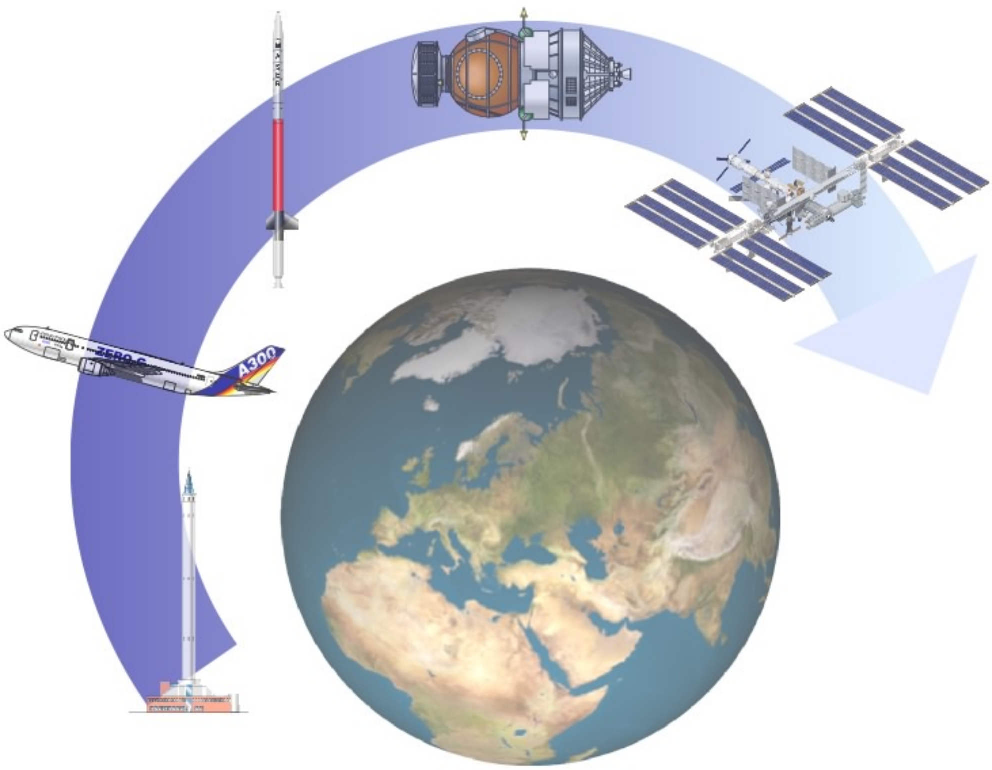
# Summary Review of the European Space Agency's Low Gravity Experiments

## Volume 4: ISS Increment 10

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# PURPOSE OF DOCUMENT

The Summary Review of the European Space Agency's Low Gravity Experiments is intended to provide a concise, but clear, overview of the objectives and scientific results obtained from ESA sponsored low gravity research, executed on/in the five low gravity platforms and other ground based facilities supported by ESA.

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# 1 INTRODUCTION

## 1.1 Background to ESA Low Gravity Research

European involvement in low gravity research began approximately 30 years ago, with nationally funded programmes (in particular those of France and Germany) and US collaborations. Later, in January 1982, a European Space Agency (ESA) funded programme was initiated by the ESA Member States, who agreed to a small programme to which governments could contribute according to their interests and budgets. The first phase of this new ESA programme (Microgravity Programme: Phase-1) was established for the period 1982-1985. This allowed ESA to participate in the German Texus Sounding Rocket programme (later extended to include Swedish Maser Sounding Rockets) to perform short duration microgravity experiments. The Phase-1 programme also covered the development of a first set of multi-user experiment facilities to be flown on the Space Shuttle Spacelab and SpaceHab missions.

Since then, ESA has sponsored more than 2000 experiments, payloads and facilities, which have been integrated and operated on various types of low gravity platforms, including:

- Drop Towers;
- Parabolic Flights;
- Sounding Rockets;
- Retrievable Capsules;
- Space Shuttle;
- MIR Space Station;
- International Space Station.

## 1.2 The Five Major Low Gravity Platforms

This document mainly covers the research executed on/in the 5 major low gravity platforms currently supported by ESA, which are:

- the ZARM (Zentrum für Angewandte Raumfahrt Microgravitation) Drop Tower, located in Bremen, Germany, which was officially declared an ESA External Facility on 2 October 2003;
- the Novespace Airbus A-300 "Zero-g" aircraft based at the Bordeaux-Mérignac airport, which has been used by ESA since 1997;
- the four ESA supported sounding rockets (miniTexus, Texus, Maser and Maxus), which are launched from the Esrange base near Kiruna, Sweden;
- the Russian Foton retrievable capsule, an unmanned Earth-orbiting spacecraft offering microgravity and space exposure, that ESA has used since the early 1990's;
- the most complex platform currently accessible through ESA, the International Space Station (ISS).

Besides the five major low-gravity platforms presented above, ESA also supports access to specific facilities and environments on Earth that simulate low gravity and the confinement of long duration space missions. Extensive and timely use of the research capabilities offered by these facilities, will not only improve the preparation of spaceflight experiments, but will also increase the level of scientific knowledge of the influence of gravity and/or extraterrestrial environments on life, physical and interdisciplinary processes.

Specific ground facilities that simulate space and planetary conditions like climate, physical and psychological isolation, low gravity, extreme environments, high velocity impacts, etc., are available in a wide range of scientific disciplines. Recent examples of these are Long Term Bed Rest Studies (refer to the following web site http://www.spaceflight.esa.int/users/file.cfm?filename=miss-gbfac) and Antarctic Isolation Studies (see http://www.esa.int/esaCP/SEMOS4T1VED_index_0.html). Both types of studies are aimed at investigating the physiological and psychological problems that may arise in conditions of isolation and confinement, such as those that will be experienced during a long duration space mission.

More detailed information regarding the above-mentioned platforms/facilities and how to access them can be found in the ESA publication "European Users Guide to Low Gravity Platforms", which can be viewed at the following web site http://www.spaceflight.esa.int/guide. A hard copy of the Users Guide can also be requested from:

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## 1.3 Release and Structure of Summary Review Document

This Summary Review document will be released in separate volumes, where each individual volume will cover the research carried out during one or more campaigns (Drop Tower, Parabolic Flight, Sounding Rocket, Ground-based), missions (Foton) or increments (International Space Station). The document will be comprised of two main parts:

- Section 1 will provide general information and a background to ESA's low gravity research, including a summary of the Research Cornerstones.
- Section 2 and beyond will introduce the platform or facility being covered, before providing an experiment-by-experiment summary, broken down per research cornerstone, for each specific campaign, mission or increment.

## 1.4 Research Cornerstones

In 2000, ESA prepared a comprehensive Research Plan defining the scientific priorities in the life and physical sciences for a 5-year period, with a horizon of 10 years. The compilation of this Research Plan was initiated by a bottom-up analysis of all the research proposals received at that time by ESA. As a next step, ESA asked the European Science Foundation (ESF) to assess the research priorities in a dedicated user consultation meeting, which took place in Bischenberg, France in November 2000. At this meeting and in the subsequent ESF recommendations, the concept of Research Cornerstones was defined.

The Research Cornerstones describe areas of research where concerted efforts at the European level have already produced, or are promising to lead to, eminence if not a leading position on a global level. They provide therefore, an excellent basis for ensuring that new proposals will address issues that have been recognised as constituting a particular strength in Europe. A particular advantage of this will be that the research objectives of the ESA programme will be better harmonised with those of other research funding agencies or entities in Europe, leading to a more efficient and complete coverage of the research efforts involved. It will also further promote the teaming of research groups at European level, thus combining strengths and increasing European knowledge and competitiveness. Finally, it will allow ESA to streamline and optimise the available and future research infrastructure to sustain those objectives.

