AEROLABS:
The Orbital Colonization Accelerator

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I. Executive Summary

Establishing a permanent human foothold on Mars presents a paradox: the initial colonization phase is when the crew is most vulnerable to biological and mechanical failure, yet it is also when they are most dependent on unproven ground-based agricultural infrastructure. Current settlement designs rely heavily on surface greenhouses that are particularly susceptible to radiation, dust storms, and thermal fluctuation while requiring human labor to construct. AEROLABS (Autonomous Ecological Research & Orbital Laboratory for Agricultural Bio-Security) resolves this paradox by decoupling the food supply from the habitat.

AEROLABS is a constellation of autonomous, centrifugal agricultural satellites deployed to Mars orbit 2.6 years prior to crew arrival. Each unit utilizes a variable-rate centrifuge to generate artificial gravity, allowing for the tuning of plant growth conditions and preventing microgravity-induced fluid physics issues. The system operates as a "Swarm", where individual satellites grow specific groups of crops to create a decentralized, modular supply chain.

By the time the crew lands, AEROLABS has already accumulated metric tons of shelf-stable, genetically optimized dry biomass. This payload is delivered to the surface via Sample Return Capsules (SRCs) – ready to eat, store, and plant – without requiring the crew to build greenhouse infrastructure first. This architecture serves as an "Orbital Colonization Accelerator" that ensures the first humans on Mars arrive not to an empty pantry, but to a secure, diverse, and abundant food supply that is immune to surface-level failures.

Generative AI has been used to validate calculations, verify AEROLABS's fidelity to engineering and scientific principles, proofread, and flag any scientific or logical incongruities in this paper.

AEROLABS follows a strict timeline:

Timeline	Description
Year 0	An AEROLABS swarm is launched to Mars orbit during a major Mars launch window.
Year 3	All satellites within the swarm have cultivated sufficient biomass.
Year 3.75	Human inhabitants land on Martian soil. Immediately, a few SRCs detach from their satellites and de-orbit to the surface for ground crew to collect. Meanwhile, bases and greenhouses are erected. Every month, new SRCs are deployed to resupply the crew.
Year 4-9	AEROLABS units function as R&D stations that ground crew can remotely operate. Through Omics research, plant growth in different gravity settings, etc., operators gain valuable growth data that helps navigate plant growth in real greenhouses.
Year 9	Without further resources to conduct research, the AEROLABS swarm has reached the end of its operational life. One by one, the satellites de-orbit safely such that ground crew can retrieve them and salvage hull material and internal components for their greenhouses.

II. Mission Architecture

2.1. Why orbital rather than ground-based modules?

Current space settlement architecture predominantly prioritizes ground-based greenhouses. However, for the initial colonization phase (Years 1-10), they could be vulnerable to certain engineering and biological risks. With current technology, the construction of a ground-based agricultural module inevitably requires physical human intervention, leading to astronauts' increased exposure with harsh surface environments (e.g., solar radiation, extreme temperature fluctuations, dust storms). Moreover, since such greenhouses must be equipped with life support systems for both human inhabitants and plant life, they require extensive maintenance and energy to maintain a safe and operable environment.

AEROLABS mitigates these risks through its orbital configuration, making it crucial especially during the initial settlement and colonization period:

- **It offers decentralized bio-security**. A ground-based failure (e.g., fungal blight, aggressive mutation, unexpectedly long dust storms) might put an entire ground colony's biosphere at risk of cross-contamination, but it cannot affect AEROLABS satellites, each of which is essentially its own isolated environment. Should biological deviation occur on one of them, it could be sterilized or de-orbited remotely without endangering other satellites or humans.
- **It simulates gravity-agnostic environments**. Cultivating crops in non-Earth gravity is significantly challenging due to the disruption of natural plant processes and the physical behavior of water and air, and acclimatizing them to new conditions requires controlled gravity changes over time. AEROLABS utilizes a variable-rate centrifuge to simulate any gravity level, allowing us to tune the environment to the crop's biological needs.
- **It is self-sufficient and efficient**. Operating in microgravity, its lightweight hull and optimized subsystems allow it to maximize internal volume for biomass – powered entirely by solar arrays – without complex life-support systems, utilities, structural support, etc. that are part and parcel of ground-based agricultural modules.
- **It is deployed in swarms**. Modular technology allows dozens, up to hundreds, of AEROLABS satellites to operate simultaneously in orbit with different crop configurations, essentially forming a diverse constellation of food supply chains. For more information, see **Section 4**.

