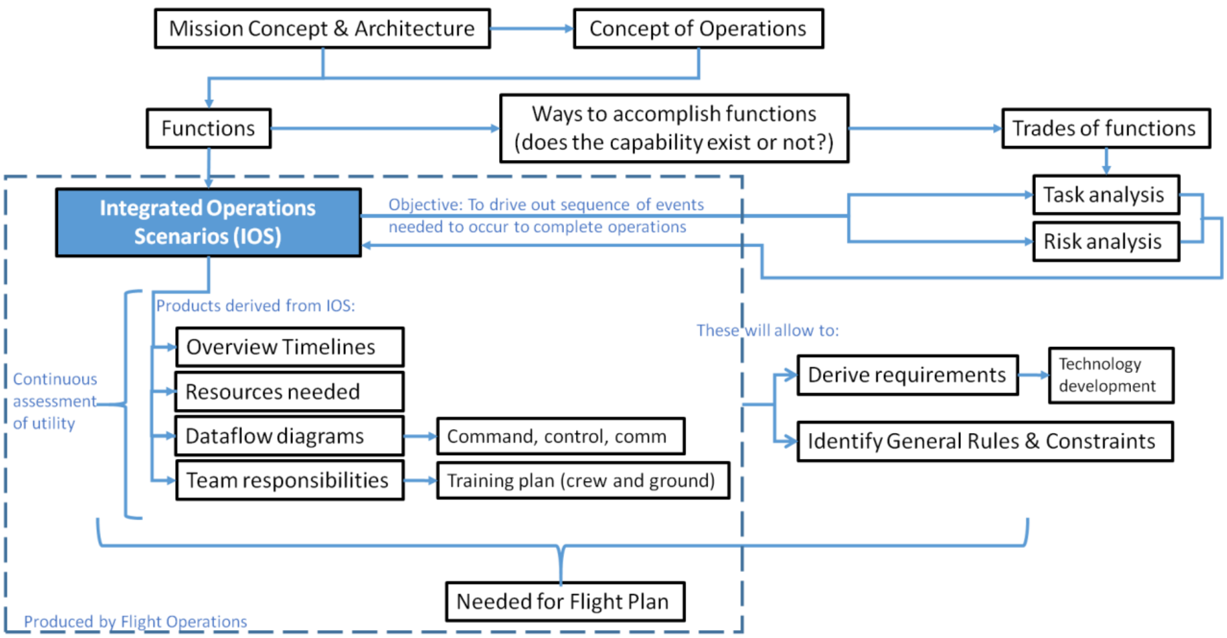

Fig. 1. Integrated Operations Scenarios Flow Diagram

1.2 Flight Plan

A flight plan is an integrated, multi-discipline, multi-program timeline used for execution and coordination, as well as for mission cognizance and situational awareness. The development process of a flight plan consists of various products that mature as they get closer to launch, designated as L minus the number of years or months (L-#). Those products start with an early mission design, which start with the mission conception through L-3 years. The IOS is developed approximately at L-4 years through L-20 months as a roadmap to the next iterations in preparation of the flight plan.

The IOS is then used to develop a preliminary or overview flight plan, which is at L-2 years through L-8.5 months. This overview plan is followed by a flight operations review (FOR) flight plan, developed at L-18 months through L-7 months. A basic flight plan can then be prepared at L-6months. This is followed by the publication of a final flight plan at L-1.5 months. Finally, a real-time execution flight plan would be put together at L-TBD through mission complete. Notice that the lifecycle of the flight plan products listed are approximated times and can vary based on mission schedules and availability of information.

As shown in Fig. 1, the operations planning products mature from the IOS, to an overview timeline, to a flight plan. Inputs used for an IOS include mission design data, system subject matter experts, commercial partner data, international partner data, crew task lists, grounded rules and assumptions, etc.

1.2 Artemis

NASA's Artemis Campaign goal is to lead humanity to the Moon as a critical step to get to Mars. Early Artemis missions include the Space Launch System (SLS) and Orion or Multi-Purpose Crew Vehicle (MPCV), which have been in development for the past decade. These along with the first Commercial Lunar Payload Services (CLPS), Capstone Cubesat, Viper, among others give space to Artemis I and II [3]. Gateway, Human Landing System (HLS), and Extravehicular Activity and Human Surface Mobility Program (EHP), are also part of NASA's sustainable Artemis Campaign. The Artemis crew lunar landing, known as Artemis IV, will use a near rectilinear halo orbit (NRHO), same as Artemis III [3]. This paper focuses on the Artemis crew landing. A profile of the current Artemis IV mission is depicted in Fig. 2. for reference. However, please keep in mind that these missions are continuously evolving.

