EDEN ISS Rack-like food production unit: results after mission in Antarctica

G. Boscheri[1], and G. Marchitelli[2], C. Lobascio[3], A. Saverino[4]
Thales Alenia Space Italia, Turin, TO, 10146, Italy

and

Paul Zabel[5]
German Aerospace Center (DLR), 28359 Bremen, Germany

Plant cultivation in large-scale closed environments is challenging and several key technologies necessary for space-based plant production are not yet space-qualified or remain in early stages of development. The Horizon2020 EDEN ISS project aims at development and demonstration of higher plant cultivation technologies, suitable for near term deployment on the International Space Station (ISS) and, in a longer term perspective, within Moon and Mars habitats. The EDEN ISS consortium, as part of the performed activities, has designed and built a plant cultivation system having form, fit and function of a European Drawer Rack 2 (EDR II) payload, with a modularity that would allow its incremental installation in the ISS homonymous rack, occupying from one-quarter rack to the full system. The developed system, named RUCOLA (Rack-like Unit for Consistent on-orbit Leafy crops Availability) was completed and tested in a laboratory environment in early 2017. The system was then operated in the highly-isolated German Antarctic Neumayer Station III, in a container-sized test facility to provide realistic mass flow relationships and interaction with a crewed environment. This paper describes the key results of the RUCOLA plant growth facility tests in Antarctica as a space-analogue environment.

Nomenclature

ACCS	=	*Atmosphere Contamination Control System*
EDR	=	*European Drawer Rack*
EI	=	*Experimental Insert*
FEG	=	*Future Exploration Greenhouse*
FTP	=	*File Transfer Protocol*
GCS	=	*Growth Chamber Short (plants)*
GCT	=	*Growth Chamber Tall (plants)*
GUI	=	*Graphical User Interface*
ISPR	=	*International Standard Payload Rack*
ISS	=	*International Space Station*
MTF	=	*Mobile Transport Facility*
RUCOLA	=	*Rack-like Unit for Consistent on-orbit Leafy crops Availability*
SW	=	*Software*
TCCS	=	*Trace Contaminants Control System*
TEC	=	*Thermoelectric Cooler*
THC	=	*Temperature and Humidity Control (system)*

[1] System Engineer, Cleanliness and Bioresources Dpt., Strada Antica di Collegno 253.
[2] System Engineer, Cleanliness and Bioresources Dpt., Strada Antica di Collegno 253.
[3] Expert, Life Support and Habitability, Strada Antica di Collegno 253.
[4] Head of Cleanliness and Bioresources, Strada Antica di Collegno 253.
[5] Doctoral Candidate, Institute of Space Systems, Robert-Hooke-Str. 7, 28359 Bremen, Germany.

I. Introduction

THE capability to produce crops in space is a key development for a sustainable human presence beyond Low Earth Orbit. In addition to the food production function, the use of higher plants-based systems provides multiple additional benefits, such as contribute to air revitalization and water processing, as well as carrying the potential of providing psychological benefit to the crew. The goal of the EDEN ISS Horizon2020 project is to advance controlled environment agriculture technologies beyond the state-of-the-art through demonstration in laboratory and space-analog environment. The main task of Thales Alenia Space (TAS) within the consortium led by the DLR Institute of Space Systems in Bremen was to develop a rack-like facility targeting at short-term safe food production and operation in microgravity, starting from a demonstration phase on-board the International Space Station (ISS), to be followed by more extensive testing in future orbiting habitats (e.g. the Lunar Orbital Platform-Gateway). The system was conceived as the next step to past and currently on-orbit operated systems (e.g. NASA Veggie[3]) as extensively analyzed in a previous ICES paper[2]. It was developed as a potential payload for the European Drawer Rack (EDR) MK II. EDR MKII will be flown to the ISS in the second half of 2019 and will provide interfaces for multiple experimental inserts (EIs). The facility, formerly called EDEN ISS ISPR[4], is now referred as RUCOLA (Rack-like Unit for Consistent on-orbit Leafy crops Availability). RUCOLA has been developed and tested in the TAS Recyclab technological area in Turin. It was then shipped to Bremen for integration in a container-sized greenhouse Mobile Test Facility (MTF) for integrated testing and subsequent shipment in later 2017 to the German Neumayer III station in Antarctica. The station is operated by the Alfred Wegener Institute and has unique capabilities and infrastructure that allowed testing plant cultivation under extreme environmental and logistical conditions. Beyond logistics, Antarctica provides also a microbial environment with characteristics analog to space, with the need to manage only the microbial contamination that is transferred by the crew and the equipment. The container-sized system hosts also a much bigger greenhouse facility[1], the FEG (Future Exploration Greenhouse), built under the responsibility of the other EDEN ISS project partners with DLR coordination, which will provide year-round fresh food supplementation for the Neumayer Station III crew.