2.2. General architecture

The AEROLABS satellite features a compact 2.2m x 2.2m x 5m bus with an estimated dry mass of 1450kg. The outer hull is constructed from Aluminum Alloy 7075-T7351. While standard 7075 offers an exceptional strength-to-weight ratio and is inherently resistant to solar radiation, the T7351 temper is specifically selected to resist stress-corrosion cracking in the harsh thermal vacuum of space so that it prolongs the satellites' structural integrity (Sessler & Weiss, 1966).

Primary power is generated by Flexible Array Concentrator Technology (FACT) solar arrays. When deployed, these arrays span 2.5m x 11m. Assuming a typical solar irradiance value of 1360 W/m² in orbit and typical FACT cell efficiency of 30%, the system generates an output of approximately $(1360 \cdot 30\%)\ W/m^2 \cdot (2.5 \cdot 11)\ m^2 \approx 11\ kW$. This provides a robust energy margin to power the centrifuge motor, growth LEDs, and other subsystems simultaneously.

The nadir side of the satellite holds the Sample Return Capsule (SRC). The SRC itself is a 1000kg blunt-body re-entry vehicle that delivers the cultivated crop yield (600kg max) down to the planet surface for immediate consumption, storage, and future cultivation of genetically resilient crops in ground-based greenhouses.

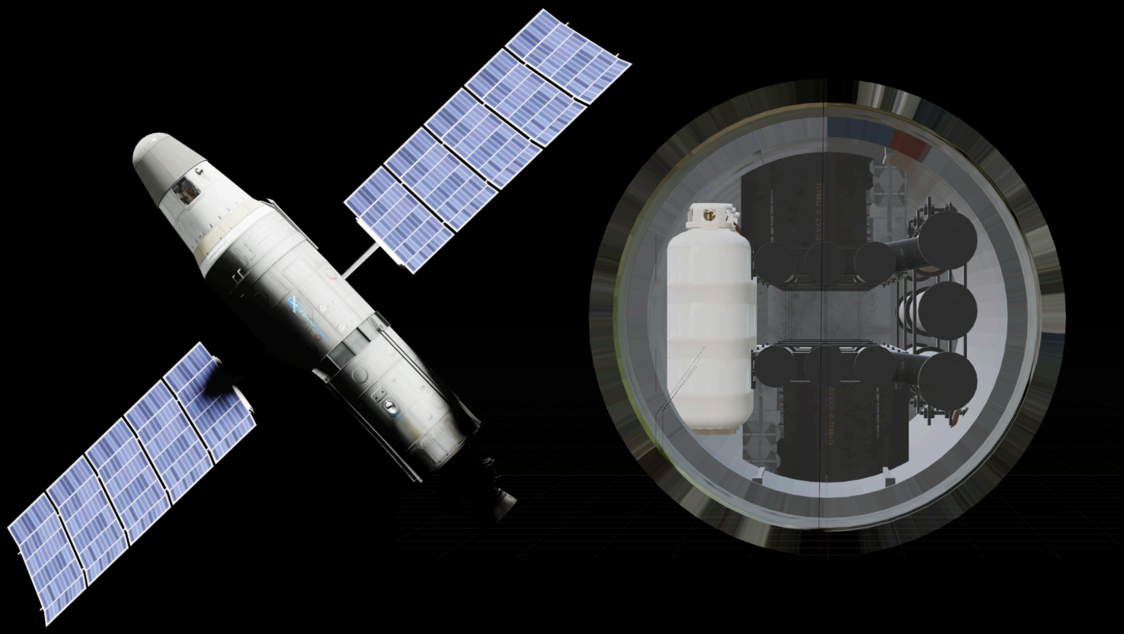

Fig. 2.2.1: AEROLABS conceptual design, depicting the external (left) and internal (right) architecture

The core innovation is the internal 2m x 2m x 4m centrifuge drum that generates artificial gravity. Since the energy required to maintain a constant rotational speed in outer space is effectively zero, it only expends minimal energy for spin-ups and speed changes. The speed is further maintained by a frictionless magnetic bearing system to minimize vibration and power consumption, as well as reaction wheels to counter internal liquid sloshing.