Already at Bischenberg it was identified that the Research Plan is by definition a living document. Research priorities may shift, new promising research fields may emerge, or new results taken into account. For that reason, it was envisaged that the process of user consultation should be repeated at regular intervals.

Following this, a second user consultation on Life and Physical Sciences in Space was organised again by ESF at Obernai, France in May 2004. On this occasion a larger number of scientists participated and more time was available to discuss the individual disciplines during two workshops. After this consultation ESF recommended updated Research Cornerstones, which ESA and its advisory committees analysed. After a full investigation, ESA produced an updated Research Plan, in which also the new Research Cornerstones were defined.

It should be stressed, however, that the Research Cornerstones are **not** used as a selection criterion in the evaluation of research proposals. In other words, the final selection of projects is based on scientific quality, regardless of the research topic addressed. This, in the view of ESA, is the only way to ensure that promising new research is identified and pursued. The Research Cornerstones should therefore be seen as a guideline to potential users who wish to carry out research in the life and physical sciences on the ISS.

### 1.4.1 Life and Physical Sciences Research Cornerstones

The following tables summarise the updated Life and Physical Sciences Research Cornerstones defined in 2004 for the period 2005-2009.

**Table 1-1: Fluid Physics Research Cornerstones**

| RESEARCH CORNERSTONES | DESCRIPTION | SCIENCE TARGETS | POTENTIAL APPLICATIONS |
|---|---|---|---|
| **Fluid and Interface Physics** | Study of multiphase systems (their phase transitions and related dynamics), critical and supercritical fluids, granular materials, liquid-solid interface phenomena and complex fluid phases.<br><br>Geophysical fluid flows. | Quantify heat transfer, mass exchange and chemical processes in multiphase systems and supercritical fluids;<br><br>Measure diffusive processes in mixtures;<br><br>Study the stability of foams and emulsions;<br><br>Describe dynamic coupling in granular materials under vibration. | Develop reactors for supercritical oxidation of industrial contaminants;<br><br>Develop high-efficiency heat exchangers;<br><br>Improve reactor design in industrial plants;<br><br>Design improved oil recovery techniques. |
| **Combustion** | Study combustion phenomena that are dominated on the ground by buoyancy convection. | Quantify fuel droplet and spray evaporation, autoignition and combustion processes;<br><br>Detail the process of soot formation in flames and the conditions for flammability of solid fuels. | Improve efficiency of electrical power plants;<br><br>Reduce emissions of engines;<br><br>Fuel-efficient and safe spacecraft for human exploration;<br><br>Improved flammability test procedures. |

**Table 1-2: Fundamental Physics Research Cornerstones**

| RESEARCH CORNERSTONES | DESCRIPTION | SCIENCE TARGETS | POTENTIAL APPLICATIONS |
|---|---|---|---|
| **Physics of Plasmas and Solid/Liquid Dust Particles** | Understand the three dimensional behaviour of particles in complex plasmas and aggregation processes that require weightlessness. | Enhance theoretical description of complex plasmas, including self-ordering and phase transition phenomena;<br><br>Improve modelling of the interaction of protoplanetesimals, their optical properties and of the behaviour of pollutants in the atmosphere. | Develop novel plasma coating techniques;<br><br>Nucleation and growth of novel substances for solar cells and plasma screens;<br><br>Improved modelling of Earth climate and environment. |
| **Cold Atom Clocks, Matter Wave Interferometers and Bose-Einstein Condensates** | Study properties and applications of cold atoms, including Bose-Einstein condensates. | Develop and operate a cold atom clock in space;<br><br>Check limits of validity of theories of relativity and quantum electrodynamics. | Improved accuracy of absolute time measurements;<br><br>Increased accuracy for navigation and geodesy systems. |

**Table 1-3: Material Sciences Research Cornerstones**

| RESEARCH CORNERSTONES | DESCRIPTION | SCIENCE TARGETS | POTENTIAL APPLICATIONS |
|---|---|---|---|
| **Thermophysical Properties of Fluids for Advanced Processes** | Utilise the extended possibilities of containerless processing in space to measure critical properties of fluids for processes that are required as input parameters for adequately describing balances in volume phases and at interfaces. | High accuracy measurements of the properties of stable and metastable (undercooled) liquid metals. | Increase the reliability of numerical simulation and control of casting facilities in the metallurgical industry. |
| **New Materials, Products and Processes** | Understand the physics of solidification and crystal growth of metals, organic and inorganic materials and biological macromolecules. | Quantify the influence of the growth conditions on the homogeneity and the defects in crystals, including protein crystals;<br><br>Enhance numerical models of the microstructure formation in metals and alloys. | Improve and validate models for predicting grain structures in industrial castings;<br><br>Develop processes towards new metallurgical products;<br><br>Improve efficiency of production of industrial crystals. |

**Table 1-4: Biology Research Cornerstones**

| RESEARCH CORNERSTONES | DESCRIPTION | SCIENCE TARGETS | POTENTIAL APPLICATIONS |
|---|---|---|---|
| **Molecular and Cell Biology** | Study the impact of gravity at the cellular and molecular levels. | Study gene expression in an altered gravitational environment in relation to cellular phenomena;<br><br>Improve understanding of the impact of gravity on signal transduction and the specific properties of cellular entities such as the membrane;<br><br>Clarification of the role of mechanical forces including those derived from gravity in triggering proliferation, differentiation, apoptotic processes and tissue formation. | Provides the basis for other disciplines, including developmental biology, physiology, health science and biotechnology;<br><br>Develop artificial functional tissues and targets for drugs screening;<br><br>Depression of the immune system;<br><br>Identify pharmacological substances for tissue regeneration;<br><br>Develop bio-regenerative life support systems for human exploration missions;<br><br>Develop novel microencapsulated drugs and cells. |
| **Plant Biology** | Understanding the impact of gravity on plant systems;<br><br>Study mechanosensory elements involved in mechanisms of graviorientation and gravishaping. | Identify molecular and cellular elements of mechanosensory mechanisms and gravity-related signalling pathways;<br><br>Study how gravity shapes plant morphology;<br><br>Identify gene interactions important in the gravistimulus response chain. | Improvement of plant growth and mechanical properties of plants;<br><br>Develop and improve biological life support systems;<br><br>Provide the basis for biotechnological applications utilised on future long-term human spaceflight;<br><br>Develop techniques for plant survival and growth in space. |
| **Developmental Biology** | Study the effect of gravity on whole-body developmental and reproductive processes. | Study altered gene expression in an altered gravitational environment;<br><br>Study the impact of the cytoskeleton architecture on signal transduction e.g. functional genomics;<br><br>Identify gravity-sensitive phases in multicellular organisms;<br><br>Understand the effect of gravity on the development of the vestibular and sensori-motor systems in vertebrates. | Design pharmacological relevant substances for animal and human applications relevant to human development;<br><br>Evaluation of the possible outcome of extraterrestrial colonisation attempts;<br><br>Develop techniques and pharmacological substances for tissue regeneration. |