The EDEN ISS project work plan and status, as well as the MTF preliminary design are described section by section in great detail in Ref. 1. The cited paper includes a description of the logistics and operations of the facility, as well as an illustration of the preliminary system budgets. The EDEN ISS RUCOLA “as designed” status is described in detail in Ref. 4. Related laboratory test campaign is described in Ref. 5. Lessons learnt from the Antarctica check out testing phase are reported in Ref. 6.

This paper quickly recalls the MTF configuration, focusing then on the developed RUCOLA system, describing the key results of tests in Antarctica as space-analogue environment.

I. Mobile Test Facility General Overview

The EDEN ISS MTF was designed to provide fresh produce for overwintering crews at the Neumayer III Antarctic station, as well as to advance the readiness of a number of plant growth technologies (including the RUCOLA plant cultivation system microgravity demonstrator) and operational procedures. The MTF, consisting of two 20 foot high cube containers, was assembled on top of an external platform at the end of 2017 approximately 400 m south from the Neumayer Station III Antarctic research station, see Figure 1.

Figure 1. The Neumayer III station (left), and the EDEN ISS MTF (right)

The MTF is subdivided into three distinct sections, as shown in Figure 2:

- Cold porch: a small room providing storage and acting as a buffer to prevent the entry of cold air into the plant cultivation and main working areas when the main entrance door of the facility is utilized.
- Service Section: houses the primary control, air management, thermal control, and nutrient delivery systems of the MTF as well as the RUCOLA plant growth demonstrator.
- Future Exploration Greenhouse (FEG): the main plant growth area of the MTF, consisting of multilevel plant growth racks operating in a precisely controlled environment.

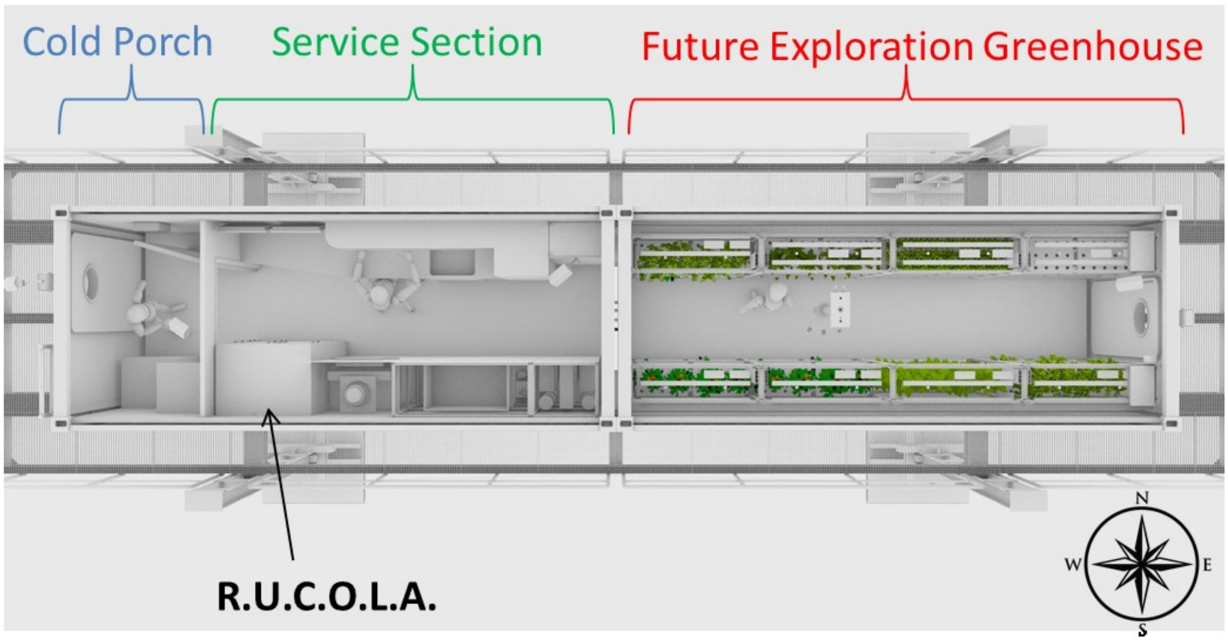


Figure 2. Overview of the EDEN ISS MTF main elements.

Most of the subsystems are housed in a rack system along the South-facing side of the Service Section. It was decided to place the RUCOLA system as close to the cold porch as possible, since there are no interfaces between the rack and the FEG, as opposed to the other subsystems which do interface with the FEG.