Attached to the centrifuge walls are columns of crop cultivation modules, inside of each are five vertically placed trays with holes. Seed/Sprout pods are planted on each tray such that they sprout out the holes on one side, with exposed roots on the other. Additionally, liquid CO_2 storage tanks are attached to the centrifuge as a fuel source for photosynthesis. A central robotic arm is also attached to it to (re)fill the trays and collect the crops for the SRC.

III. Cultivation Architecture: Aeroponic Racks & Subsystems

On an AEROLABS satellite, there are four evenly spaced compartments attached to the centrifuge walls. Within each compartment lies a column of five cultivation modules and their corresponding horticultural LED array system, along with a liquid CO_2 tank and a 1000-liter Serpentine Bioreactor to sustain microalgae life. This section will mainly focus on the cultivation modules.

3.1. Crop management

To maximize volumetric efficiency and robotic accessibility within the cultivation modules, AEROLABS uses high-density vertical rack systems. Similar to server racks, each module houses five vertical trays that feature diagonally offset holes (much like stadium seating). This configuration ensures that even plants at the bottom of the module receive illumination from the LED panel and reflected light.

Thermal Control is integrated into the trays themselves: thin, flat, net-like copper wires within the walls act as a heat-transfer system that draws waste thermal energy generated by the horticultural LED arrays away from the Root Zone to maintain an optimal temperature (e.g., 28°C for Sweet Potato crops) (Reddy et al. 2013). Also embedded in the trays are microsensors that constantly monitor plant physiology (through biochemical and electrical signals, water flow, etc.). An onboard AI system then processes this data and adjusts the nutrient mist administration for specific trays according to a pretrained ML model.

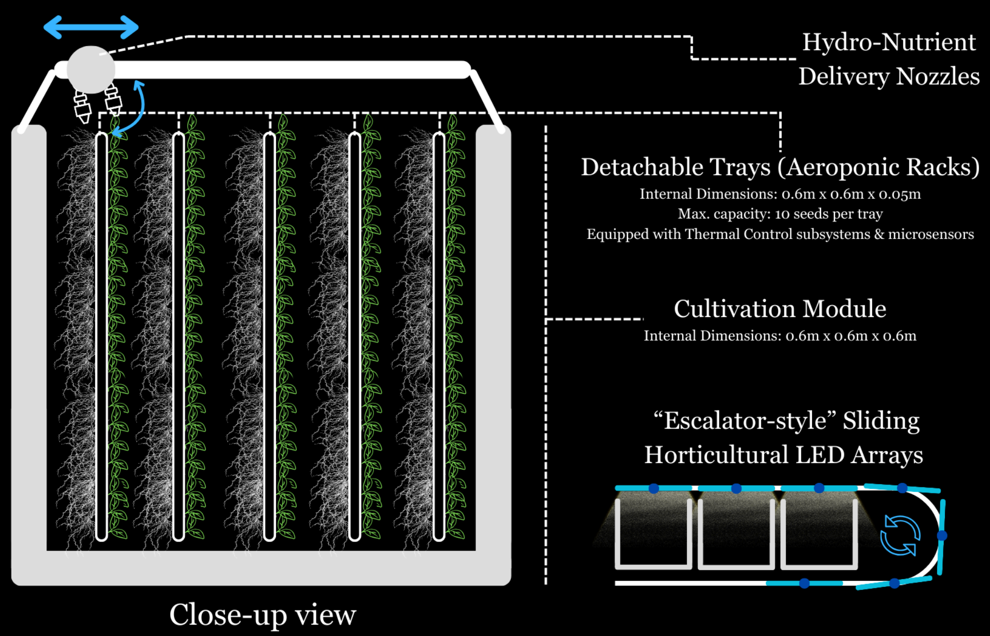

Fig. 3.1.1: Visualization of a cultivation module and sliding horticultural LED arrays

Each cultivation module is equipped with suspended hydro-nutrient delivery nozzles that spray nutrient-rich mist directly onto the roots, moving along a linear rail as they do so. Due to the artificial gravity, excess solution naturally trickles down the walls and roots to a collection pan (not visualized), where it is pumped back to the main tank for filtration and recirculation.