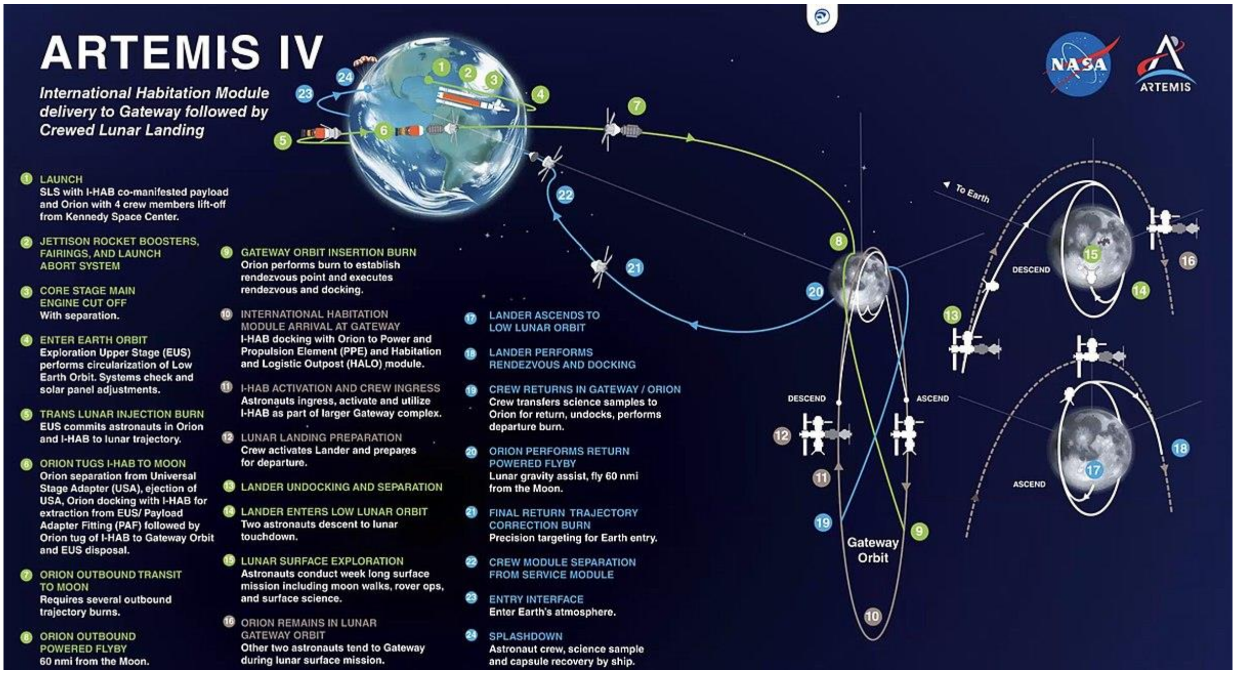

Fig. 2. Artemis IV Profile Mission

2. Conceptual Framework

The International Space Station (ISS) and Shuttle Programs developed IOS for each of their assembly flights, and they were very extensive. The Constellation Program also developed IOS, but as it is known the program got cancelled [4-9]. The Artemis Campaign builds its mission IOS on previous programs' experience and is updated as new information from the different Artemis programs and providers is made available.

A first IOS product was developed for the Artemis IV sustainable mission, which is an Orion, Gateway, HLS cross-program product covering nominal crew and mission control operations needed to accomplish mission objectives [10-25]. Fig. 3. shows an example of the mission summary by flight days (FD). It describes the sequence of tasks required to accomplish end to end functions from launch through transit, on-orbit operations, to safely return to Earth. IOS serve as reference for ongoing discussions during requirements development, task and risk analyses, concept of operations development, and as foundation to prepare a space mission flight plan.