II. RUCOLA Cultivation System Overview

The main objective of the laboratory and Antarctica RUCOLA system demonstration is to advance the TRL of the plant growth facility technologies, as well as to identify necessary design and operational procedures updates in view of a near term experiment on the ISS. The facility was designed to represent an increment with respect to current flight capabilities represented by the NASA Veggie system, mainly in terms of:

- Higher available growth surface (0.5-1.0 m^2 range)
- Longer production cycle possible by complete nutrient solution circulation (and not only watering of substrate with slow release fertilization)
- Robust and reliable safe and high quality food production (while Veggie control capability may be considered limited)
- Taller crop can be accommodated (up to 60 cm available for tall growth chamber shoot zone)

Figure 3 is an image of the EDEN ISS RUCOLA system as integrated in the MTF together with a description of its main building blocks. It is designed as precursor of ISS EDR MKII plant growth payload. The lower section of the rack is dedicated to the interfaces (power, data and cooling water) with the Mobile Test Facility, mimicking the EDR MKII functions. Above this section are placed the interfaces between the rack and the plant growth facility, exactly as for EDR MKII Experimental Insert (EI) interface panels. In the central portion of the system, the following payload drawers are accommodated:

- Power, Command and Data Handling Module
- Nutrient Storage and Distribution Module
- Growth chamber Modules (1 for short plants, 1 for taller plants), including each chamber dedicated air management systems, root modules and crop shoot-zone volumes
- Illumination Modules (one for each growth chamber)

In the top portion of the rack, a panel for manual monitoring and control via a LabVIEW based interactive graphical user interface of the rack's functional parameters is present, together with a storage volume.

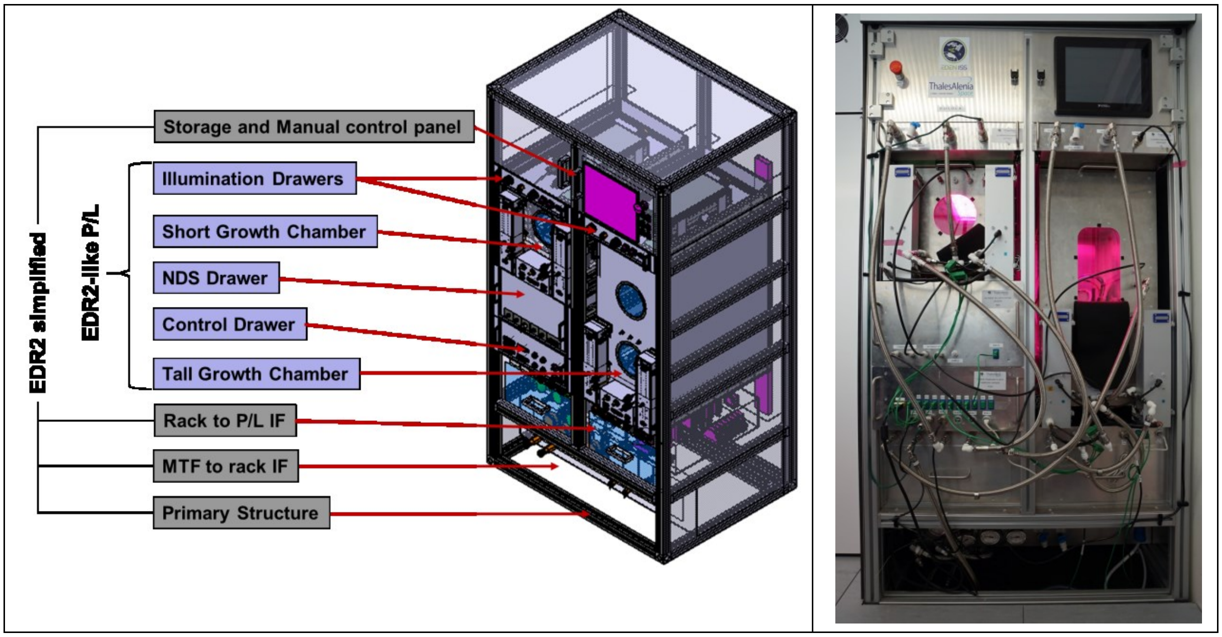


Figure 3. The EDEN ISS RUCOLA cultivation system 3D image (left) and Antarctica installed HW (right).

The Antarctica test campaign was focused on evaluating performance in a logistically and microbiologically space analog environment for the following two key subsystems: the air management subsystem, and the nutrient delivery subsystem. The following sections provide a quick overview of these subsystems, and the next chapter reports the main test results and lessons learnt.