**Table 1-5: Physiology Research Cornerstones**

| RESEARCH CORNERSTONES | DESCRIPTION | SCIENCE TARGETS | POTENTIAL APPLICATIONS |
|---|---|---|---|
| **Integrative Gravitational Physiology** | Explore, in an interdisciplinary way, systems that are sensitive to gravity, e.g. cardiovascular system, pulmonary system, nervous system, fluid-electrolyte homeostasis, skeletal system, immune system, etc. | Study cardiovascular control and regulation;<br><br>Study the mechanisms for fluid regulation by the kidneys;<br><br>Investigate the interaction of the vestibular system with other inputs relevant to locomotion and posture (e.g. vision, proprioception);<br><br>Study effects of changes in load on muscle atrophy and plasticity;<br><br>Understand and quantify bone mass turnover as a function of e.g. local blood perfusion and mechanical stress;<br><br>Study the mechanisms of osteoporosis. | Improve techniques and devices for medical applications e.g. sports medicine;<br><br>Improve rehabilitation after long-term incapacitation, particularly involving bed rest;<br><br>Improve treatment of patients with decreased lung-function;<br><br>Develop improved approaches for the treatment of neurological diseases;<br><br>Improve means for diagnostics, prevention and treatment of osteoporosis, and reduce bone loss in astronauts for future long duration missions;<br><br>Improve treatment of diseases like hypertension. |
| **Non-Gravitational Physiology of Spaceflight** | Explore the effects of the non-gravitational extreme environment of space, e.g. radiation, isolation, nutrition, confinement, noise, disruption of circadian rhythms, hypobaric conditions (e.g. EVA), etc. | Study effects of isolation, group dynamics, cultural differences, etc.;<br><br>Study effects of radiation on DNA damage;<br><br>Study close coupling between nutrition and health, e.g. testing new space foods;<br><br>Investigate effects of dust inhalation on airway inflammation;<br><br>Investigate possibilities of decompression sickness in connection with EVA. | Improve crew selection techniques for future long duration missions;<br><br>Develop new nutritional methods for the improvement of health;<br><br>Develop new protection measures for people exposed to radiation;<br><br>Improve prevention and treatment for patients suffering from decompression sickness. |
| **Countermeasures** | Develop physiological, pharmacological, psychological, and mechanical countermeasures. | Understand the mechanisms leading to various problems such as: spatial disorientation (nausea, imbalance), orthostatic intolerance, bone loss and microarchitectural deterioration, muscle atrophy and weakness, cardiac atrophy, etc. | Develop improved approaches, treatment and countermeasures for a variety of Earth and space based disorders and maladies. |

**Table 1-6: Exobiology Research Cornerstones**

| RESEARCH CORNERSTONES | DESCRIPTION | SCIENCE TARGETS | POTENTIAL APPLICATIONS |
|---|---|---|---|
| **Origin, Evolution and Distribution of Life** | Study the survivability of organisms under extreme conditions on Earth (extremophiles) and in space. | Investigate the contribution of space conditions, including radiation, to the formation of prebiotic molecules;<br><br>Identify the conditions for survivability of micro-organisms from and in space, including planetary surfaces;<br><br>Identify markers and tools to search for extinct and extant life. | Identify novel enzymes and bacteria from extreme physical and chemical environments with industrial application e.g. biocatalysis. |

**Table 1-7: Exploration Research Cornerstones**

| RESEARCH CORNERSTONES | DESCRIPTION | SCIENCE TARGETS | POTENTIAL APPLICATIONS |
|---|---|---|---|
| **Human Planetary Exploration** | Study novel aspect of human planetary expeditions. | Quantify radiation risk for human beings and understand the specific biological action of space radiation;<br><br>Study effects of isolation in high-stress environments;<br><br>Quantify needs for consumables during missions;<br><br>Perform simulation tests on in-situ resource utilisation potential. | Develop advanced radiation sensors and countermeasure devices;<br><br>Develop technology for telemedicine/telesurgery in remote areas;<br><br>Develop protocols for handling stress effects;<br><br>Develop methods for in-situ resource utilisation;<br><br>Develop life-support systems for use in space and other isolated environments;<br><br>Develop the technologies for identification and utilisation of in-situ resources. |

For more details regarding Life and Physical Sciences research, please contact:

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## 1.5 Erasmus Experiment Archive (EEA)

An important resource for low gravity research scientists and users is the Erasmus Experiment Archive (EEA), maintained by the Erasmus Centre (HME-UC). The EEA is a database of ESA funded or co-funded experiments covering a wide range of scientific areas, which were performed during missions and campaigns on/in various space platforms and microgravity ground-based facilities over the past 30 years. The archive is continuously being updated and as of June 2007, contained more than 2000 experiment records. The major items of information covered in the EEA include:

- Research cornerstone;
- Date of experiment;
- Mission name;
- Team members and institutes;
- List of publications/references;
- Experiment objectives;
- Experiment procedures;
- Experiment results;
- Attachments (figures, graphs, videos, etc.).

The EEA depends highly on the support provided by users; therefore users are encouraged to send inputs to the contact coordinates below, once they have executed an experiment. In fact, users who perform ESA funded experiments have the obligation to provide an abstract to the EEA. Failure to meet this obligation will be taken into account when deciding on new experiment opportunities/proposals from the user team in question.
Users are invited to visit the database, from which they can, among other things, obtain further information regarding experiments in their field of research already carried out in the past. The EEA web address is the following: http://www.spaceflight.esa.int/eea. For further details regarding the EEA, please contact the following by phone, fax, mail or e-mail:

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# 2 THE INTERNATIONAL SPACE STATION (ISS)

## 2.1 ESA Utilisation Rights and Additional Flight Opportunities

The National Aeronautics and Space Administration (NASA) provides the overall leadership of the ISS programme development and implementation, and together with Russia provides the major building blocks of the ISS. The European Space Agency (ESA), together with the Japan Aerospace Exploration Agency (JAXA) and the Canadian Space Agency (CSA) are providing additional elements, which significantly enhance the Space Station. The overall ISS utilisation rights are divided among the Partners, according to the elements and infrastructure they provide (e.g. Columbus Laboratory for ESA). The main principle is that each International Partner may utilise equipment and facilities in or on each other Partner's elements in accordance with their respective "utilisation rights". Those rights are defined in the Intergovernmental Agreement (Article 9) and the different Memoranda of Understanding signed by all of the Partners.

In return for its contribution to the ISS, ESA has a resource allocation of 51 % of the internal and external user accommodation of the Columbus Laboratory. Other allocation rights to ESA comprise 8.3 % of the total ISS utilisation resources and 8.3 % of the total crew time. Note that this excludes all of the Russian accommodations and resources, as this is retained by Russia for its own use.

In May 2001, ESA and the then Russian Aviation and Space Agency (Rosaviakosmos), now Roscosmos, signed a Framework Agreement for the provision of Russian ISS flight opportunities. The Agreement documents the principles, terms and conditions for the cooperation between ESA and Roscosmos concerning ISS operations and utilisation, through the provision by the latter of fare-paying ISS flight opportunities in the period 2001-2006, for members of the European Astronaut Corps. The actual commitment for a specific flight opportunity is entered by ESA upon signature of an ISS Flight Order Contract (IFOC) for a specific flight.
The Framework Agreement, establishes a solid and stable basis for the strategic planning of the European Astronaut Corps, and it represents an important step towards the further development of operational expertise of the ESA astronauts prior to the full European utilisation of the ISS with the launch of Columbus.

Two types of flight opportunities are considered under the Agreement as ISS flight opportunities:

- ISS "taxi flights" (this term is reported in the original agreement, but is no longer used), which are defined as short duration Soyuz flights to the ISS for the purpose of exchanging the ISS docked Soyuz, including a short duration stay (approximately 7-8 days) on-board the ISS;
- ISS increment flights, which are defined as ISS crew exchange flights, including a 3-6 months (one increment) stay on-board the ISS.

The assignment of back-up astronauts/cosmonauts for ISS flight opportunities, involving ESA astronauts, is agreed upon between ESA and Roscosmos for each flight.
On-board activities are not restricted to the mandatory system operations and maintenance activities, but also allow for the conduct of activities or experimental programmes in the interest of ESA and national organisations of the ESA Member States. The terms and conditions of such activities are agreed upon in each specific IFOC. The IFOC defines the terms and conditions specific to the implementation of an agreed ISS flight opportunity. Such terms and conditions take precedence over the terms and conditions defined in the Framework Agreement.

