ESA CAVES: TRAINING ASTRONAUTS FOR SPACE EXPLORATION

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The first spaceflight was several decades ago, and yet extraterrestrial exploration is only at the beginning and has mainly been carried out by robotic probes and rovers sent to extraterrestrial planets and deep space. In the future human extraterrestrial exploration will take place and to get ready for long periods of permanence in space, astronauts are trained during long duration missions on the International Space Station (ISS). To prepare for such endeavours, team training activities are performed in extreme environments on Earth, as isolated deserts, base camps on Antarctica, or stations built on the bottom of the sea, trying to simulate the conditions and operations of space. Space agencies are also particularly interested in the search of signs of life forms in past or present extreme natural environments, such as salt lakes in remote deserts, very deep ocean habitats, submarine volcanic areas, sulphuric acid caves, and lava tubes. One natural environment that very realistically mimics an extraterrestrial exploration habitat is the cave. Caves are dark, remote places, with constant temperature, many logistic problems and stressors (isolation, communication and supply difficulties, physical barriers), and their exploration requires discipline, teamwork, technical skills and a great deal of behavioural adaptation. For this reason, since 2008 the European Space Agency has carried out training activities in the subterranean environment and the CAVES project is one of those training courses, probably the most realistic one. CAVES stands for Cooperative Adventure for Valuing and Exercising human behaviour and performance Skills, and is meant as a multidisciplinary multicultural team exploration mission in a cave. It has been developed by ESA in the past few years (2008–2011) and is open for training of astronauts of the ISS Partner Space Agencies (USA, Russia, Japan, Canada, and Europe). Astronauts are first trained for 5 days to explore, document and survey a karst system, then take on a cave exploration mission for 6 days underground. A team of expert cave instructors, a Human Behaviour and Performance facilitator, scientists and video reporters, ensure that all tasks are performed in complete safety and guides all these astronauts' activities. During the underground mission the astronauts' technical competences are challenged (exploring, surveying, taking pictures), their human behaviour and decision-making skills are debriefed, and they are required to carry out an operational programme which entails performing scientific tasks and testing equipment, similarly to what they are required to do on the ISS. The science program includes environmental and air circulation monitoring, mineralogy, microbiology, chemical composition of waters, and search for life forms adapted to the cavern environment. The CAVES 2012 Course will be explained and the first interesting scientific results will be presented.

1. Introduction

Space agencies are concerned with the training of their astronauts for future extraterrestrial exploration. Preparing for expeditions to other planets and deep space requires the individuation of space analogue environments in which extreme conditions are encountered, and which replicate stressors similar to those encountered in long duration spaceflight (Morphew 2011).

CAVES (Cooperative Adventure for Valuing and Exercising human behaviour and performance Skills) is the name of a multidisciplinary exploration mission in a cave environment. Developed by the European Space Agency (ESA) since 2008, this course puts together technical challenges, human behaviour and teamwork skills, and a complex scientific programme, run according to space operation protocols. Besides the description of the course concept, this article relates on the first scientific results obtained during the September 2011 and September 2012 CAVES courses, held in Sardinia (Italy).

2. The "CAVES" course concept

Long-duration spaceflight mission crews should spend time together in high-fidelity analogues (Raymond 2011). The need to find relevant terrestrial analogues to prepare teams operating in extraterrestrial environments is driven by extraordinary demands for safety and mission success (Bishop 2011). Space agencies have long struggled to identify best analogues.

Caves are a hostile and dangerous environment that must be dealt with acquired competences on progression techniques and clear operational safety rules. The environment is however just a "container": analogies should be based on similarities in experiences, not just in environment (Bishop 2011).

During CAVES astronauts are trained to use simple rope ascending and descending tools and to negotiate difficult and long traverses rigged with iron cables (Marbach and Rocourt 1980). This technical training resembles skills and protocols that are required to move and operate in extravehicular activity, with reduced field of view, shadows, tri-dimensional progression through viable paths, confused perception of obstacles and distances, and no-touch zones (Figs. 1–2).