A. Air Management Subsystem

Each of the 2 plant growth volumes has an independent temperature and humidity control subsystem. Identical components have been used for both the Tall Growth Chamber (GCT, 192L volume) and short growth chamber (GCS, 84L volume), despite the different volumes. The air extracted from the shoot-zone volume is cooled by a Thermo-Electric Cooler (TEC, using Peltier effect) to remove sensible heat loads as well as latent heat loads through condensation of water vapor. The water vapor is then collected by gravity in a custom designed recipient, and then pumped through a 0.2µm filter to the De-Ionized (DI) water reservoir within the Nutrient Storage Module. The TEC is an air to water heat exchanger, and the heat collected at the water side is removed by a cooling water loop connected to a chiller external to the rack, designed to provide similar performance to the EDR II rack cooling provision (up to 180 L/h of water at 16-20°C). Each Growth chamber has two fully redundant temperature and humidity control easily replaceable units, nominally operating in parallel at about 50% of their maximum capabilities. Each of those is capable of sustaining the basic atmosphere control functions alone, in order to cope with the special logistics conditions of the Antarctica operating framework. A failure of the one element of the cooling HW (e.g. fan, TEC, etc.) would not be catastrophical for the crop growth, also in the eventuality of not being able to access the MTF for multiple days (e.g. in case of heavy storm).

The same logic is applied to the airborne contaminants control system, placed in series to each of the above mentioned air management lines, and consisting into a particulate filter, a 0.2µm HEPA filter including active charcoal in the mesh, followed by an additional filter for low molecular weight organics (like ethylene).

The overall air management subsystem block diagram is reported in **Error! Reference source not found.** in a conceptual form.

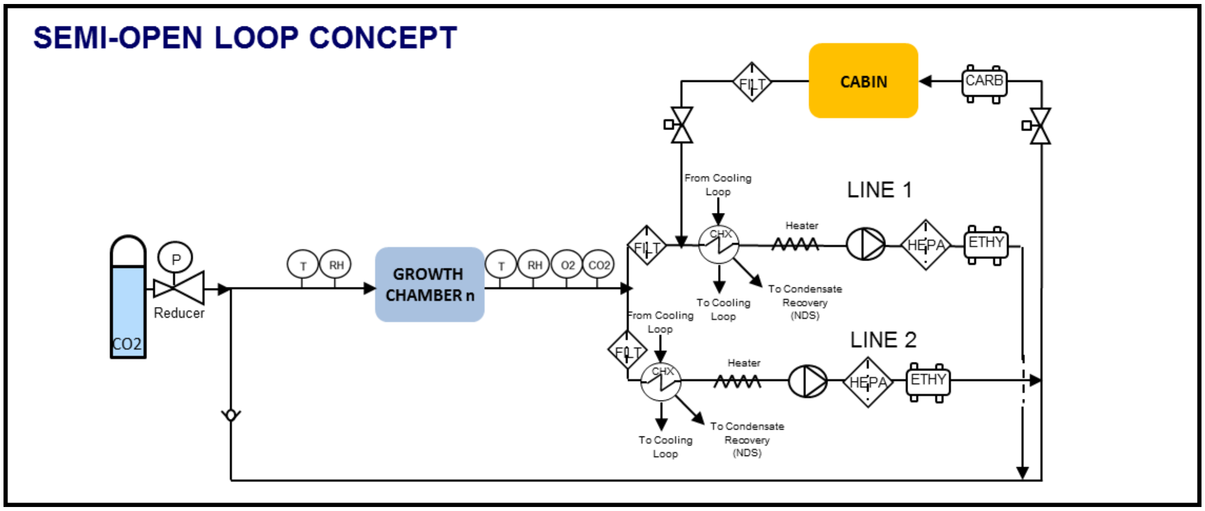


Figure 4. Overall air management system conceptual block diagram

B. Nutrient Delivery Subsystem

The Nutrient Delivery System (NDS)[5] contains the reservoirs (stock solutions, acid/base, DI water, and nutrient solution), the delivery pumps, the nutrient solution quality monitoring sensors, and the condensate recovery system. DI water is used also in case of salt accumulation within the root module (Electrical Conductivity - EC - increment within the substrate or porous elements cleaning to prevent clogging). The DI water pH is monitored and controlled by acid/base injection. The nutrient solution EC and pH are monitored and controlled by water or stock solution (from dedicated reservoirs) injection. Injection is allowed by LabVIEW® controlled piston pumps. Concentrated solution tanks are flexible, replaceable (self-locking QD), stored dry and filled with water only before use. Both the Main Nutrient Tank and the DI Water Tank are relying on a polymeric bellows technology, capable of allowing long term chemical and microbiological stability of the contained solutions and of operating also in microgravity conditions. Either DI water or nutrient solution can be delivered to the root modules. The NDS block diagram is reported in Figure 5.