The following table (Table 2-1) summarises the Russian ISS flight opportunities that have thus far included an ESA astronaut on-board, following the signature of the Framework Agreement in May 2001.

**Table 2-1: ESA Russian flight opportunities deriving from ESA/Roscosmos Framework Agreement (May 2001)**

| ISS MISSION | ESA MISSION NAME | VEHICLE ID | LAUNCH DATE | LANDING DATE | ESA ASTRONAUT | ASTRONAUT NATIONALITY |
|---|---|---|---|---|---|---|
| **ISS 3S** | Andromede | Soyuz TM-33 | 21/10/2001 | 31/10/2001 | Claudie Haigneré | French |
| **ISS 4S** | Marco Polo | Soyuz TM-34 | 25/04/2002 | 05/05/2002 | Roberto Vittori | Italian |
| **ISS 5S** | Odissea | Soyuz TMA-1 | 30/10/2002 | 10/11/2002 | Frank De Winne | Belgian |
| **ISS 7S** | Cervantes | Soyuz TMA-3 | 18/10/2003 | 28/10/2003 | Pedro Duque | Spanish |
| **ISS 8S** | DELTA | Soyuz TMA-4 | 19/04/2004 | 30/04/2004 | Andre Kuipers | Dutch |
| **ISS 10S** | Eneide | Soyuz TMA-6 | 15/04/2005 | 25/04/2005 | Roberto Vittori | Italian |
| **ISS ULF1.1** | Astrolab | Shuttle STS-121 | 04/07/2006 | 22/12/2006 | Thomas Reiter | German |

## 2.2 Increment Timeline

The summary review of experiments carried out on board the ISS will be presented per Increment, i.e. the period of time between the launch of a vehicle carrying an exchange crew to the ISS, and the undocking of a vehicle for return of that crew. The length of an increment ranges anywhere from 3 months to about 6 months.
The Summary Reviews of European ISS experiments will be covered as from the Belgian Soyuz Mission ("Odissea"), i.e. as from the end of Increment 5.
The following schematic (Figure 2-1) presents a basic timeline of launch events and Increments of the ISS programme, and serves as a quick reference for users of this document.

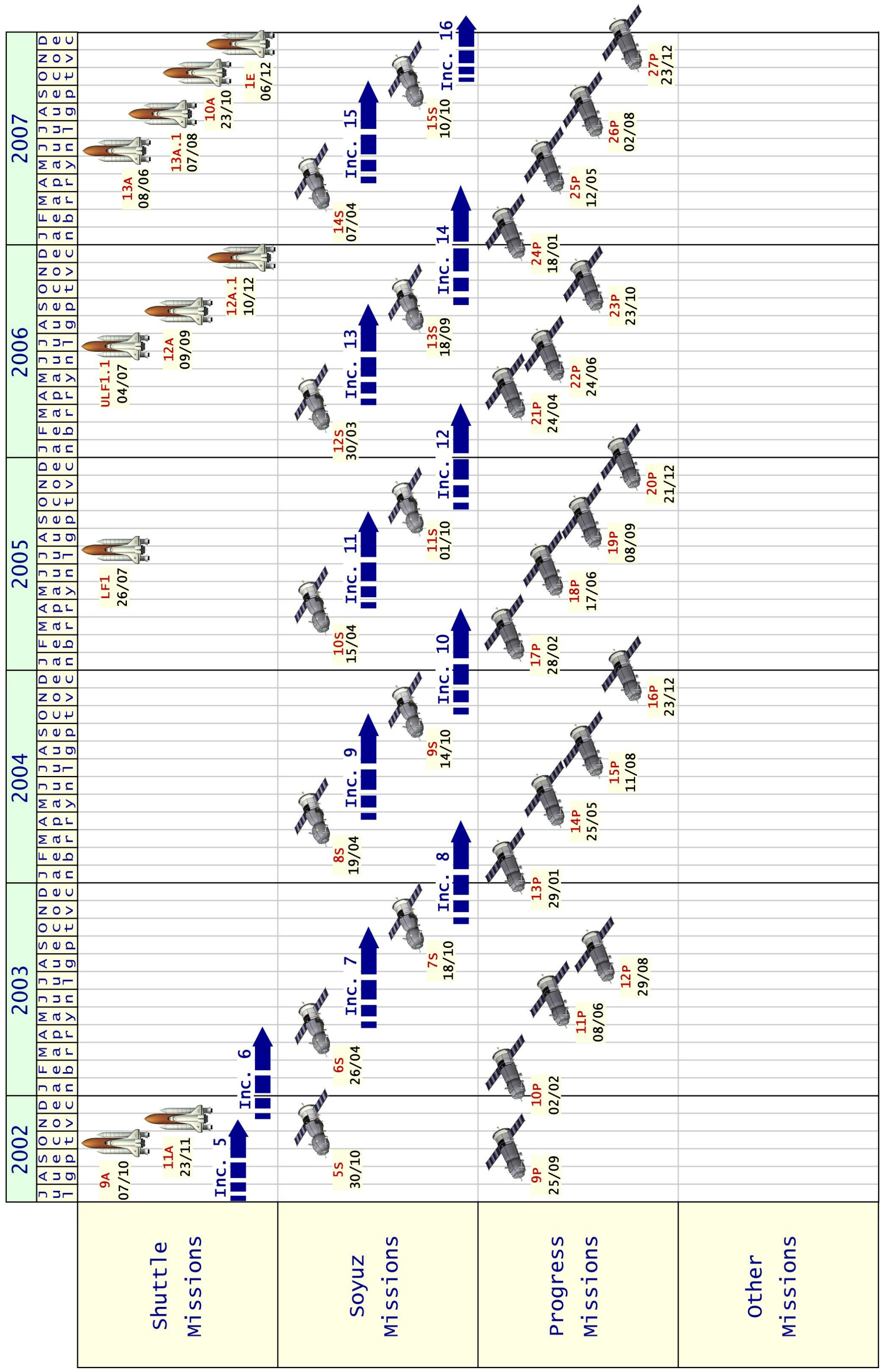

**Figure 2-1: ISS Programme Launch Events and Increments (July 2002 - December 2007)**

## 2.3 Increment 10: ESA experiments

The following table (Table 2-2) lists the 3 ESA experiments that will be covered by this report.

**Table 2-2: List of Life Sciences ESA experiments for Increment 10**

| NAME OF EXPERIMENT | RESEARCH CORNERSTONE |
|---|---|
| Study of the linear energy transfer, energy and charge distribution in a human phantom in space **(MATROSHKA-1)** | Biology: Molecular and cell biology |
| Cardiovascular adaptation to weightlessness **(CARDIOCOG-1)** | Physiology: Integrative gravitational physiology |
| Directed attention brain potentials in virtual 3-D space in weightlessness **(NeuroCOG)** | Physiology: Integrative gravitational physiology |

## 2.3.1 Life Sciences

### 2.3.1.1 Biology: Molecular and cell biology

#### 2.3.1.1.1 Study of the linear energy transfer, energy and charge distribution in a human phantom in space (MATROSHKA-1)

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## 2.3.1.1.1.1 Background, Objectives and Procedures

The scientific objective of the experiment was to investigate the dynamics of the radiation dose accumulated in various parts of an astronaut simulator and tissue-equivalent anthropomorphous phantom. The purpose is to improve space dosimetry methods, and evaluate the radiation hazard of astronaut exposure to radiation. The MATROSHKA facility was launched by the Russian Progress Cargo Vehicle and installed during an EVA on the outside of the Russian Service Module “Zvezda” of the ISS.

