National Aeronautics and Space Administration

A Researcher's Guide to:

INTERNATIONAL SPACE STATION

Fundamental Physics

This International Space Station (ISS) Researcher's Guide is published by
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Authors:

Inseob Hahn	Jet Propulsion Laboratory, California Institute of Technology
Nan Yu	Jet Propulsion Laboratory, California Institute of Technology
Ulf Israelsson	Jet Propulsion Laboratory, California Institute of Technology
John Goree	University of Iowa

Executive Editor: Amelia Rai
Technical Editor: Neesha Hosein
Designer: Cory Duke

Cover and back cover:

a. Fundamental Physics Research on the ISS spans research from understanding the quantum nature at very small scales to understanding gravitation and its role in shaping the destiny of the universe, at extremely large scales. The balance on the front cover depicts an artists rendering of the key role fundamental physics on the ISS has to measure these extremes of nature. (Credit: JPL graphics department)

b. Computer Simulation of 3D structures in a liquid-like dusty plasma. The color indicates the height above the bottom plane. For clarity, the diameter of dust particle microspheres is exaggerated. (Image credit: B. Liu and J. Goree, Phys. Rev. E 89, 043107 (2014)

c. Artist rendering of Cold Atom Laboratory Magneto Optical Trap with atom chip shown at the stop. (Image credit: CAL Project Scientist Rob Thompson, JPL)

The Lab is Open

Soaring 250 miles above Earth, the International Space Station (ISS) is a modern wonder of the world, combining the efforts of 15 countries and thousands of scientists, engineers and technicians. The ISS is a magnificent platform for all kinds of research to improve life on Earth, enable future space exploration and understand the universe. This researcher's guide mini-book is intended to help potential researchers plan experiments that would be exposed to the space environment, while externally attached to or deployed from the ISS. It covers all the pertinent aspects of the space environment, how to best translate ground research to flight results and lessons learned from previous experiments. It also details what power and data are available on the ISS in various external locations.