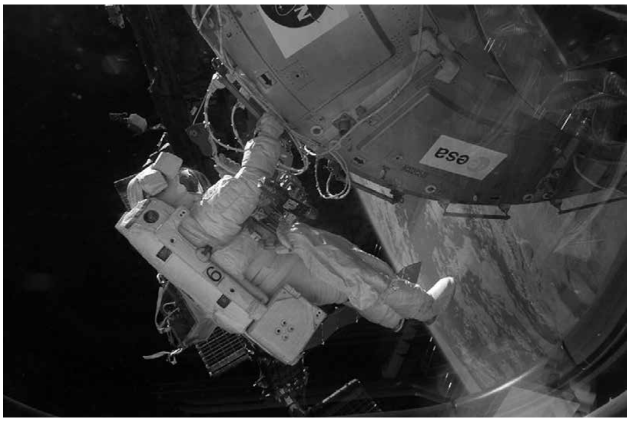

Figure 1. Spacewalking (Credit NASA).

This preparatory training is propedeutical to an extended caves exploration phase, where the astronauts autonomously perform an expedition as a multicultural and multidisciplinary team. For safety, astronauts are followed by instructors and experienced cavers, but they are trained to use a buddy system and to maintain team situational awareness through briefings and debriefings in order to maintain control on the safety of the whole group, to allow informed decision making for each member of the team, and to enable team learning through analysis of failures and successes.

Analogue team training needs to be based on the concept of operations (Raymond 2011), and provide real challenges, stressors and a credible programme. During the CAVES mission, astronauts will explore new branches of the cave, and are required to survey all explored areas, as well as provide photographic documentation of all activities performed.

As for space missions, astronauts are trained to carry out a scientific programme, according to a flexible operational timeline and space-like procedures. Twice/day the astronauts hold planning conferences with a "ground" control team to report on daily achievements and confirm plans ahead.

The scientific tasks that the astronauts are asked to carry out are numerous: microbiological sampling of air, water, and solid material, monitoring of cave air temperature, relative humidity, and wind speed and direction, sampling of waters and minerals for successive laboratory analyses, and monitoring (and, in some cases, sampling) of cave dwelling fauna (mainly troglobites).

Equipment testing is also a common task during space missions. To increase safety of cave exploration operations, a new digital wireless underground radio communication system was also tested.

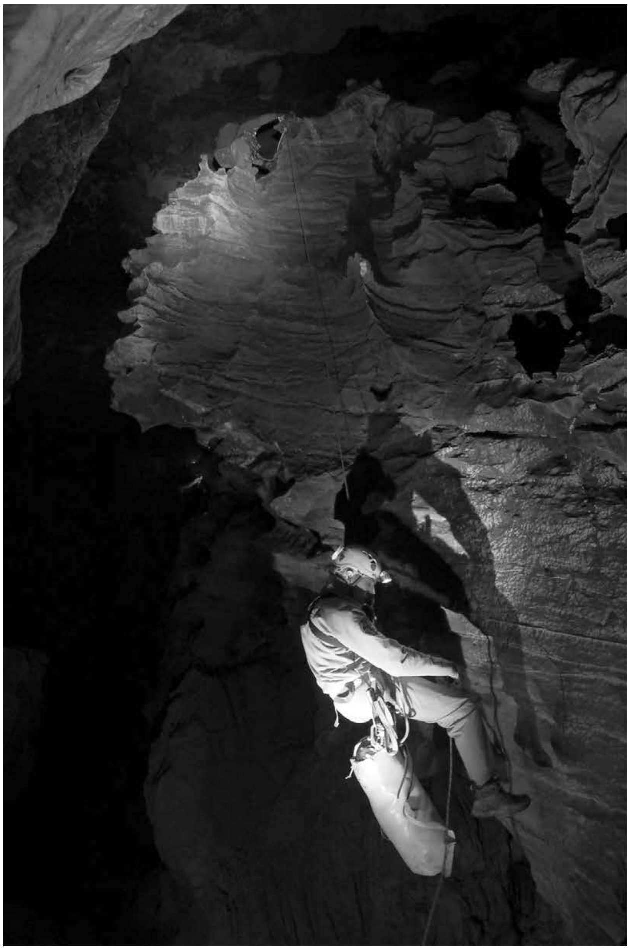

Figure 2. Cavewalking (Credit ESA – V. Crobu).