2.1 General Assumptions

- Artemis IV scenario is a 30 days mission, including 6.5 day lunar sortie.
- Activity times are best estimates based on subject matter experts (SME), ISS, and Shuttle experience, as well as currently known design aspects. These will need to be updated based on design and issues or undetermined tasks encountered while in operations (e.g. if design does not meet certain requirements, then operations time will increase).
- Given the status of the different Artemis IV programs, there are still various unknowns, and many assumptions were made for each of the activities within the IOS product.

Flight Day	Orion/Gateway Activities/Tasks	Crewed Lunar-Lander Activities/Tasks
	Pre-Launch	
FD01	TLI, OTC-1, Outbound Transit	
FD02	OTC-2, Lunar Transit Activities	
FD03	Lunar Transit Activities	
FD04	OTC-3 & 4, Prep for Docking	
FD05	OTC-5 & 6, OPF, Crew Off-Duty Day	
FD06	**Gateway RNDZ/Docking/Ingress**	
FD07	**LM Ingress, AE Ingress, Outfittings**	
FD08	Lunar Sortie Prep	
FD09	Lunar Sortie Prep	
FD10	Lunar Sortie Prep, Pre-Departure Checks	Pre-Departure Checks
FD11	**Gateway/AE Hatch Close, HLS Departure for Lunar Surface**	**Gateway/AE Hatch Close, HLS Departure for Lunar Surface**
FD12	**Gateway Reduced Crew Duty**	**HLS Landing, Lunar Surface Operations, EVA 1**
FD13	Gateway Outfitting, Utilization	EVA 2
FD14	Gateway Crew Off-Duty Day	HLS Crew Reduced Work Day
FD15	Gateway Outfitting, Utilization	EVA 3
FD16	Gateway Outfitting, Utilization	EVA 4
FD17	**AE Arrival from Lunar Surface, Gateway/AE Hatch Open**	**Lunar Ascent, AE Arrival from Lunar Surface, Gateway/AE Hatch Open**
FD18	Transfer Ops	
FD19-20	Crew Off-Duty	
FD21	Transfer Ops, Maintenance	
FD22	Prep Gateway for Uncrewed Ops, AE & LM Egress	
FD23	**Gateway Egress, Orion Undock and Departure**	
FD24	Orion Transit to Flyby	
FD25	Orion RPF	
FD26	Orion Transit to Earth	
FD27	Orion Transit to Earth, Crew Off-Duty Day	
FD28	Orion Transit to Earth, Correction Burns	
FD29	**Earth Return and Landing**	

Fig. 3. Example of Mission Summary by Flight Days

2.2 IOS Product Content Overview

The Artemis IV IOS product contains flight day, crew and hardware/software activities, description, rationale, assumptions, constraints, source and date of acquired information, owner, status and additional comments. Although many tools were considered, due to the anticipated continuous changes this product would need, Excel was selected as the tool to develop and maintain the IOS. The product itself was divided into tabs, providing background, general assumptions, glossary, legend, Artemis IV mission scenario, extra-vehicular activity (EVA), and routine crew activities. EVA had a separate tab as the activities are repetitive and the specific science or utilization activities were unknown during the development of this first IOS.

Data was added to the product as new information from the various Artemis programs was made available. Then, working meetings were held with operations subject matter experts in various disciplines, including rendezvous, proximity operations, propulsion, guidance navigation and control, mechanical, crew systems, environmental, thermal, crew portable devices, communications, inventory, power, extra-vehicular activities, command and data handling, crew medical operations, exercise, and flight activities planning.

The IOS development and reviews included SMEs in the operations field. Further reviews of the initial product have been performed by experts of different programs and organizations participating in the Artemis mission.

3. Initial IOS of Nominal Activities

An example of the level of detail the IOS carries is shown in Fig. 4. This shows activities that support ingress based on visiting vehicle experience, such as, opening of hatches, collecting air sample, donning and doffing personal protective equipment, etc. Going through this exercise, also drives questions such as whether we need a vestibule configuration prior to ascent module hatch open. This and other similar questions derived as the IOS is developed can be answered when vendor architectures are known.