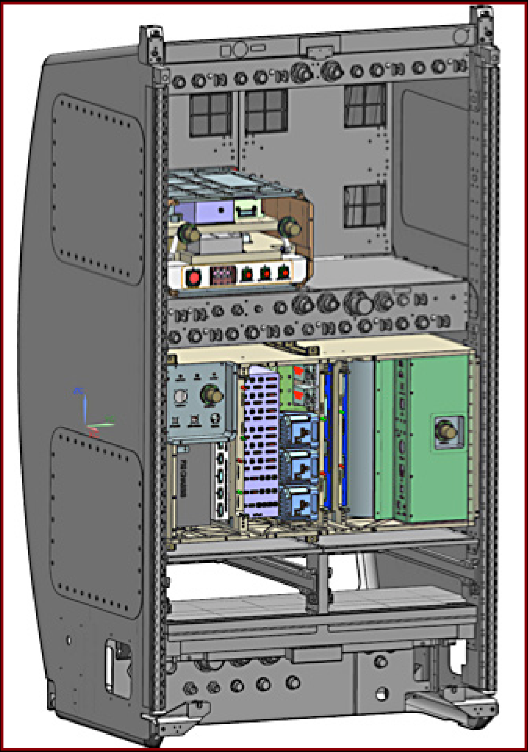
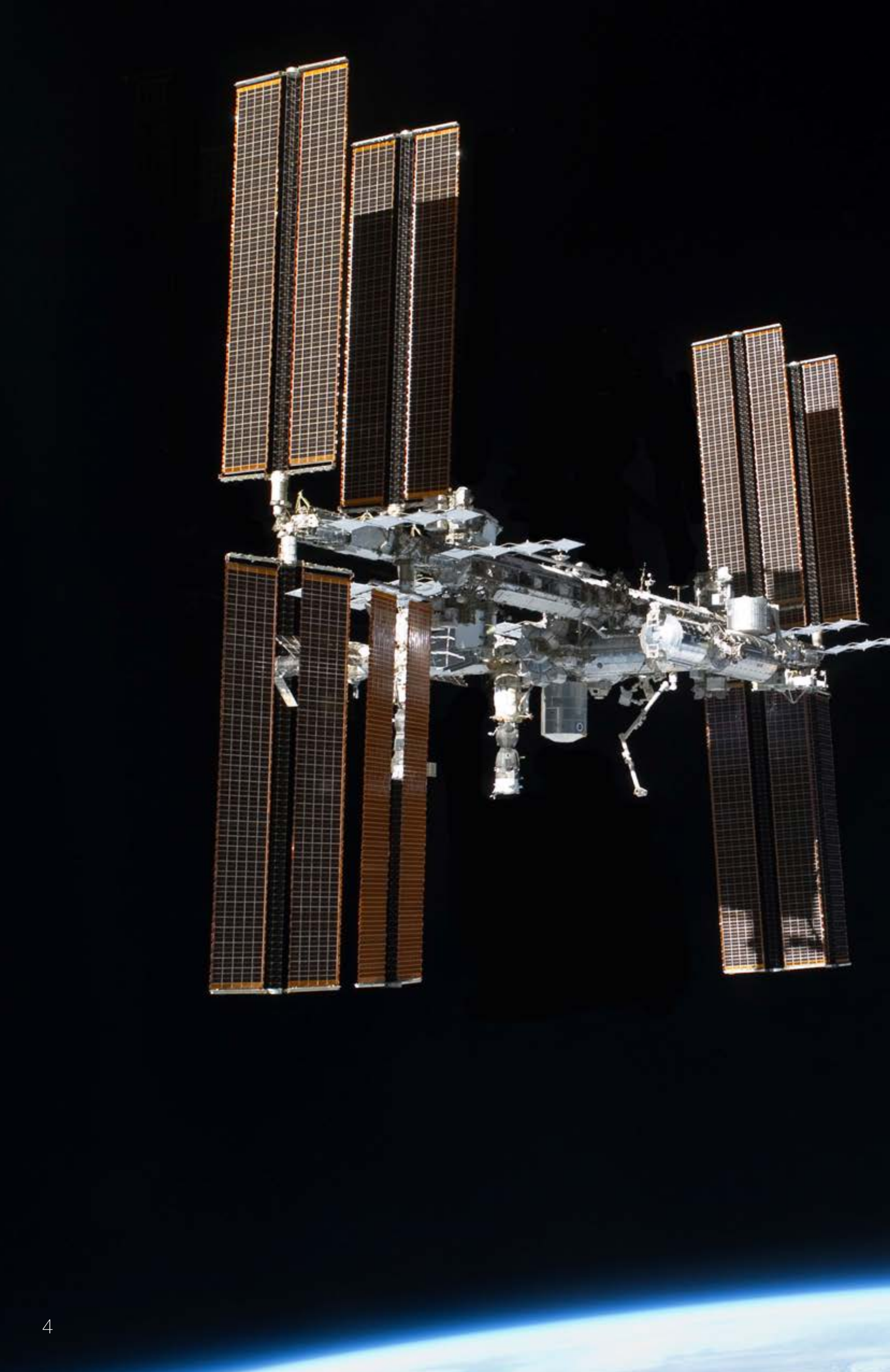


Figure 1. The planned Cold Atom Laboratory payload in an ISS experimental rack. (Source: NASA's Jet Propulsion Laboratory CAL project)



Unique Features of the ISS Research Environment

1. **Microgravity**, or weightlessness, alters many observable phenomena within the physical and life sciences. Systems and processes affected by microgravity include surface wetting and interfacial tension, multiphase flow and heat transfer, multiphase system dynamics, solidification, and fire phenomena and combustion. Microgravity induces a vast array of changes in organisms ranging from bacteria to humans, including global alterations in gene expression and 3-D aggregation of cells into tissue-like architecture.
2. **Extreme conditions** in the ISS space environment include exposure to extreme heat and cold cycling, ultra-vacuum, atomic oxygen, and high-energy radiation. Testing and qualification of materials exposed to these extreme conditions have provided data to enable the manufacturing of long-life reliable components used on Earth as well as in the world's most sophisticated satellite and spacecraft components.
3. **Low-Earth orbit** at 51degrees inclination and at a 90-minute orbit affords ISS a unique vantage point with an altitude of approximately 240 miles (400 kilometers) and an orbital path over 90 percent of the Earth's population. This can provide improved spatial resolution and variable lighting conditions compared to the sun-synchronous orbits of typical Earth remote-sensing satellites.