3. Methods

3.1. Exploration and survey

Astronauts are asked to make a survey of the areas they explore (Fig. 3). Normal Grade 5 cave mapping techniques with Leica DistoX, handheld Suunto Compass and Clinometer for in cave measurements have been used, with map detail grades 2 and using Compass software for restitution (with loop adjustment and closure) (Grade UISv1 5-2-B, cfr. Haüselmann 2011).

Figure 3. Astronauts surveying the cave (Credit ESA – S. Sechi).

3.2. Mineralogy and Water chemistry

Mineral samples have been taken making use of a steel spoon or a geological hammer (normally scratching of secondary minerals crusts or coatings), placing a few grams of material in a small plastic cylindrical container. A detailed analysis of all the samples under stereoscopic microscope was performed to distinguish and to separate the different mineralogical phases present. Single phases were analyzed by an X-ray diffractometer (Philips PW 1050/25) or in a Gandolfi camera (Ø: 114.6 mm, exposition: 24/48 hrs). Experimental conditions were a 40 Kv and 20 mA tube and CuKα Ni filtered radiation (λ = 1.5418 Å). Chemical qualitative analyses were carried out through an electron scanning microscope (ESEM Philips XL40) with an electronic microprobe (EDS-EDAX 9900) at the C.I.G.S. (Centro Interdipartimentale Grandi Strumenti) of the Modena and Reggio Emilia University.

Water samples were composed of two bottles: a cylindrical one of 250 ml containing unfiltered and unacidified water, and a square one of 100 ml of filtered (0.45 μm) water acidified with 1 ml of concentrated HNO_3. Two water samples are collected at each site (250 ml of normal water and 100 ml of water filtered with a 0.45 μm sterile filter and acidified with 1 ml of concentrated HNO_3). At each sampling site pH, temperature (T), Electrical Conductivity (EC) and Total Dissolved Salts (TDS) are measured in situ with a Hanna HI 991301 portable sensor. Fundamental metals (Na^+, K^+, Mg^{2+} and Ca^{2+}) were analysed with an Atomic Absorption Spectrophotometer (AAS), minor and trace metals and semimetals (Pb, As (tot.), Cu, Zn, Cd etc.) with ICP-OES instead. Major anions (SO_4^{2+}, Cl^-, F^-, Br^- and NO_3^-) were analysed with Ionic Chromatography, the nitrogen species (NH_4^+, NO_2^-) by Colorimetry, Chemical Oxygen Demand (COD) through a return titration after oxidation with Potassium dichromate.

3.3. Cave meteorology

Three Onset HOBO U23 Pro v2 Temperature/Relative Humidity (RH) data loggers have been placed in several spots in the cave during both 2011 and 2012 missions. Sensors have an accuracy of 0.2 °C and 5% RH and measurements were set at 30 minute intervals. The 2011 mission investigated the camp area, with data loggers placed far away or close to the tents and kitchen on a horizontal plane, while in 2012 a vertical log has been made placing the data loggers at the lake level, the safe haven (mid height) and close to the roof above the Camp site.

A CR200 Data logger of Campbell Scientific Inc. equipped with an MP100A Temperature/RH sensor (accuracy 0.5 ºC/2% RH) and a Windsonic ultrasonic wind sensor (accuracy 3º wind direction and 2% of reading in wind speed) has been installed in a windy passage in the summer of 2011 (Fig. 4). Reading interval was set at twice an hour and data were downloaded every 3 months. During the missions astronauts have programmed the station to take measures every minute for 4 to 5 days consecutively, and data were downloaded at the end of this test period, switching the readings back to twice an hour.

3.4. Microbiology

To investigate if humans change the microbial environment by their presence, astronauts were equipped with agar plates containing different nutrient media (Fig 5). At selected places (e.g., camp kitchen area) plates were exposed to cave air for 30 min. For each sample site, temperature and humidity were determined.