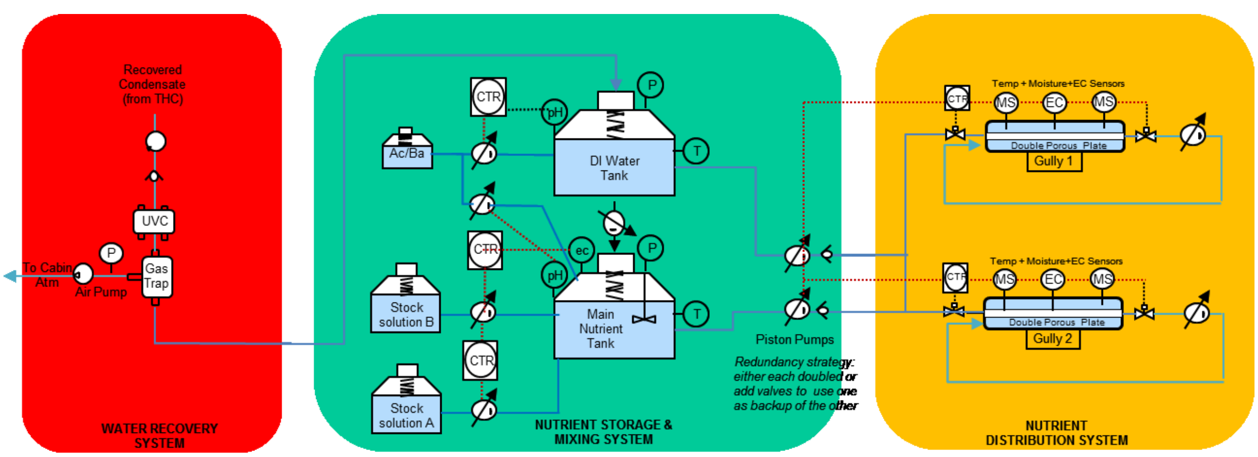


Figure 5. Nutrient Delivery System Conceptual Block Diagram

III. Antarctica Test Campaign main results

A. Air Management Subsystem

The air management system Antarctica test campaign main results are summarized in the following sections for each of the key functional subsystems.

1. Temperature and humidity control subsystem

The major performance of the built temperature and humidity control subsystem as verified prior to and during the deployment in Antarctica are reported in Table 1 for both the tall (GCT) and short (GCS) growth chambers. The laboratory environment testing phase is detailed in a previous ICES paper[5].

Table 1. Temperature and humidity control subsystem performance prior to (1 growth cycle, 26 days) and during Antarctica test campaign (4 growth cycles, 128 days)

Performance Type	As Designed	As tested in lab. env.		As tested in Antarctica	
		GCS	GCT	GCS	GCT
Temp. control range [°C]	15-30 ± 1.5	15-30 ± 1.9	15-30 ± 2.1	22.3-30 ± 2.0	22.5-30 ± 2.2
Humidity control range (only de-humidification)	60-80% ± 5%	60-80% ± 6%	60-80% ± 7%	60-80% ± 7%	60-80% ± 8%
Nominal recirculation mass flow – [m^3/h]	5	3.7±0.5	3.6±0.5	4.4±0.5	4.0±0.5
Leak rate – [vol/day]	10%	32%	18%	37%	26%

The system performance in Antarctica had some sensible difference with respect to the laboratory test campaign. The temperature and humidity control system was fully verified ahead of the Antarctica deployment phase with the RUCOLA rack in TAS Torino laboratory environment, with main results reported in in Table 1. From the data available on the operative environment prior to the FEG deployment, that resulted as a worst case hot scenario, with lower temperature expected in the following phases.

However, since no requirement on acoustics was placed, no verification on audible noise level was performed with the system operating installed in the MTF in fully operational conditions. Since the greenhouse Antarctica operator working station is just in front of the rack, it was clear soon after deployment that the fans audible noise was too high. There is no equipment in situ to measure sound intensity and frequency, so this measurement was postponed to the next summer season. The resources available in situ also did not allow providing additional acoustics insulation. For this reason it was necessary to reduce sensibly the maximum fan speed during working hours. A lower allowed air circulation velocity resulted into a challenge for the temperature and humidity control functions, leading to a lower capability of managing sensible heat, since an increase in the thermoelectric cooler power resulted in higher condensation rates rather than reducing growth chambers temperature. In the winter season this will not be an issue, but in the initial test phase, with the sun shining 24 hours a day on the MTF, coupled with the snow albedo, as well as up to 5 persons present in the MTF in the same time, this required to reduce the greenhouse illumination level below nominal set point. For future development proper acoustics insulation will be implemented so to restore the nominal performance.

2. Atmosphere contamination control system (ACCS)

In its final Antarctica demonstrator configuration, the RUCOLA ACCS consisted into the following components placed on each air recirculation line (in the TCCS units):

- the HEPA filter with embedded activated carbon;
- the custom made ethylene scrubber based on custom-coated ceramic porous pellets.

The HEPA filter itself did not induce any failure and performed as expected. However, there were worst case hot operating conditions in the initial Antarctica summer period when a lot of sensible and latent heat need to be removed from the Growth Chamber Short (GCS), and an air flow rate above design values was required. The filter was offering an excessive pressure loss limiting the system capability to raise the air flux above the design threshold. For this reason, in one case (growth cycle 1) it was necessary to remove the filter from the air loop of the Growth Chamber Short.