Table of Contents

Why use the ISS as a Laboratory

Studies in fundamental physics address space, time, energy, and the building blocks of matter. The primary theories of modern physics are based upon Einstein's theory of relativity and the standard model of particle physics. However, as scientists, we know that the picture painted by these theories remains incomplete. Einstein's theory of gravitation remains unproved to be consistent with the theories that define other forces of nature in all length scales. Furthermore, recent astronomical observation and cosmological models strongly suggest that dark matter and dark energy, which are entities not directly observed and not at all understood, dominate these interactions at the largest scales. All these unexplained observations and inconsistencies point to the potential for discovery of new theories. The ISS provides a modern and well-equipped orbiting laboratory for long-term microgravity environment research. Routine and continued access to this environment allows for fundamental physics research to be performed from a completely different vantage point.

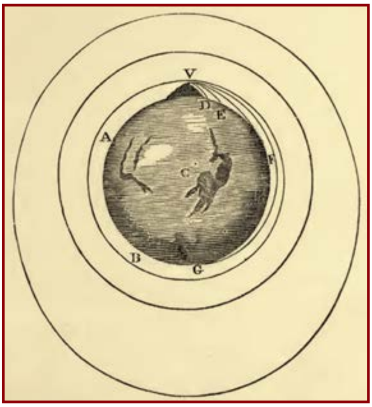


Figure 2.1 Newton's original thought experiment on the orbiting object around the Earth. (Source: Philosophie Naturalis Principia Mathematica, 1686)

The International Space Station provides a unique space laboratory for a set of fundamental physics experiments with regimes and precision not achievable on the ground. Some of the advantages of the space environment for experiments include:

- Long-duration exposure to the orbital free-fall environment.
- Ease of measurement of changes of gravitational potential and relative motions.
- Study of very small accelerations on celestial bodies.
- Reduced atmospheric interference on the propagation of optical and radio signals.
- Ability to track and fit to theory very long time segments of body orbital motion.

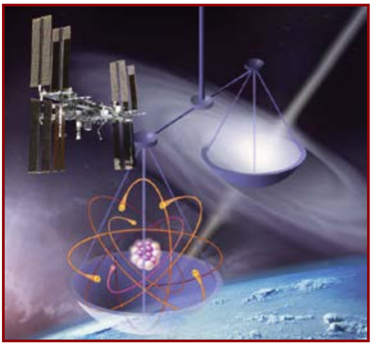


Figure 2.2 Artist concept of the International Space Station as a laboratory for fundamental physics. (Source: NASA's Jet Propulsion Laboratory)

Past Research Program

In 2011, a decadal review commissioned by Congress was completed titled "*Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era.*" In the "Fundamental Physical Sciences in Space" section of the report, the highest priority recommendations are made in four research thrust areas:

- Research on Complex Fluids and Soft Matter.
- Research That Tests and Expands Understanding of the Fundamental Forces and Symmetries of Nature.
- Research Related to the Physics and Applications of Quantum Gases.
- Investigations of Matter in the Vicinity of Critical Points.

A vigorous NASA fundamental physics research program developed over, approximately, the last 20 years consisting of more than 100 ground-based investigations from institutions across the U.S. and 17 flight or flight definition experiments in the areas of: low temperature and condensed matter physics; laser cooling and atomic physics; and relativistic and gravitational physics. This section provides a summary of accomplishments to date from fundamental physics research performed on a non-crewed science satellite, the space shuttle and the ISS. In addition, this section identifies some of the initial design development activities performed during the same period of time. Initial experiments done on non-crewed satellites and the space shuttle demonstrated the benefits afforded by the microgravity space environment for performing research in these areas and led to the development of plans for advanced research on the ISS. In 2004, NASA elected to concentrate ISS research toward activities directly related to human exploration. U.S. investigations in the fundamental physics program were conducted on a lower priority basis. Recently, the U.S. fundamental physics program was expanded through an international agreement allowing U.S. researchers access to ISS European Space Agency (ESA) facilities to accomplish U.S. research investigations in the complex fluids, soft condensed matter physics, and atomic physics thrust areas.