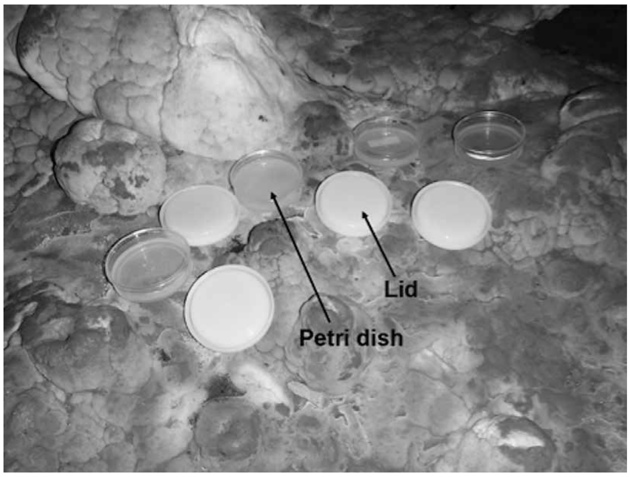

Figure 5. Agar plates exposed to cave air (Credit ESA – V. Crobu).

For follow-up molecular studies, astronauts were asked to collect soil and water samples using special sterile Falcon tubes (Fig. 6). They selected appropriate sampling sites and collected soil or dirt by scrapping the surface with a sterile metal spatula. Genomic DNA was extracted from soil samples using the XS buffer method as previously described (Tillett and Neilan 2000). A nested PCR approach using the

Figure 4. The wind station in the narrow squeeze. (Credit ESA – V. Crobu).

Figure 6. Sampling of soil for molecular analysis (Credit ESA – V. Crobu).

primer combinations E27F / 1492R and 340F/1000R were used to screen for archaeal diversity in the samples. Furthermore, soil samples were plated in the laboratory as well to identify soil associated organisms.

3.5. Biology

Terrestrial and aquatic cave dwelling fauna were attracted using baits composed of liver and/or cheese and placed in plastic containers. Animals were free to enter and exit the containers at all times.

To position the baits, the astronauts have looked out for a wet area, if possible with organic material. Baits have been placed underneath stones and rocks, and the aquatic ones on the bottom of a pool or a lake. Baits have been checked each day, if possible, looking for animals inside the bait, close by and under stones near the station. Species were collected using tweezers or a paintbrush, and put in a bowl for counting, photography, or, in some cases, final sampling.

Also direct sampling has been carried out by astronauts, checking for cave-dwelling animals under stones and pebbles, but also on walls and in protected niches close to organic material (animals often "hide" after lunch). All observation and sampling stations have been localised on a map and linked to the nearest survey station.

Known animals were recognised using a photographic manual and counted, while unknown species were sampled in 100% or 70% alcohol in small plastic cylindrical probes (Fig. 7). Samples have been sent to specialists for determination.

Figure 7. Biological sampling (credit ESA – V. Crobu).

3.6. TEDRA communication system test

TEDRA™-S1 (Through Earth Digital Radio Appliance) system is a ground transmission radio device constituted of two units by which voice is carried as electric signal from the emission point to the reception one (Villarroel et al. 2007; Muñoz et al. 2011). This system fed with a 12V power source is able to inject an electric current in the ground in emit mode and to reconstruct the signal of this small voltage variation in receive mode using a LF (70 kHz) carrier wave and single side-band modulation. The amplified signal is transmitted in the ground by electrodes and the electric current lines follow their underground path crossing the whole surrounding medium. Each TEDRA™-S1 unit contains an electronic emission/ reception apparatus, two pair of stainless steel electrodes (2 stakes for thick ground and 2 contact meshes for wet and muddy substrates), cables for connecting the electronic unit and electrodes (two 25-metres cables) and a "push to talk" microphone/speaker.

Thanks to CNSAS cave rescue, who has provided the equipment, one TEDRA™-S1 communication unit has been tested in a variety of in-outside locations and configurations (stake and mesh electrodes, different electrodes distances and orientations, vertical and horizontal lines) during the CAVES 2012 mission.