The MATROSHKA facility basically consists of a human phantom upper torso equipped with several active and passive radiation dosimeters, a base structure and a container. The container as well as the phantom torso is mounted to the base structure, which serves as a footprint for the human phantom. The container is a carbon fibre structure and forms, with the base structure, a closed volume that contains a dry oxygen atmosphere at ambient pressure.

The MATROSHKA facility is intended to provide a science platform for the determination of the depth and the organ dose in a simulated human upper torso. For radiation risk assessment the knowledge of organ (or tissue equivalent) doses in critical radiosensitive organs is an important prerequisite. The main objective of the experiment was therefore to use the MATROSHKA facility in order to determine the empirical relations between measurable absorbed doses and the required tissue absorbed doses in a realistic human phantom. Therefore, several passive and active sensors are exposed at the surface and at different locations inside the phantom.
MATROSHKA was used for the first time for measurements of the radiation distribution inside a human phantom under EVA conditions. These measurements shall be continued and expanded using the facility for at least a second external exposure (MATROSHKA 2 – Phase C) to investigate the depth dose distribution for different times inside the solar cycle. In addition, MATROSHKA will also be used for measurements inside the station (MATROSHKA 2 Phase A/B).

Sets of passive detectors, such as thermoluminescence dosimeter (TLD) and nuclear track detector (NTD) foils with and without converter foils were provided for mission integrated measurements of absorbed dose, neutron dose and flux of heavy ions and their spectral composition with respect to charge, energy and linear energy transfer (LET). The installed active detectors developed by the investigators, the silicon detector telescope DOSTEL, the scintillator/silicon detectors (SSDs) and the tissue equivalent proportional counter are used to measure the flux of neutrons and of charged particles and the corresponding dose rate and LET spectra separately for galactic cosmic particles and trapped particles as a function of time. All detector systems are calibrated using different on ground irradiation sources. For the passive devices an on-ground reference program was performed. The different systems allow for in-flight cross-calibrations.
The results of MATROSHKA shall provide a baseline for further testing of the current established radiation transport codes, and shall, in the future, lead to a better risk assessment for long duration space flight.

The figure below (Figure 2-2) shows the uploaded MATROSHKA hardware: (from left to right) the phantom torso, the torso equipped with poncho and hood, the torso with carbon fibre glass container simulating the EVA suit, and the torso with multilayer insulation (MLI) two days prior to launch.

**Figure 2-2: MATROSHKA facility uploaded hardware**

The Poncho and the Hood are equipped with polyethylene stripes with sewn-in TLDs (around the whole torso) to measure the skin dose. Further, the Poncho is equipped with six NTDP (Nuclear Track Detector Packages) in similar dimensions as in the organs (two in front, two in the back and one on each side of the torso). To account for neutrons, 20 neutron detector packages are mounted on the Poncho. At the top of the phantom head, a NTDP

as well as the Silicon Telescope DOSTEL are located. Inside the torso, in the organ dose slices, a plastic scintillator covered with silicon diodes with anticoincidence to measure the neutron dose, is positioned.
The 33 slices of the phantom are equipped with 356 channels where the TLDs from the participating groups are located at a total of 1634 positions arranged in a one-inch grid at each of the slices. Figure 2-3 below provides an example of Slice #4 (Phantom Head) with the dosimeter distribution and 26 dosimeter positions for depth dose determination.

**Figure 2-3: Dosimeter distribution in Phantom Head slice #4**

### 2.3.1.1.1.2 Results

After storage of the facility inside the ISS, MATROSHKA was mounted outside the Russian Service Module by the Expedition 8 crew, Alexander Kaleri and Michael Foale, in February 2004. The MATROSHKA facility was activated during Increment 9 and remained outside the ISS for 539 days during Increments 9, 10 and 11. Within this timeframe the "housekeeping data" and the "scientific data" of the active radiation detectors were transmitted to the onboard computer inside the ISS, and later stored on PCMCIA cards, as well as down linked via the US Voice Link.
On August 18$^{th}$, 2005 the 2$^{nd}$ EVA was performed by Expedition 11 crew, Sergei Krikalev and John Phillips. The MATROSHKA facility was brought back into the station and on September 14$^{th}$, 2005 the passive detectors were removed from the facility and downloaded with a Soyuz capsule in October 2005. After returning to ground, the passive detectors were distributed to the co-investigators for data evaluation (November 2005 to January 2006).
Data coverage is not available for the whole exposure period, due to some difficulties with the Russian onboard computer, and the communication between the MATROSHKA and the onboard computer. Nevertheless the downloaded housekeeping (temperature and pressure of the facility) and scientific (dose rate, particle LET spectra) data is of very good quality.
Evaluation of the science data of MATROSHKA is still in progress and results will be published in the Summary Review of Increment 11.

## 2.3.1.1.1.3 Conclusions and Recommendations

Not available.

## 2.3.1.1.1.4 Publications

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## 2.3.1.2 Physiology: Integrative gravitational physiology

### 2.3.1.2.1 Cardiovascular adaptation to weightlessness (CARDIOCOG-1)

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#### 2.3.1.2.1.1 Background, Objectives and Procedures

Orthostatic 'intolerance' (OI), an important physiological consequence of human space flight, is primarily characterised by a fall in stroke volume in the upright position after landing. The underlying pathophysiological mechanisms of OI have been investigated extensively, but no single satisfactory explanation has been proposed yet.
The aim of this study was to assess the relative contribution of (1) autonomic baroreceptor responses and (2) circulatory adjustments in different topographic vascular beds to the mechanism of OI.

The hypotheses underlying this study are that:
1. the observed perturbations in autonomic cardiovascular (baroreflex) control may be more severe after long duration space flight (6 months) leading to more pronounced problems of orthostatic intolerance compared to the alterations observed after short duration (10 days) space flight;
2. the duration of return to normal values after long space flights might persist at least 25 days after return;

3. the maximal flow velocity will be altered at the lower limb arterial level whereas it will not be affected at the cerebral level;
4. the flow supplying the splanchnic area may not reduce in response to fluid shift towards the legs (orthostatic test) which could contribute to make the cardiac output redistribution towards the brain less efficient.

The different tests and measurements that were applied in the protocols allowed to investigate the different functions of the autonomic nervous system and to study hemodynamics. The research objectives were as follows:
1. How is the autonomic control of both heart rate and blood pressure affected during these long-term missions? How is the baroreflex system affected during 6 months in space?
2. What is the time frame in which these changes take place? Do the changes continue after 2 weeks in space, or is an equilibrium reached?
3. Is orthostatic intolerance more severe after long duration than after short duration spaceflight?
4. What is the relative contribution of baroreflex control of heart rate and total peripheral resistance in the recovery after spaceflight and the decrease in orthostatic tolerance?
5. How does blood flow in cerebral/vascular beds influence the observed decrease in cerebral/femoral flow ratio (calf vein, portal vein) contributing to a reduction in brain blood supply leading to OI?

To achieve these goals the following experimental design was proposed:
1. a standard computerised (HICOPS) protocol combining supine and standing provocative tests: head flexion, arrhythmic stress, fixed respiration (pre-, in-, and post-flight);
2. a tilt test protocol that provides insight into circulatory control during orthostatic (pre- and post flight);
3. a 24h ECG Holter-protocol to investigate circadian variations of cardiovascular autonomic control (pre- and post flight);
4. cerebral and lower limb flow measurements (echo-Doppler) that provided data on circulatory regulation in different vascular beds (cerebrovascular, femoral, splanchnic), (pre- and post-flight).