Flight Da	Orion/Gateway Activities/Tasks	Description	Rationale / Assumptions / Constraints
FD07	Stowage Prep	Configure stowage areas in first module of Gateway in preparation for cargo transfer from the logistics module	
FD07	LM Ingress	LM (Logistics Module) hatch open and ingress	Assume ground has prepared LM for ingress by completing activation and pressure seal check.
FD07	Vestibule Pressurization & Leak Check	Design dependent, if equalization to IMV can be established prior to docking then additional atmospheric sample will not be required	Assume pressure seal checks are part of the pressurization procedure. Assume 1.5-2hours depending on vehicle design.
FD07	TBD Orion ARS Reconfig	Potentially increasing CO2 and humidity control to account for IMV interfaces	
FD07	Don PPE		
FD07	Gateway to LM Hatch Open		Assume 5min for this activity.
FD07	Vestibule Config	Is there any configuration needed in the vestibule prior to AE hatch open?	Assume 20-60 min depending on vehicle design.
FD07	LM Hatch Open		Assume 5min for this activity.
FD07	Collect Air Sample	Take Air Sample of LM atmosphere	Assume 1-5min for this activity.
FD07	Configure IMV	Configuring LM/HALO IMV and deploying the duct into the LM	Included in 20-60 min of vestibule config.
FD07	Doff PPE		
FD07	Perform Comm System Checkout	Confirm good voice communication from MCC - Orion - Gateway	Assume LM has comm system capability.
FD07	C&W Checkouts	Crew confirmation that C&W system is working correctly (includes C&W messages, tones, etc.)	Assume LM has comm system capability.
FD07	Logistics Transfer	Configure HALO and LM cabins for logistics operations and Transfer TBD equipment from LM required for HALO outfitting	
FD07	Unstow GPCs and Peripherals, and Set up on Gateway	These are the ones stowed in the logistics module	
FD07	PAO Event		Assume video camera and peripherals were unstow and set up the day before prior to the first PAO.
FD07	Mandatory System/Utilization Support		Per ECSC-040, up to 2 hours per crew of mandatory system/utilization support is permitted on each off-duty day.

Fig. 4. Excerpt Example of IOS Product showing some ingress and outfitting activities

3.1 Early Findings

The initial IOS review helped identify some technical integration items, for example:

- Conflicting documentation from programs on crew cabin pressure mission profile. Gateway and Orion pressure assumed the pressure would be reduced to 10.2 psi prior to the start of pre-breath of the first EVA, and then adjust Gateway pressure from 10.2 to 14.7 psi after Gateway and HLS hatch closed. HLS assumption was that it could operate up to 14.9 psi. These disconnects brought up a couple of questions, whether we could leave Gateway at 10.2 psi during the lunar mission, and whether we could stay at 10.2 psi until Orion hatch closure.
- Programs had different assumptions for when the first EVA would occur. The IOS followed Gateway assumption that the first EVA would occur the same FD as crew lands on the Moon, based on Apollo experience. HLS assumption was that the first EVA would occur on the next day after arrival to the lunar surface. This could ultimately be driven by the crew medical community.

These items were since addressed through more in-depth discussions. Furthermore, they have increased the cross-program communication to ensure consistency. Currently, there is an interoperability risk managed at the Artemis Campaign level.

The initial IOS version was provided to programs as part of the Integrated Analysis Cycle (IAC), and shared/presented at various program and directorate forums. Furthermore, the Gateway Human Systems Integration Working Group used it as a starting point to develop their crew task analysis, and it was used to inform HLS of possible crew activities.

3.2 Preliminary Assessment

As an example of the type of assessments that can be done from an IOS product, an assessment was performed to find the minimum duration between Orion docking and HLS undocking based on the initial IOS Gateway profile.

The general assumptions for this preliminary assessment were:

- All durations are best estimates based on SMEs and ISS experience, and data available from the various Artemis programs.
- It is expected that vehicle architectures and designs will be leading factors to changes needed in this assessment.
- The assessment does not account for unknowns that may increase crew time and operations (e.g. seat liner adjustments, suit drying, suit adjustments, cargo readjustments, etc.).
- The assessment does not characterize aggregate crew time that does not count against their work schedule, such as medical conferences, exercise, meal, pre/post-sleep.

The following assumptions were related to xEMU or xEVA preparation activities:

- xEMU hardware, ancillary and permanent, EVA tools and equipment, and spares would be manifested in the Logistics Module (LM).
- EVA gloves, other custom hardware, last time consumables, and xEMU patch kits would be launched in Orion.
- Some xEVA tools would also be launched on HLS.
- xEVA crewmembers would perform all xEVA tasks. This is what drives the activities to be performed in series.