Horticultural LED lights are integral to photosynthesis. However, since directly affixing them to the top of the cultivation modules prevents the central robotic arm (in the middle of the centrifuge) from accessing the trays, they must retract on demand. AEROLABS specifically uses an escalator-like mechanism, where the LED panels – normally positioned above the modules – slide underneath them when access is required.

Through the same nutrient delivery nozzles, CO_2 is periodically released in gas form (sourced from liquid CO_2 storage tanks) to drive photosynthesis. The delivery lines are also equipped with Thermal Control subsystems to prevent freezing from the rapid cooling that happens when converting liquid CO_2 to its gaseous form.

3.2. Crop deployment & harvesting

Crop deployment and harvesting are all managed by a central robotic arm at the core of the centrifuge. The robotic system is a two-joint mechanical arm attached to a rotatable shaft that extends all the way through the centrifuge, allowing it to have an absolute degree of freedom. The arm attaches to objects through a common docking interface rather than traditional suction- or gripper-based approaches to ensure secure locking.

When an AEROLABS satellite is stable in orbit around the target planet, crop deployment begins. For each tray of each cultivation module, the robotic arm attaches to it and inserts it into the Bio-Plug Dispenser. The mechanism proceeds to populate the tray by stuffing stored Bio-Plugs (tiny seed-infused dirt balls) into the holes, after which the tray is placed back in its original position. When all trays have been filled, horticultural LED panels slide into place, subsystems are activated, and the cultivation stage begins.

On harvesting the crops, the robotic arm inserts the ready trays into the Biomass Separation Unit, where a mechanical blade scrapes the mature tubers and foliage into vacuum bags. They are then dried to remove moisture, sealed, and sent – via a pneumatic tube – to the nadir side of the satellite, where they are stored in the Sample Return Capsule. The trays could be refilled via the Bio-Plug Dispenser if the resources for that particular column of cultivation modules are available.

The excess evaporated moisture from the drying process, meanwhile, is captured and recirculated directly into the hydro-nutrient tanks.

3.3. Variations in layout

AEROLABS's versatile cultivation modules allow it to grow a variety of crops, but certain strains like microalgae require specialized chambers. Therefore, to maximize yield, each AEROLABS unit's architecture is slightly altered depending on "Mission Profile", which are crop groups cultivated to fulfill specific daily nutritional requirements (See **Section IV** for details).

Satellites assigned with the "Baseload" and "Lipid" Mission Profiles (crop groups containing microalgae) use the standard "4-columns-of-5 Cultivation Modules + 4 Serpentine Bioreactors" configuration (**the beginning of Section III** describes this). Meanwhile, satellites with the "Sensory" Profile (the group not containing microalgae) use the "8-columns-of-5 Cultivation Modules" configuration, since it replaces the Bioreactors with more cultivation modules.

IV. The Diverse Diet & Modular Supply Chain

4.1. The Swarm configuration

A fundamental advantage of AEROLABS lies in its numbers: while a single unit could only deploy at most 600kg of payload, a constellation of simultaneously operating satellites could provide ground crew with tons of diverse produce year-round. This Swarm configuration effectively forms a modular supply chain and decentralized storage medium.

The constellation is configured into three distinct Mission Profiles – each with a different role – allowing ground crew to satisfy both their nutritional and psychological needs.

4.2. Allocated Mission Profiles

Mission Profile	Crop Payload	Swarm Allocation	Primary Role
Baseload (Calorie/Protein)	Sweet Potatoes, Microalgae Powder (Chlorella)	60%	**Bulk Survival**: Sustained carbohydrates (Resistant Starch) and complete protein.
Lipid (Fat/Oil)	Dwarf Soybeans, Microalgae Powder (Schizochytrium)	20%	**Metabolic Health**: Provides essential fatty acids and extractable cooking oil to prevent "rabbit starvation" (protein poisoning).
Sensory (Psychological)	Dwarf Chilies, Strawberries	20%	**Morale & Cognition**: High-impact flavors (e.g., capsaicin) and fresh textures counteract menu fatigue and microgravity-induced dulling of taste/smell.