The ECG, finger blood pressure (non-invasive Portapres), echo/Doppler and respiration (abdominal sensor) were continuously recorded and analysed off-line using linear and non-linear techniques of heart rate variability (HRV), blood pressure variability (BPV) and baroreflex sensitivity (BRS). Changes in hemodynamic parameters (stroke volume, cardiac output and total peripheral resistance) were estimated by modelling flow from finger arterial pressure (Modelflow).

CARDIOCOG-1 was a continuation of the experiment initially conducted as part of the experimental package of the ESA supported Spanish Soyuz Mission, "Cervantes" (ISS 7S mission), which took place in October 2003 during increment 8. CARDIOCOG-1 was later also executed during increment 10.
The experimental protocols were performed by 5 cosmonauts before, during and after a 10-day mission and by 2 cosmonauts during a 6-month mission, and contributed in determining the differences in autonomic cardiovascular modulation between long and short term spaceflight.

All in-flight protocol measurements were non-invasive. During all protocols, the cosmonaut was guided through the experiment with a software program developed by a member of the research group and this program was used during all previous missions using the CARDIOCOG protocol. A minimum of 4 repetitions were executed in-flight.
The pre- and post-flight baseline data collections (BDCs) of the CARDIOCOG protocol were performed in 3 postures (supine, sitting and standing). The timeframe for the pre-flight session was Launch-50 days. In order to execute a comparison with the findings of previous missions it was important to reproduce these results at more or less the same days. Especially the first days were critical and the long-term follow-up. The timeframe for the post-flight measurements was R+1, 7, 10, 20, 30 and R+40. Because of limitations in cosmonaut time in the first days after return, a shortened version of the CARDIOCOG protocol was proposed at R+1 (duration <1 hour).

The variables measured during the experimental protocols were the following:

- Respiration (an important modulator of HRV) was monitored continuously (pressure sensor on abdomen).
- _ECG_ electrodes were applied to the chest wall.
- _Continuous blood pressure_ was determined (Portapres) with a non-invasive pulse method at the finger and converted to brachial blood pressure

- *Cerebral flow and vascular resistance, Femoral flow and vascular resistance* Flow distribution between these areas and total regional sympathetic power at cerebral and lower limb level. Main arteries were investigated by Doppler ultrasound using sensors fixed on the skin by strap and bandeau. For the cerebral flow the Doppler probe was placed at the upper level of the zygomatic arch facing the middle cerebral artery, the appropriate orientation was found with help of a rotula. The rotula was mounted on a head helmet in order to maintain a stable orientation. For the femoral artery the probe was placed in front of the superficial femoral artery, at the upper part of the thigh, and was fixed using 2 thigh and abdominal belts. This Cardiolab Doppler system allowed continuous and simultaneous recording of the flow velocities in 3 vessels. A similar Doppler system was used several times in-flight on cosmonauts while performing LBNP test onboard MIR then during pre and post flight Stand test. The system was also used on head down tilt (HDT) subjects.
- *Venous echography, Calf and Portal veins:* (Portal vein flow and diameter, Tibial and gastrocnemian vein section, Tissue (calf muscle) liquid content) These 2 central and peripheral veins selected were investigated by echography, the probe being fixed on the calf skin at the posterior face of the calf, the probe being handled by a sonographer for the Portal vein. The echographic image of calf vein was recorded in real time (at rest or during stand tests) while the Portal vein image was recorded when required.

## 2.3.1.2.1.2 Results

Not available.

## 2.3.1.2.1.3 Conclusions and Recommendations

The real applications will have to be investigated further in the future, but advantages with the data for clinical studies in syncope patients are expected. These patients often faint (similar to orthostatic intolerance) and the cosmonaut data can help provide insights in the cardiovascular control mechanisms and how it responds to changes in adaptability to orthostatic stress.

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## 2.3.1.2.2 Directed attention brain potentials in virtual 3-D space in weightlessness (NeuroCOG)

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### 2.3.1.2.2.1 Background, Objectives and Procedures

The NeuroCOG experiment was designed to further investigate modifications in the perception of whole-body motion in space found during the French Soyuz Mission, "Andromede", in October 2001. The NeuroCOG experiment went a step further in understanding the neural mechanisms underlying the perceptual processes by combining the psychophysical experiments with measurements of visually-evoked EEG potentials.

The human being in his natural environment moves, because of the constraints of gravity, over a relatively flat two-dimensional surface. During Earth-bound navigation, only yaw rotations are typically used when moving from one place to another. Even when moving through three-dimensional structures, human beings tend to remain upright with respect to gravity. In weightlessness, astronauts can translate and rotate in any direction, thus their trajectory is no longer ascribed to two-dimensional surfaces. In contrast with Earth-bound navigation, astronauts can freely use pitch and roll rotations when moving through three-dimensional space. The semi-circular canals measure relative rotations around all three axes (roll, pitch and yaw). This provides relative information about the amplitude of a rotation, but does not provide absolute information about orientation. The otoliths and other graviceptor cues (tactile sensors, proprioception, etc.) can potentially indicate the absolute orientation of the head and body with respect to the vertical axis. Neural processes that allow us to perceive, interact and navigate within this world may thus be specialised for the internal representation of spatial relationships with respect to gravity.
The novel conditions of microgravity might therefore place an increased load on the cognitive capacity of the human brain because sensory signals must be processed and interpreted in a new context. By placing electrodes on the scalp of a human subject one can get a glimpse at the electrical activity underlying perceptual processes in the brain. Through the analysis of the variations in electrical potential between different locations on the scalp, one can make inferences about various neural processes such as the sensitivity to sensory information, the attention state of the system and the decision making process.
This project studies how the brain functions with respect to gravity through the use of electroencephalography (ECG) or EEG. In this experiment the role of gravity in the perception of self-motion is evaluated. In a series of psychophysical tests, a comparison is made on how human subjects interpret visual-flow information both on the ground and in the weightless conditions of orbital flight. Also, evoked potentials through surface electrodes applied to the scalp are measured in order to determine the spatial and temporal components of information processing in the brain in the absence of gravity. Through these experiments observations were made on how the CNS (Central Nervous System) adapts from its habitual environment in which gravity plays an ever-present and

dominant role, to a novel environment in which the movements of our bodies no longer adhere to the constraints imposed by gravity.

The hypothesis is that gravity should influence the perception of pitch but not yaw turns. Performing perception tasks in microgravity should evoke different cognitive responses and should activate different cortical circuits, depending on whether the information to be interpreted by the subject involved turns around a pitch or yaw axis.

Subjects performed a set of 2 psychophysical tasks with simultaneous recording of EEG activity. For each subject, the performance of these tasks was compared to a set of pre-flight, in-flight and post-flight procedures to test for an effect of weightlessness on the visual perception of orientation and movement and on the ability to navigate in three dimensions. Backup crewmembers were asked to perform all pre-flight training and baseline data collection (BDC) tests and were asked to work in parallel with the orbital crew-members during and after the flight to provide a matched control group for comparison.
Subjects take up the position and postural support depending on the gravitational conditions (ground or in-flight) and on the instructions for a particular protocol:

1. *Ground Seated*: The subject sits upright in a chair, with the elbows resting on adjustable-height elbow supports of the ground support stand. The ground support stand is adjusted to position the mask/tunnel/laptop at the level of the eyes for viewing. The height of the elbow pads is adjusted to allow the subject to comfortably grasp the grips on the laptop support.
2. *In-flight Restrained*: The subject sits in front of the laptop, which is attached to a mechanical support. Waist and foot straps are used to hold the subject securely in a seated posture.
3. *In-flight Free floating*: The subject adopts a free-floating posture and has no rigid contact with the Station structure during the performance of the experiment in this mode. A second cosmonaut assists the subject to stabilise his/her posture at the beginning of this phase of the experiment.