4. Results and discussion

4.1. Exploration and survey

The survey from the entrance to the Camp area inside the cave, and the area around the Camp site up to the start of the Lake Branch and the Wind Station have been mapped by the instructors for a total length of 600 metres. Starting from these known parts, astronauts explored over 3 km of cave passages in the expeditions of September 2011 and 2012. The first team of 5 astronauts surveyed a total of 700 m of cave, exploring several hundreds of metres without mapping. The 2012 team, composed of 6 astronauts and having one more day underground, surveyed a total of 1.3 km of passages, exploring several hundreds of metres especially in the lake branch. A total of 120 survey shots have been carried out and registered in the Compass software. The 3D model of the mapped cave areas is shown in Figure 8.

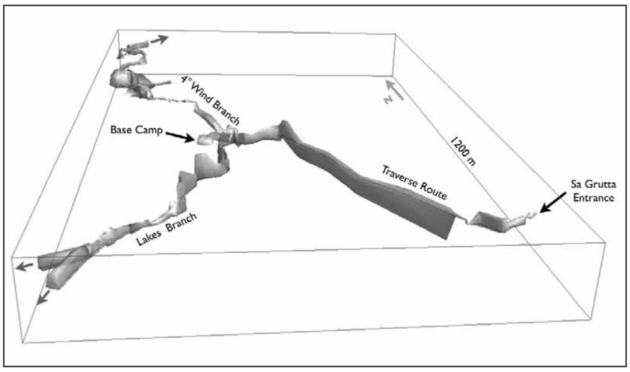

Figure 8. Three-dimensional view of the mapped cave passages.

4.2. Mineralogy and Water chemistry

A total of 6 mineral samples have been collected from the cave, 5 in 2011 and only 1 in 2012. All collected minerals were composed of the common carbonates calcite, aragonite and hydromagnesite. These two last minerals indicate the presence of certain amounts of Mg in the drip waters.

Water samples have been taken in the lakes and in small ponds along the explored cave branches. Most are characterised by the typical calcium bicarbonate chemistry, slightly undersaturated with respect to both calcite and aragonite.

4.3. Cave meteorology

The Temperature and RH measurements on a horizontal and vertical profile have shown the influence of the Camp site to be very minimal and localised.

The wind station, instead, has measured some very interesting data that are still being elaborated (Fig. 9). Wind speed ranges from 0 to 10 m/s in a 0.5 m^2 squeeze. The airflow changes direction when outside temperature becomes close to that of the cave (around 16 ºC), becoming colder or warmer. During winter a temporary sump located some metres further in the cave can fill with water closing the passage completely. These flooding episodes are well recorded by the wind station with a complete stop of all airflows inside the squeeze. The sump lowers and allows airflow to reestablish in less than 2 days time.

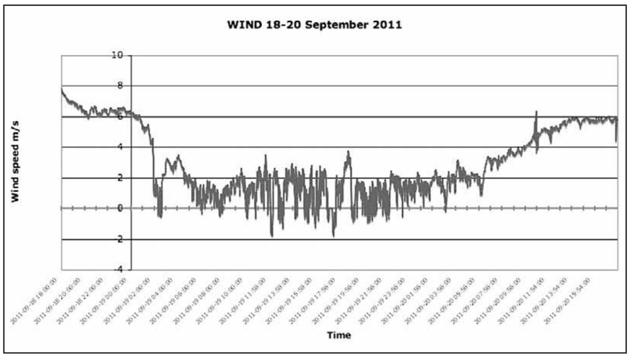

Figure 9. Wind flow in the period 18–20 September 2011, during the astronaut's permanence in the cave. Negative values represent inverted airflow.

4.4. Microbiology

After evaluating the exposed plates, we found that 58 % of all identified bacteria were environmental and 42 % of them were associated with humans (Fig. 10). Species identified belong to the genus *Staphylococcus* and *Micrococcus*. In sharp contrast to these results, plated soil samples showed only 4 % human associated organisms.