No microbial contamination event of the crops was recorded in the whole mission timeframe except for the single run when the HEPA filter was not inline (see Table 2). During Growth Cycle 1 some mold stains were observed on the growth substrate pillow at the end of the cycle. In the experiment timeframe multiple operators were attending the MTF for startup purposes, contributing to keep high the environmental microbial load, otherwise really low.

Table 2: Observed crops microbial contamination per growth cycle

		Observed microbial contamination per growth cycle			
Chamber	**Inspected location**	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Cycle 4**
GCS	Substrate at planting	none	none	none	none
	Substrate at cycle end	mold stains	none	none	none
	Crop at cycle end	none	none	none	none
GCT	Substrate at planting	none	none	none	n/a
	Substrate at cycle end	none	none	none	n/a
	Crop at cycle end	none	none	none	n/a

The good microbial contamination control performance was achieved despite of the high leak rate reported in Table 1. This is justified by the fact that the main leak path is within the THC unit, which is mounted upstream of the TCCS. However, this same high leakage rate does not allow to properly assess the performance of the trace gases control solutions during the Antarctica test campaign.

3. Condensate recovery subsystem – microbial contamination control

The atmospheric condensate recovery subsystem was tested in laboratory environment in three configurations, all aiming to mitigate the risk of injecting microbial contaminants into the nutrient solution distribution loop after crew access to the growth chamber volume. In the first configuration an inline 0.2µm filter was used for microbial contamination control; in the second configuration a UVC LED disinfection unit was used instead; in the third configuration both units were used simultaneously. The test results are reported in Ref. 6. The Antarctica test campaign was performed with the first configuration, which resulted sufficient as a microbial contamination control mean, without need for replacement for the mission duration and minimizing power consumption. The filter worked as expected, as shown in Table 3.

Table 3: Observed nutrient solution microbial contamination per growth cycle

	Observed microbial contamination per growth cycle			
Inspected location	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Cycle 4**
Concentrated nutrient solution at cycle start	0 CFU/ml	0 CFU/ml	0 CFU/ml	0 CFU/ml
Diluted nutrient solution at cycle end	0 CFU/ml	0 CFU/ml	0 CFU/ml	0 CFU/ml
Demineralized/recovered condensate water at cycle end	0 CFU/ml	0 CFU/ml	0 CFU/ml	0 CFU/ml

B. Nutrient Delivery and Distribution Subsystem

The main functional performances of the RUCOLA nutrient delivery subsystem components are detailed in a previous ICES paper[5]. This section collects the functional performances highlights of the Antarctica test campaign.

1. *Optical pH sensor drift*

Addition of concentrated nutrient solution and acid/base to the diluted nutrient solution reservoir was performed based on feedback from the electrical conductivity (EC) and pH sensors mounted downstream the reservoir in the line from the reservoir to the root module (see Figure 5).

A custom pH sensor obtained from modification of a dissolved oxygen optical sensor was used. A sensor measurement drift was observed also during periods of unmodified nutrient solution properties (see Table 4). The root cause of this behavior is to be seen in a deterioration of the flow cell (e.g. deposition of salts or biofilm) or of the active sensor spot (e.g. interference of the epoxy glue used to fix it on the fiber optic with the monitored fluid). The design of the sensor does not allow an in situ inspection of the HW. A destructive test will performed when the HW will be back in Italy in order to better frame the sensor behavior root cause.

Table 4: pH measurement in unchanged nutrient solution

Date	03.03.18	10.03.18	17.03.18	24.03.18	31.03.18	07.04.18	14.04.18	21.04.18	28.04.18
pH	5.52	5.51	5.42	5.45	5.36	5.29	5.12	5.19	4.93