Complex Fluids and Soft Condensed Matter

Research of complex fluids and soft condensed matter field is very rich and diverse. It includes colloids, emulsions, foams, liquid crystals, dusty plasmas, and granular material. Refined experiments in these topics can be used as models for a wide variety of the more complex physical phenomena witnessed in everyday life. Over the years, there have been a number of related investigations completed on non-crewed satellites, the space shuttle and the ISS. There have also been a few ground-based investigations completed in this sub-discipline.

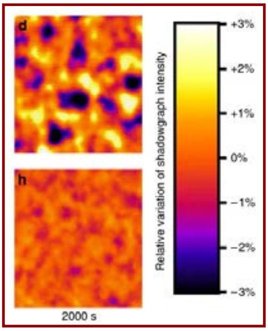


Figure 3.1.1 Long timescale fluctuations in microgravity and on Earth. (Source: A. Vailati et al, J. Phys: 327, 012023, 2011)

Gradient Driven Fluctuations Experiment (GRADFLEX)

GRADFLEX was completed aboard a Russian Foton-M3 non-crewed science satellite in 2008. This ESA-led program was a collaborative effort of Italian and U.S. scientists. The U.S. principal investigator was University of California at Santa Barbara professor David Cannell. The objectives of the experiment were to study gradient-driven density and concentration fluctuations that are strongly enhanced in fluids by the absence of gravity and to achieve a quantitative understanding of gradient-driven fluctuations on Earth as well as in the Foton-M3 microgravity environment. The experiment used two samples, one a single-component fluid of a 3-mm-thick layer of carbon disulphide (single-component), and the other a 1-mm-thick layer of 1.8-wt.-percent polystyrene (Molecular Weight 9,000) in toluene (mixture). These samples are representative of any single-component fluid or mixture. The samples were driven out of equilibrium by applying temperature differences across the layers, up to 30 Kelvin (K) for the single-component fluid and 20 K for the mixture. The experiment verified to a high level of accuracy the predicted gradient-driven fluctuations in fluid samples enhanced by the absence of gravity (Takacs, 2011; Vailati, 2011).

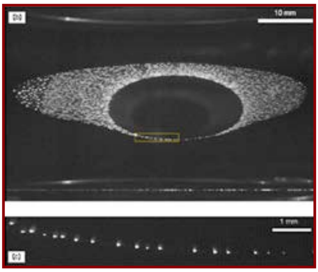


Figure 3.1.2 A Dusty Plasma in microgravity. (Source: J. Goree).

Plasma Kristall (PK-3+)

The “self-structuring in dusty plasma” project was carried out with the Plasma Kristall (PK-3+) instrument on the ISS. This investigation was a collaborative effort of Russian, German and U.S. scientists. Like its predecessor, PKE-Nefedov, PK-3+ was a German-Russian-developed instrument. University of Iowa professor John Goree, the U.S. principal investigator, participated in the initial design of the instrument and the data analysis. For this microgravity experiment, 6.8 micron diameter polymer microspheres were injected into a symmetrically driven, radio frequency plasma discharge. The plasma was ignited from Neon inert gas at 120 mTorr and a 13 MHz Radio Frequency (rf) voltage of 44 Volts (V). The resonance frequency of a single layer of particles on the edge of a central void was measured by video microscopy allowing the determination of plasma parameters. The measured parameters included the particle charge and electron temperature. Ground-based measurement of the parameters is not possible. This experiment required the microgravity conditions available aboard the ISS. The absence of Earth's gravity prevented severe sedimentation, which would have prohibited the formation of the 3-D particle suspension with its central void (Liu, 2009).