The assessment also included outfitting activities needed for crew safety and short-term habitability, with the following assumptions:

- All estimated times for configurations and outfitting depend on vehicles' final design and launch configuration.
- Assume hardware from LM is required, so activities span prior to and after LM ingress.

There were also other activities not included in the previous lists of assumptions for xEVA/xEMU preparation and outfitting, which must happen before HLS departure. For those types of activities, the following assumptions were made:

- First module of Gateway, HLS, LM operations would be similar to operations for visiting vehicles to ISS, thus 2 hours for ingress and 2 hours for hatch closure activities were assumed. There may be some opportunities to decrease that duration but could not tell for sure without knowing the design details.
- Only crew activities were shown in the assessment and did not include ground activities.

There were no specific requirements for limitations on a crew workday. Using Artemis II and the MORD [23], the crew needs 13.5 hours for pre-sleep, post-sleep, sleep, and midday meal, plus 2 hours of exercise, which makes 15.5 hours. This leaves 8.5 hours for crew work time available. Since there is some leeway during pre and post sleep, this can be rounded to 9 hours. Thus, this assessment used 9 hours for crew work time available to estimate the minimum number of days.

Therefore, assuming crew is working 9 hours per day, the total minimum days between Orion docking and HLS departure would be equals to 3.5 days:

- xEMU/EVA preparation activities: no less than 1.5 days.
- First module of Gateway and HLS outfitting needed for crew safety and short-term habitability: no less than half a day.
- Other critical activities not accounted in the previous two groupings: no less than 1.5 days.

Assuming Orion docking occurs around midday on FD06, the second half of FD06 could be used for configurations. Transfer and outfitting of xEMU preparation activities could be split between FD07-FD09. HLS undocking could be done on FD09 and be on the lunar surface on FD10.

Important items to take into consideration with this preliminary assessment:

- Assessment assumes optimum operations, where orbital mechanics and crew schedule align such that all operations can be completed as laid out in the schedule.
- Assessment does not protect for any contingency situations, such as (a) cargo packing/unpacking operations may increase since it is dependent upon what pre-pack has been completed leading up to undock day, and (b) cargo packing/unpacking operations may increase based upon late manifest change needs not originally accounted.

- Assessment assumes nominal checkout operations, where the first time these operations are completed additional checkout time may be required.
- Assessment does not account for first time validation/demonstrations that may be required and the timing of those demonstrations may vary.
- There may be additional activities, not in the HLS undock critical path, that are desirable to complete as soon as possible after arrival on Gateway to buydown contingency scenario risk (e.g. additional nitrogen/oxygen recharge system tank transfers, critical logistics unpack).

This minimum number is only likely to grow in the future and drives launch and mission availability expectations due to NRHO trajectory challenges.

4. Forward Work

The IOS keeps evolving and is updated as designs of the different Artemis missions and programs mature. Given that the initial IOS was performed for nominal operations, the continuation will be to add contingency scenarios as well. Assumptions will need to be revisited to ensure they still align to the overall mission concept and architecture.

The IOS flow diagram presented in this paper can also be further developed to include products led by Directorates other than Flight Operations, such as human risk analysis, human in the loop evaluations, human-hardware-software analysis/tests, modeling and simulations, and human rating certification processes led by Human Health and Performance and Safety and Mission Assurance Directorates.

5. Conclusions

The IOS provides a holistic view of the sequence of activities and functions that need to be done to complete operations. This paper concentrated in the development of an IOS product for a space mission, specifically a human spaceflight mission to the lunar surface, Artemis IV Gateway profile. An initial version was developed using available resources from past programs and Artemis programs documentation, as well as the valuable inputs from operations SMEs. As a result, some program disconnects were found on the operations system, which were communicated and resolved with appropriate stakeholders. Many assumptions were made, and it is expected that information will change as we learn more from vendors' architectures. A preliminary assessment was made using the initial IOS of nominal operations; and found that the main drivers for the minimum duration between Orion docking and HLS undocking are: xEMU/xEVA preparation activities, and outfitting needed for crew safety and short-term habitability. This was an example of the types of assessments that can be derived from the IOS, helping to identify key issues and drivers on the operations system early in the mission lifecycle.

Acknowledgements

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