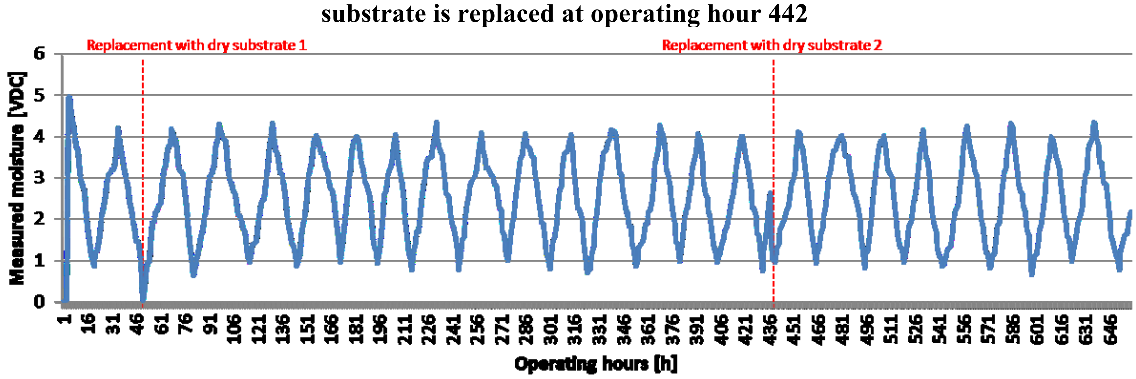
2. *Automated water re-filling*

The water reservoir re-filling was planned to be performed manually by the operator with a hand pump. During the lab test the water filling could be performed in 10 minutes of hand pumping by switching operator each minute. However, during the first test in Antarctica it was soon clear that a solo operator would require much more time and that the activity was not the best in term of ergonomics. For this reason an automatic water filling procedure was established in situ. A dedicated LabVIEW-assisted user interface was developed. The filling now exploits the condensate recovery pump for filling the DI water reservoir.

3. *Root zone moisture monitoring*

The main monitored quantity of the root zone is the moisture level, performed with 2 moisture sensors for each substrate block. Since commercial off the shelf (COTS) sensor not optimized for the selected substrate were used, they displayed a value not linear with substrate moisture level. About 0 VDC are displayed when the sensor is dry, values of 1 to 2 VDC are red when the sensor is only minimally wet (solution in injected when measurement is below 1 VDC), while 4 to 5 VDC are red when the sensor is well wet (solution injection is stopped when measurement is above 4 VDC). However, during the Antarctica test campaign periodically sensors started displaying values of 1 VDC also when dry (see Table 5). The root cause of this behavior was related to a partial corrosion of the electrodes after a few months of utilization. The sensors need to be replaced periodically. The maintenance strategy was changed from corrective (based on visual inspection between growth cycles) to preventive (every 30 days or every growth cycle if shorter).

Table 5: Substrate moisture measurement set, showing off-nominal behavior of moisture sensor when dry substrate is replaced at operating hour 442



IV. Remote experiment management – analysis of the available tools

The RUCOLA system was deployed in Antarctica within the Mobile Test Facility at the beginning of January 2018. The first month of activities was dedicated to integration and check out of the system, including a first plant growth trial with the key objective of testing procedures in situ and identifying site-dependent patterns of concern for the subsequent plant growth test phase. The second phase of the test campaign included the beginning of the first agronomical tests set in the two growth chambers, after seeding of Rucola (cultivated) in the GCS and of Dwarf Tomato in the GCT. In this second phase only the greenhouse operator from DLR was on site, while the rest of the team provided remote support. The RUCOLA experiment management was performed with a tools set described as follows. Table 6 summarises the results of the analysis performed on the utilization of the RUCOLA experiment management tools during the Antarctica test campaign.

Table 6: Summary report of the utilization of the RUCOLA experiment management tools during the Antarctica test campaign

Tool	Use frequency	Utility report	Issues report
On-site GUI	~1/day	Mandatory tool, allowing status check and system control efficiently also in the limited allowable space for intervention of the MTF. To increase utility the number of errors/warnings visible to the on-site user was reduced to those requiring action.	1. Errors/warnings visible to the on-site user too high, incl. those not requiring user intervention. The user tended to ignore the errors after few weeks, with the risk of overseeing important events. 2. Touch screen monitor requiring a pen instead of fingers was not the best solution, often requiring connection of external keyboard and mouse to the available USB ports.
Client GUI	Rare	It was rarely used, although displaying faster the same information of the remote desktop control tool. To increase utility the number of remote commands was increased in a Client SW update.	The GUI allowed mainly visualization of information and not remote action, while most of the times a remote control authority was necessary.
Remote Desktop control	~1/week	Extremely useful, the main tool used during remote support events without the on-site user (e.g. in case of bad weather, or for HW/SW status verification from system developer).	The remote desktop sessions efficiency was much lowered by the data transfer speed, resulting in really long delay time between actions and associated visual feedback. Higher bandwidth was needed.
Data download to FTP	1/day	Extremely useful, the main tool used to collect telemetry.	The automated tool failed a few times downloading the target files.
Automatic e-mailing system	1-10/day	Extremely useful, the main tool used promptly receive notification of errors for remote support provision.	Errors/warnings received too high, incl. those not requiring intervention. We tended to ignore the errors after few weeks, with the risk of overseeing important events.
Teleconferences	<1/week	Extremely useful, the main tool used to remotely support critical operations of the on-site crew.	Telephone connection to the MTF was not always available.
Periodical Work Report	~2/week	Useful for recording of crew intervention data and have an overview of operations carried autonomously by the user.	No issues.

A. On site Graphical User Interface (On-site GUI)

The on-site Graphical User Interface is accessible from the crew via a touch screen placed on the RUCOLA system, in the upper right panel as well as from each computer of the Neumayer Station III via LAN connection. This tool allowed the following operations: RUCOLA status monitoring (day/night period, target set-points, sensor readings, actuators on/off status, etc.); RUCOLA errors/warnings visualization; RUCOLA errors/warnings clearing, as well as SW-assisted crew operations.