4.3. The Baseload, Lipid, and Sensory Profiles

The “Baseload” Profile provides the foundational diet for ground crew. Sweet potatoes, upon harvesting, are flash-dried to preserve resistant starch, which acts as a prebiotic fiber. This nourishes the astronaut's gut microbiome and therefore strengthens their immune system (Zheng et al. 2016). Sweet potatoes’ complex carbohydrates also prevent insulin spikes and ensure cognitive stability (Feikes, 2023). The second component of the “Baseload” Profile, chlorella, is chosen as a potent meat substitute; it prevents muscular atrophy through its complete protein profile containing all essential amino acids (Lorenzo et al., 2023).

The remaining 40% of the Swarm is dedicated to addressing critical nutrient gaps present in the “Baseload” Profile, and also human factors required for mission success.

The “Lipid” Profile covers the lipid gap. The Dwarf soybean variety is selected for its high protein and oil content (40% and 20% respectively) (Jin et al., 2023). Soybeans grow vertically, which is ideal for the Aeroponic Racks system. The processed soybean oil is necessary for caloric density and for cooking, which drastically improves the palatability of otherwise monotonous staple foods. On the other hand, schizochytrium is the chosen microalgae for this Profile due to its high lipid yield (50% to 77% of its dry weight) and Omega-3 fatty acid content (Jin et al., 2024).

The “Sensory” Profile further diversifies the diet variety, but primarily serves the crew’s psychological needs: the high capsaicin content in chilies overcomes the congestion and dulled senses common in space with its flavor punch (Fokkens et al., 2016); the freeze-dried strawberries offer a sweet, tart flavor and a crunchy texture as a dessert. In general, chilies and strawberries, being palatable and familiar foods, boost astronauts’ morale and help them cope with stress and isolation.

4.4. Meal plan

The following meal plan is based on the daily nutritional requirements for an active adult male astronaut (Space Food Design Challenge, 2024). These requirements are chosen on the grounds that such a meal plan would also satisfy or exceed the nutritional demands of female astronauts.

Meal	Nutritional Value	Ingredients	Purpose
Breakfast: Sweet Potato Porridge with Chlorella and Berries	**Calories: 850** Protein: 37.1g Fat: 28.3g Carbs: 111.4g Other: Fiber	Sweet potato flour, chlorella powder, freeze-dried berry powder, soybean oil (for light frying/mixing)	High carbs for energy; fat for satiety; fruit for Vitamin C and taste
Lunch: Soy Protein Patty with	**Calories: 1050** Protein: 45.9g Fat: 35g	Sweet potato tuber flour & leaves, chili flakes infused with	Balanced macros and rich

Schizo-Chili Oil and Greens	Carbs: 137.8g Other: Omega-3	Omega-3 oil (from schizochytrium), patty (from soy protein concentrate)	savory flavor for midday energy reboost
Dinner: Potato Gnocchi with Algae-Butter Sauce	**Calories: 1100** Protein: 48.2g Fat: 36.7g Carbs: 144.5g Other: Iron, Calcium, Magnesium, Potassium, Zinc	Sweet potato tuber flour, chlorella powder (for the base sauce), soy nut butter paste blended with schizochytrium oil (for umami flavor), chili powder	High caloric density for recovery; strong flavor contrast to prevent palate boredom

NOTE: "Other" nutritional values require rigorous examination of the exact formulation and preparation of each ingredient to be accurately quantified.

This daily meal plan requires, per person, a total of 500g of Sweet Potato Flour/Leaves; 30g of Chlorella Powder; 200g of Soy Oil and Protein Isolate; and 55g of Chili/Berry.

4.5. Potential for Omics research and Genetic enhancement

The sophisticated cultivation module sensors and AI systems aboard AEROLABS serve not just crop monitoring and data collection purposes, but also as a phenotyping platform.

The AI Core collects two primary data streams: phenomic data from multispectral imaging (via internal cameras and the Retractable LED Array) and metabolomic data from CO_2/O_2 gas exchange sensors. This allows the AI to non-invasively track plant health indicators (e.g., chlorophyll fluorescence for photosynthetic efficiency). By correlating these real-time physical observations with the plant's pre-loaded reference genome, the AI can infer changes at the micro (gene activity) level. This closed-loop system provides instant feedback on the success of CRISPR-Cas9 trials by identifying hyper-efficient, radiation-resistant strains to be included in the Sample Return Capsule, thus accelerating the in-orbit genetic engineering cycle.