The overall bacterial burden in this environment was with 10^4–10^6 cells per milligram of soil lower than normal soil, however, this is not unexpected due to the lack of nutrients. Molecular analysis thus far suggests that there is a diverse pool of archaea present within the cave, however, further analysis is necessary to better characterise the findings.

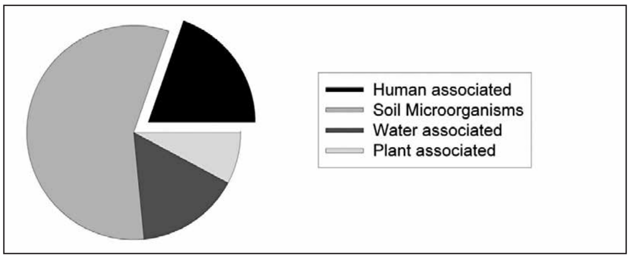

Figure 10. Diagram showing the distribution and association of recovered bacteria.

4.5. Biology

During their stay in the cave, the astronauts have observed, counted and sometimes sampled various specimens belonging to different groups of invertebrates, in particular, Insecta Diplura, Coleoptera and Crustacea.

In each station of sampling, the astronauts have taken note of the kind of substrate, the temperature, and the number of specimens observed. Throughout the whole expedition they have monitored 12 specimens of the crustacean genus *Alpioniscus* (some of which were also sampled), 67 *Ovobathysciola majori* and 5 larval stages of this species, and 12 *Patrizicampa sardoa*.

The Crustacea belong to the Order Isopoda, Suborder Oniscidea, Family Trichoniscidae, and have revealed to be very interesting from the beginning, because of their different morphology, compared to already known species belonging to the genus *Alpioniscus*. The ancestors of these terrestrial isopods seem to have evolved from the aquatic habitat to the terrestrial one. Surprisingly, the astronauts found a species that has returned living in water, completing an evolutionary full circle (Fig. 11). This discovery is very important because the few aquatic woodlice we know of were thought to be primitive forms primarily living in subterranean waters (Vandel 1965). Now it is clear that these animals are specialised forms which have evolved to live in water again. This is demonstrated by the presence of a water conducting system on their 7th pair of legs, a structure that is typical of terrestrial species. This is changing in part the point of view of the specialists on evolutionary processes concerning terrestrial isopods living in an aquatic environment. It also confirms the theory that evolution is not a one-way process but that species can evolve to live in previously forgotten habitats.

Figure 11. The new species of Isopoda discovered in the lake gallery (credit: ESA – M. Fincke).

4.6. TEDRA communications system test

CAVES 2012 extended exploration phase allowed to perform four different TEDRA™-S1 communication tests between underground participants (at the Camp area, Survey Point VE 23 and Survey Point FR 6) and surface support team (at the Mountain peak, a point on the surface that was approximately above the Camp site, and at the Refuge Sa Oche (close to the cave entrance). Subsurface and surface stations distances were 200 metres in depth from the cave to the Mountain peak and around 500 metres at the same altitude from inside to outside. Each test was planned during daily DPC and also arranged in progress during TEDRA communication, after the first contact, in function of the cave exploration (Fig. 12).

The surface antenna length was 10 metres at the Mountain peak and 15 metres at the Refuge Sa Oche, whereas the subsurface antenna length varied from 50 to 25 metres. Both the stakes and the contact meshes were used as electrodes within the cave, while only the stakes were used outside. To optimise the electrical contact with the dry substrate, some water was poured to moisten the electrodes. The electrodes have been placed within the cave grounds in large and flat bedrock covered by several centimetres of loose but moist dust and soil at the Camp site, in a wide field of boulders cemented together with thick mud, with significant vertical height changes and uneven terrain at the Survey Point VE 23 and in loose gravel of various size, extending to a considerable depth at the Survey Point FR 6.