In all cases, the subject places his/her face into the facemask and attaches an elastic band behind the head to hold the head in place. By manipulating the buttons and trackball, the subject starts the experiment program on the laptop, identifying him/herself to the program and performs a set of experimental trials consisting of the following:

- Virtual Turns – The subject is situated in a visually-presented 3-D virtual tunnel. On the press of a button, the subject will virtually either move through a tunnel at constant speed, passing through a single bend between two linear segments or undergo a rotation in place (no apparent translation). At the end of the trial, the subject indicates the extent of the turn (i.e. how many degrees) in one of two ways:
    1. The subject observes a bird's eye view of a planar workspace with two cylindrical tunnels connected by a variable angle. By manipulating the trackball, the subject adjusts the magnitude of the turn to reconstruct a planar representation of the virtual tunnel just experienced.
    2. The subject sees a pictogram indicating his/her starting orientation in the plane. By manipulating the trackball, the subject changes the orientation of the pictogram to indicate the amount of rotation that is perceived.
- EEG Recordings – EEG signals from 14 locations on the scalp are recorded during the above trials. The subject performs a total of 48 trials for either stimulus type, for a total of 96 trials per session. Trials are broken into blocks of 12 trials each, with pauses imposed between blocks. At a nominal rate of 4-5 trials per minute (including pauses), complete execution of this protocol (turning in-place or passage through the tunnels) is performed within 20-25 minutes. EEG is also recorded under four control conditions:
    1. The subject relaxes and does nothing, first with his/her eyes closed, then while looking at a neutral screen.
    2. An alternating checkerboard is presented to the subject on the screen, with the colours switching between black and white every 3 seconds.
    3. The subject follows the movement of a luminous spot as it makes a sinusoidal movement across the screen.
    4. Subjects blink their eyes in synchrony with an audible metronome. Control recordings last no more than 5 minutes.

## 2.3.1.2.2.2 Results

After subjects emerged from the end of the tunnel, they were asked to report the perceived turn angle by adjusting a visual indicator with a trackball. Figure 2-4 shows the difference between left and right turns (left–right) and between upward and downward turns (downward–upward) as a measure of this asymmetry. On Earth, yaw turns led to equal, symmetrical errors in the estimation of the perceived angle change, but the estimation of pitch turns was greater for forward (nose-down) versus backward (nose-up) turns. The interest of this experiment lies in this asymmetry. One can observe a clear reduction in the asymmetry of vertical turns in microgravity. In summary, it appears that the microgravity conditions of orbit reduce the asymmetry of vertical turn estimation, but only in the free-floating condition. The NeuroCOG experiment revealed interesting EEG correlations of these effects observed via psychophysical measurements. Alpha rhythms were analysed in response to a standard alternating checkerboard pattern (visual evoked potential, VEP) and in response to the initial presentation of the virtual 3D tunnel (event related potentials, ERP). It was demonstrated for the first time that the VEP responses and phase locking of alpha rhythms are preserved in the microgravity. In contrast, the ERP evoked by the presentation of the tunnel was considerably perturbed in the ISS. Unspecific factors such as a noisy environment in the ISS, anxiety, stress, muscular artefacts and basic physiological factors (brain and body blood circulation differences) seem to be unlikely culprits because the classical VEP in response to the reversing checkerboard pattern is maintained. This latter phenomenon occurs through the conservation of the phase locking mechanism of the VEP in the alpha band frequency, as seen on the ground. These results (see Figure 2-5) can be interpreted in light of the specific informational content of the different visual stimuli (checkerboard vs. tunnel) that the associated task demands. The major difference between the classical checkerboard testing and the virtual tunnel task is that in the former situation the subject was mainly passive (only looking at the computer screen) while in the latter situation the subject was involved in a 3D spatial perception task. This task directly contained directional information related to the gravitational frame of reference, which may play the role of a top-down control. In the presence of gravity, this neural context implicitly contributed to the evoked response. Thus a change of perceptual context or a basic interference in the dynamics of the neural networks could be expected, resulting in the different patterns in EEG measurements between the 2 tasks.

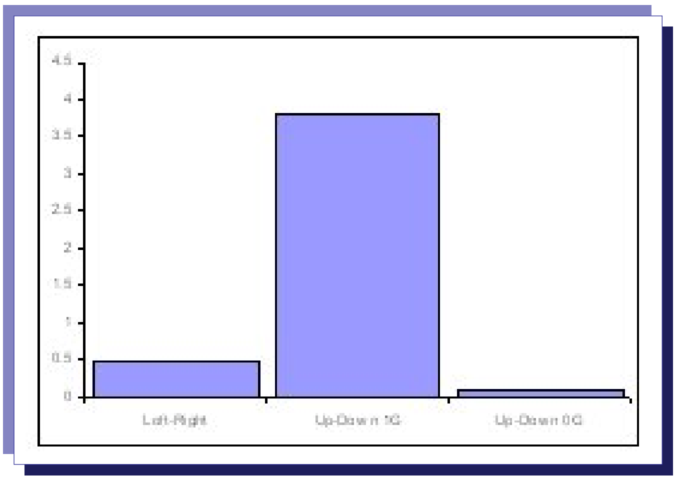


**Figure 2-4: Asymmetry in the estimation of turn angles for virtual rotations around horizontal and vertical axes**

In the NeuroCOG experiment before the navigation task, the arrest reaction of the alpha rhythm was used (Berger, 1929) because it is a highly stable reaction, which occurs over a large part of the brain and provides two distinct physiological states induced by opening or closing the eyes. The head figurines of Figure 2-6 illustrate the difference in the power gain of 10 Hz activity between the recordings performed in the ISS and on Earth (with data recorded before and after flight pooled together) for cosmonauts (A) and for control subjects (B). Statistical analysis revealed that the gain values recorded in parieto-occipital (O1, O2, Pz, P3, P4) and central (C3, C4, Cz) loci were significantly increased in weightlessness. The three latter electrodes are situated over the sensorimotor cortex, which is the site of the mu rhythm. In contrast, the 10 Hz gain value of the frontal recordings (Fz, F3, F4, F7, F8) remained unchanged in the absence of gravity. The same analysis performed in the control subjects showed a great stability of the gain value throughout the same period of time in all recorded channels. The findings demonstrate that the power of the spontaneous EEG alpha rhythm recorded in the parieto-occipital regions and in the sensorimotor areas (mu rhythm) are increased and that the spectral perturbations of these rhythmic activities produced by eye-opening/closure state transition, increase in the absence of gravity. This demonstrates the influence of the absence of gravity on alpha oscillation, which is likely to be linked to the gating of sensory input. Alpha and mu rhythms may also participate in memory and cognitive processing. In this context, the finding of enhanced alpha and mu rhythm in weightlessness supports their physiological implication in the gain-field mechanism allowing the adaptation of the neural representation of space.