V. Payload Yield & Implications

Since any edible biomass aboard AEROLABS must be dried to eliminate unnecessary water weight, each satellite's Sample Return Capsule can carry an astonishingly energy-dense payload at a maximum of 600kg. Every month, a "Baseload" Payload is deployed, along with "Lipid" and "Sensory" Payloads every two months.

5.1. Predicted yield by Mission Profile

A "cultivation cycle" is defined as the time it takes for an AEROLABS unit to complete its assigned Profile (i.e., for all the crops in said Profile to grow fully).

Based on satellite configuration and the crops' growth duration, yield, and average dried mass, the total yield, cultivation cycle duration, and required cycles of a given AEROLABS unit is as follows (see **calculations** ***(External)*** for biomass yield + required cycles deduction):

Mission Profile	Dry Biomass Yield Per Cycle	Cycle Duration	Required Cycles to Reach Maximum Capsule Capacity
Baseload	**123.38kg** - 14.58kg Sweet Potato tubers - 50kg Sweet Potato canopy (leaves/roots) - 58.8kg Chlorella	147 Days (Tibbits et al., 1994)	5 Cycles
Lipid	**265.58kg** - 77.4kg Dwarf Soybean - 188.18kg Schizochytrium	97 Days (SpaceRef., 2003)	2 Cycles
Sensory	**84kg** - 40kg Dwarf Chili - 44kg Strawberry	137 Days (NASA, 2021; Grant, 2025)	7 Cycles

While these yields could very well support a 10-person crew (see **Section 5.2**), their biggest caveat is the slow cycles. This means that AEROLABS constellations must be launched ahead of time (up to 2.6 years) prior to crew arrival so that the satellites have sufficient time to complete their cycles as required by their assigned Mission Profile.

5.2. How long payloads last for a 10-person crew

Based on the Meal plan (**Section 4.4**), the daily meal plan for each astronaut requires approximately 785 grams of consumable dry mass. For a 10-person crew, this amounts to 235.5kg of required dry mass per month, for which just three Payloads with distinct Mission Profiles can more than sufficiently accommodate. In fact, they can last the crew over 7 months.

Since each AEROLABS satellite is only fitted with one Sample Return Capsule, it can only deploy its payload once in its lifetime (hence the need for multiple cycles to accumulate biomass in the Capsule). However, to support a 10-person crew for one year (enough to erect ground-based greenhouses and other facilities), there only needs to be a constellation of 5 AEROLABS units (each managing a different Mission Profile) plus a few surplus units for backup in case a main one is compromised.

VI. Orbital Logistics (Mars Colonization)

Although AEROLABS intends to be self-contained (and thus independent of the target habitat), we may assume, for this section, a Mars colonization scenario for the sake of specificity.

We may also assume that extensive testing, refinement, and validation have already been conducted such that the procedures to be described execute with near-absolute success rates.

6.1. Launch and payload deployment

Although an AEROLABS satellite has a dry mass of 1450kg, its launch mass can exceed 11 metric tons due to the amount of liquid required for life-support systems (aeroponics, Bioreactors), and propulsion. Given this mass, launching one unit to orbit requires the use of a Heavy-Lift Launch Vehicle such as the Starship – a vehicle developed by SpaceX that supports a maximum payload capacity of over 100 metric tons.

During a major Mars launch window, a Heavy-Lift Launch Vehicle carries a swarm of 9 AEROLABS units to Martian orbit (5-6 “Baseload” units; 2 “Lipid” units; 1-2 “Sensory” units). Once in stable orbit, the FACT solar arrays deploy, the internal centrifuge spins to match Martian gravity, and the cultivation process begins. The swarm remains in orbit for the next 2.6 years as biomass grows, frequently beaming crop health and growth data back home for analysis and potential manual intervention should any biological deviation occur.

Once the Sample Return Capsules (SRCs) reach maximum capacity, the AEROLABS units enter low-power mode to wait for the crew. Any excess biomass produced during this time continues to be monitored and its data recorded. For specific units that have Bioreactors, any excess harvested biomass is used to feed the algae through heterotrophic growth.

Once the crew lands and establishes a base, Mission Control initiates the deployment sequence for all 3 Mission Profiles. The SRCs – fitted with chemical propulsion systems, parachutes, and heat shields – are thus deployed to the Martian surface, after which astronauts retrieve them via rovers. Back at their base, astronauts open the vacuumed containers to extract the crops and their seeds.