The allowed SW-assisted crew operations are the following:

- System start/self-test and shut down
- water refilling
- system priming/ emptying
- seeding/harvesting
- camera pictures management

B. Client SW Graphical User Interface (Client GUI)

The Client SW Graphical User Interface (Client GUI) is accessible from any computer with access to the Neumayer III VPN and with the RUCOLA Client SW executable file. This tool allowed the following operations: RUCOLA status monitoring (day/night period, target set-points, sensor readings, actuators on/off status, etc.); RUCOLA errors/warnings visualization, RUCOLA errors/warnings clearing; main SW-assisted crew operations, such as camera pictures management as well as system start/self-test and shut down.

C. Remote Desktop control

A Remote Desktop control capability was available, accessible from any computer with access to the Neumayer III VPN, protected by an additional security level. This tool allowed the following operations: Total control of the RUCOLA system as per On site Graphical User Interface (GUI); Flushing of the RUCOLA CUP RAM and remote computer restart; Download and upload of files from/to the RUCOLA CPU, used for the following tasks:

- Download telemetry, pictures and errors in case of automated means failure
- Download detailed log of operations
- Upload RUCOLA LabVIEW SW updates
- Upload text files with updated operations for on-site crew

D. Telemetry download

A Piton-assisted automatic download of RUCOLA system telemetry, pictures and errors onto FTP server outside of the Neumayer VPN was available, so to allow access to data to all project partners having the FTP password.

E. Automatic e-mailing system

An automatic e-mailing system was implemented, delivering real time warnings and errors to a list of users with access to the Client GUI, so to promptly take action in case of need.

F. Teleconferences

Teleconferences from Thales Alenia Space RUCOLA control center in Torino with on-site user were schedulked nominally weekly, with increased frequency in extraordinary situations. This tool was generally used to assist the on-site user during critical nominal operations (e.g. seeding, harvesting, system re-conditioning between growth cycles) as well as during off-nominal operations (e.g. HW failure management, SW failure management, plant health issues investigation). Additional uses of the tool were the training of the on-site user after SW upgrades as well as after operational procedures update.

G. Periodical Work Report

A Periodical Work Report was generated by the on-site user, reporting all actions performed and allowing tracking of nominal and off-nominal events (including minor events that did not request any support or warning of the remote support team)

V. Conclusion

This paper quickly recalls the MTF configuration, focusing then on the developed RUCOLA system, describing the key results of about 8 months of operations in Antarctica as space-analogue environment.

The data collected showed generally good performances of the system, while highlighting necessary upgrades. The temperature and humidity control system displayed performances slightly below requirement for unexpected environmental challenges. Noise reduction solutions need to be implemented as a minimum in order to use system capabilities to their maximum extent. The prolonged utilization of the system highlighted the need to review the design/selection of nutrient solution pH sensor as well as soil and moisture sensors. The microbial contamination control system allowed contamination-free operations and no major improvements are foreseen, achieving one of the major requirements for the test campaign, which was exploiting Antarctica as a microbial contamination space-analog.

The remote experiment management strategy was carefully reviewed and provided crucial information for follow up of a subsequent flight experiment.

Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 63650.

The authors also gratefully thank all of our other EDEN ISS team members who are working on the project, but are not explicitly mentioned in the author list.

References

[1]Bamsey, M., Zabel, P., Zeidler, C., Gyimesi, D., Schubert, D., et al., "The preliminary design of the EDEN ISS Mobile Test Facility - An Antarctic greenhouse" *46th International Conference on Environmental Systems*, 2016.

[2]Zabel, P., Bamsey, M., Schubert, D., and Tajmar, M., "Review and analysis of plant growth chambers and greenhouse modules for space," *44th International Conference on Environmental Systems*, 2014.

[3]Wheeler, R. M., "Horticulture for Mars," *Acta Horticulturae (ISHS)*, Vol. 642, 2004, pp. 201–215.

[4]Boscheri, G., Guarnieri, V., Locantore, I., Lamantea, M., Lobascio, C., Schubert, D., "The EDEN ISS Rack-Like Plant Growth Facility" *46th International Conference on Environmental Systems*, 2016.

[5]Boscheri, G., Volponi, M., Lamantea, M., Lobascio, C., Schubert, D., "Main performance results of the EDEN ISS Rack-Like Plant Growth Facility" *47th International Conference on Environmental Systems*, 2017.

[6]Boscheri, G., Marchitelli, G., Volponi, M., Zabel, P., "Status of the EDEN ISS Rack-like food production unit after five months in Antarctica" *48th International Conference on Environmental Systems*, 2018.