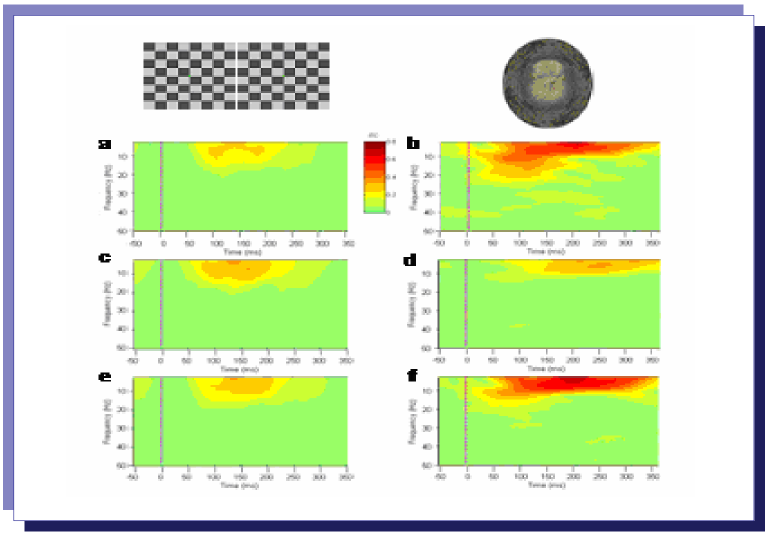


**Figure 2-5: Inter-trials coherence of theta and alpha rhythms in response to a standard checkerboard pattern (a, c, e) and to the presentation of a curved tunnel (b, d ,f) on the ground before flight (a, b) in flight (c,d) and on the ground after flight (e, f)**

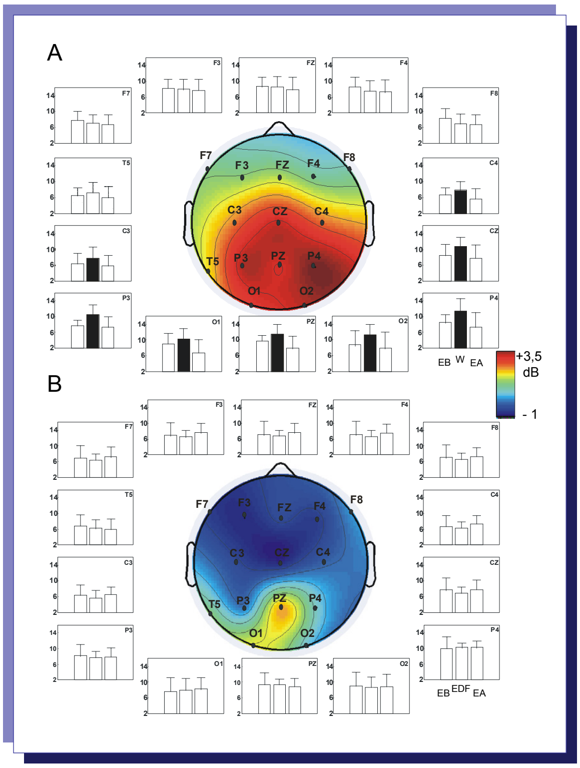


**Figure 2-6: Difference in the power gain of 10 Hz activity between the recordings performed in the ISS and on Earth**

Motion-onset related visual evoked potentials (M-VEPs) were recorded at a latency of ~200 ms (N200) when the first in depth motion appeared during the virtual navigation. The N200 was supported by a very significant phase locking in the theta range oscillation. It was shown for the first time that this N200 and the related phase locking in theta oscillation are suppressed during the first days in weightlessness and that this effect is reinforced in free-floating condition. Interestingly, this M-VEP reappeared with the time passed in weightlessness and will be carefully followed in the long-term ISS missions.

## 2.3.1.2.2.3 Conclusions and Recommendations

Three main conclusions can be made from the results obtained:

1. Weightlessness specifically affects event related potential related to the presentation of a virtual 3-D navigation tunnel.
2. Weightlessness increases alpha rhythm gain during transition between eyes-closed and eyes-open states.
3. Moving in virtual navigation induced midfrontal N200 event related potentials supported by a transient theta ringing altered in weightlessness.

In any given EEG recording session a complete loss of signal (flat line) was sometimes observed on one or more of the 14 EEG channels. This loss of signal is often accompanied by a zero impedance level during the impedance check prior to the start of recording. This may be due to changing characteristics of the conductive cream with time, differences in environmental conditions between ground and flight (humidity, temperature, etc.) or due to the application of a greater quantity of cream during in-flight sessions than on the ground. Post-flight debriefing with the cosmonaut suggested that the latter may have been the case.
Future experiments using EEG should provide real-time or quasi-real-time monitoring of EEG signals on the ground. Downlink should be timely enough to allow for the correction of problems during the course of a data collection session, or at least soon enough to allow for the repetition of a session in the case of data loss.
The assurance of adequate training time should be a critical factor in the planning of future experiments.

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# 3 ACRONYMS

| | |
|---|---|
| ARGES | Atomic densities measured Radially in metal halide lamps under microGravity conditions with Emission and absorption Spectroscopy |
| ATCC | American Type Culture Collection |
| BDC | Baseline data collection |
| BPV | Blood pressure variability |
| BRS | Baroflex sensitivity |
| CARDIOCOG | Cardiovascular adaptation to weightlessness |
| CHROMOSOME | Chromosomal aberrations in blood lymphocytes of astronauts |
| CNS | Central nervous system |
| CSA | Canadian Space Agency |
| DGGE | Density Gradient Gel Electrophoresis |
| DNA | Deoxyribonucleic acid |
| E | Epinephrine |
| ECG | Electrocardiogram |
| EEA | Erasmus Experiment Archive |
| EEG | Electroencephalogram |
| EGF | Epidermal growth factor |
| ERP | Event related potential |
| ESA | European Space Agency |
| ESF | European Science Foundation |
| ETD | Eye tracking device |
| EVA | Extra Vehicular Activity |
| EVP | Event related potential |
| FISH | Fluorescence in-situ hybridisation |
| FO | Flight operations; Functional objective |
| HDBR | Head down bed rest |
| HDT | Head down tilt |
| HF | High-frequency |
| HID | High-intensity discharge |
| HMI | Human machine interface |
| HP | Heat pipes |
| HR | Heart rate |
| HRV | Heart rate variability |
| HUT | Head-up tilt |
| IBI | Interbeat interval |
| IFOC | ISS Flight Order Contract |
| ISS | International Space Station |
| IU | International units |
| JAXA | Japan Aerospace Exploration Agency |
| LBP | Low back pain |
| LED | Light-emitting diode |
| LET | Linear energy transfer |
| LF | Low frequency |
| LP | Listing's plane |
| MASER | MAterial Science Experiment Rocket |
| MESSAGE | Microbial experiment on Space Station about gene expression |
| MLI | Multilayer insulation |
| MSG | Microgravity Science Glovebox |
| M-VEP | Motion-onset related visual evoked potential |
| NASA | National Aeronautics and Space Administration |
| NE | Norepinephrine |
| NeuroCOG | Directed attention brain potentials in virtual 3-D space in weightlessness |
| NO | Nitric oxide |
| NRS | Numeric rating scale |

| | |
|---|---|
| NSR | Nose, skin and rectum |
| NTD | Nuclear track detector |
| OI | Orthostatic intolerance |
| OLP | Ordered liquid phases |
| PBU | Plunger box unit |
| PCB | Printed circuit board |
| PromISS | Counterdiffusion protein crystallisation in microgravity and its observation with the Protein Microscope for the ISS |
| Q-PCR | Quantitative polymerase chain reaction |
| ROI | Region of interest |
| Roscosmos | Russian Space Agency |
| SAS | Space adaptation syndrome |
| SBP | Systolic blood pressure |
| SE | Standard error |
| SIC | Sickness induced by centrifugation |
| SSD | Scintillator/silicon detectors |
| SV | Stroke volume |
| SYMPATHO | Sympathoadrenal activity in humans during spaceflight |
| TEXUS | Technologische EXperimente Unter Schwerelosigkeit |
| TIM | Thermotoga marirtima triose phosphate isomerase |
| TLD | Thermoluminescence dosimeter |
| US | United States |
| VEP | Visual evoked potential |
| VOR | Vestibulo-oculomotor response |
| ZARM | Zentrum für Angewandte Raumfahrt Microgravitation |