6.2. Post-deployment utility & Decommissioning

Once an AEROLABS unit has released its SRC, it could no longer deploy any more produce. With the remaining Bio-Plugs aboard, it effectively becomes an orbital R&D station: all systems become fully manual for ground crew or Mission Control to remotely conduct research on crop growth – perhaps in different gravity settings, with Omics research, or for general data collection. This is a crucial phase, as the data could be utilized to develop more efficient crop cultivation methods to be used in greenhouses from the get-go.

An AEROLABS satellite is expected to remain in service for at least 5 more years post-SRC-deployment. At the end of its operational lifespan, the unit is decommissioned: solar arrays retract, the centrifuge locks in place, and the satellite performs a retrograde landing in similar fashion to its SRC. Upon touchdown, the bus lands on heavy-duty shock legs such that the internal components remain intact: the satellite is going to be salvaged, not destroyed.

Indeed, this is where the mission ROI proves itself. The crew disassembles the landed satellite to further expand their permanent ground greenhouses. The hull, made of a high-grade, radiation-hardened aluminum alloy, is reused for structural beams and additional shielding from solar radiation. The cultivation modules, horticultural LEDs, and Bioreactors (along with most internal components of the satellite) can be reused as is or repurposed.

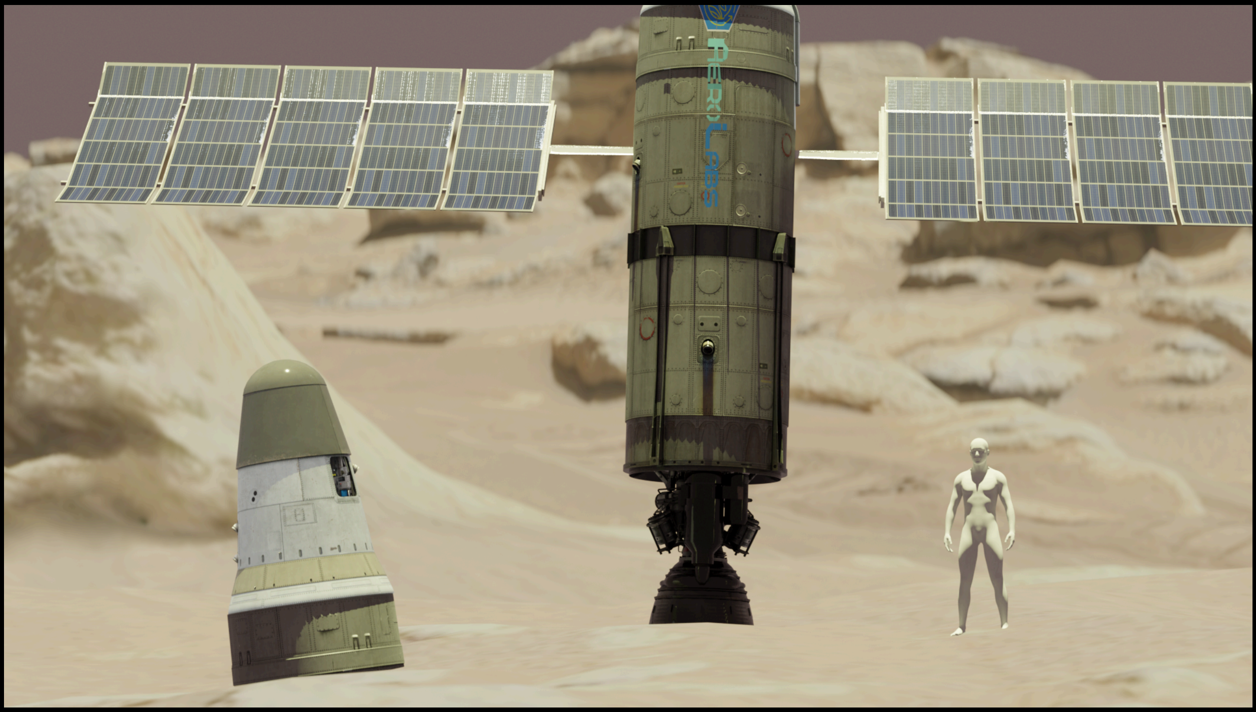

Fig. 6.2.1: Size comparison between an SRC, its AEROLABS unit, and an astronaut (left to right)

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