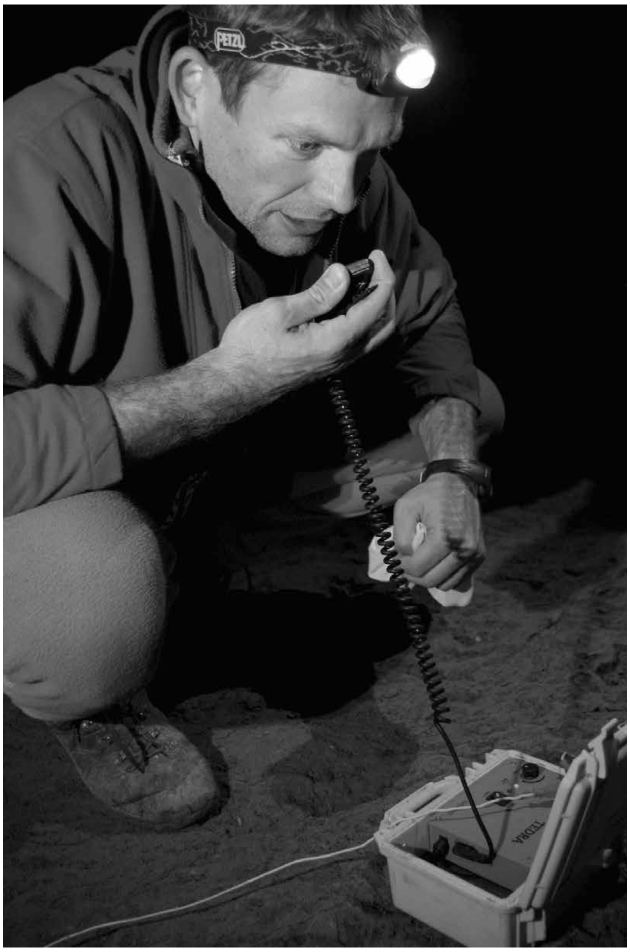

Figure 12. Using the TEDRA communication system (credit: ESA – V. Crobu).

On the surface, the Mountain peak is constituted by a 10 m large valley with limestone bedrock covered by a few centimetres of loose and dry soil while the Refuge Sa Oche substrate was large and flat bedrock covered by few centimetres of dense and dry soil. Regarding the orientation of the electrodes of each TEDRA unit, the angle was chosen in a way that both lines were as parallel as possible, with 10° of tolerance.

Clear and audible communication was always established from the Cave to the Mountain peak, both stakes and meshes were used as electrodes. The exception was Test 3, during which reception was initially understandable but not as good as previous tests, due perhaps to a significant echo effect in the narrow cave. Changing the installation from a full antenna length of 50 m to 40 m, the radio contact was degraded but still possible, but became impossible when the antenna length was further decreased to 34 m and then increased to 50 m again. The degraded communication was attributed to the graveled substrate where stakes were buried.

Very clear and audible TEDRA™-S1 performance was established from cave to the Refuge Sa Oche too, using antenna lengths of both 50 m and 25 m.

5. Conclusions

CAVES has been recognized by all participant astronauts and, in particular, by experienced spacefares as a very realistic spaceflight analogue, providing a unique ISS-representative multicultural operational team training opportunity, where experienced flown astronauts can share their knowledge with younger crewmates.

The cave environment requires adaptation and induces stress and fatigue, requiring constant attention to operational safety procedures. Exploration and documentation tasks and scientific activities provide a realistic set of technical challenges, which carried out in spaceflight-like format, allow the build-up of spaceflight operationally relevant expertise. Behavioural briefings and debriefings enable an invaluable team learning experience, carried out in an environment where the effects of mistaken decisions can have severe impact on safety and mission goals.

The scientific programme not only offers a set of realistic tasks and objectives, but it also provides really interesting scientific results. Multidisciplinary researches allow a continuative and detailed study on the caves visited during the course. The environmental monitoring and the geological and geochemical studies are giving important information about the cave environment in this karst area of Sardinia. Moreover systematic microbiological and biological researches provide new information on these peculiar ecosystems, even discovering previously unknown species. All these important scientific goals were achieved thanks to the careful astronauts' performance of strict scientific protocols and delicate procedures.

In addition CAVES represent an opportunity to test new cave-dedicated technologies, like for the TEDRA™-S1 communications test.

Acknowledgments

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