Fundamental Forces and Symmetries

Experiments related to fundamental forces and symmetries are performed to verify with high precision the underlying assumptions and the consequences of Einstein's special and general theories of relativity as well as the standard model of physics. Gravitational interaction is the weakest of the four known fundamental forces of nature. Yet by virtue of its universal attraction, it is the dominant force at long ranges and plays a central role in forming the structure and governing the motion of planets, stars, galaxies, and exotic objects such as neutron stars and black holes.

Over the years, NASA has sponsored about 32 researchers in this sub-discipline to perform ground-based research and develop plans for performing measurements on the ISS or using non-crewed science satellites. The research conducted to date has focused on: Einstein's Equivalence Principle (EEP), Eddington's gamma-parameter (the bending of light by a massive body), redshift tests of gravity, Lorentz symmetry, and the inverse square law (Turyshev, 2007).

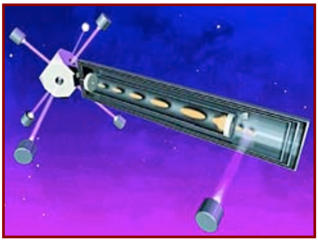


Figure 3.2.1. Artist concept of Primary Atomic Reference Clock in Space. (Source: NASA's Jet Propulsion Laboratory)

Primary Atomic Reference Clock in Space (PARCS) Preliminary Design

Measurement tests of gravitational redshift, Lorentz symmetry and of EEP employ the use of a variety of high-precision clocks as a common technique. The Primary Atomic Reference Clock in Space (PARCS) was an ISS clock experiment that had the objectives of improving the current measurement precision capability of gravitational redshift, testing of local position invariance, and testing of the anisotropy of the speed of light. It also had the design goal to demonstrate global clock synchronization and comparison capability, leading to a better realization of the definition of the second. PARCS had completed its preliminary design prior to program termination. ESA has elected to develop the Atomic Clock Ensemble in Space (ACES), which is similar to PARCS and scheduled for ISS operation in the 2015.

Rubidium Atomic Clock Experiments (RACE) Concept Definition

RACE represents an advanced clock experiment to complement and extend the goals of science and technology established by its ISS predecessors. There are three primary goals envisioned for the RACE investigation:

- Advanced atomic clock science and techniques to enable measurements with accuracies of 1 part in 1017
- Significantly improve the classic clock test of general relativity
- Distribute the highest achievable time and frequency stability from the ISS

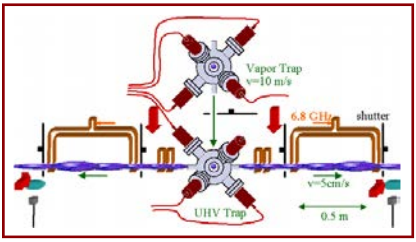


Figure 3.2.2 Schematic for juggling microgravity Rubidium Atomic Clock Experiments. (Source: NASA's Jet Propulsion Laboratory)

The RACE investigations are designed to extend the understanding of physical effects on atomic clocks to a fractional accuracy of 10^{17} and vastly improve the classic clock test of general relativity. A laser-cooled atomic clock based on the ground state hyperfine splitting in 87Rb will be flown aboard the ISS and compared to a laser-cooled rubidium clock on the ground, as well as other clocks worldwide. The long atom interrogation time allowed by the microgravity environment makes it possible to achieve greater accuracy for laser-cooled clocks with high, short-term stability as compared to their earthbound counterparts. The use of 87Rb reduces the collision shift by a factor of 30 over a similar cesium instrument, allowing greater stability and accuracy.

Quantum Interferometer Test of Equivalence (QUITE)

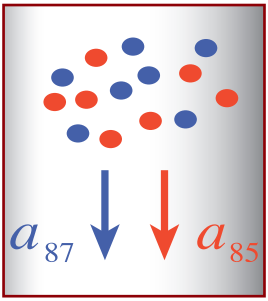


Figure 3.2.3 Freely falling clouds of atoms of different atomic number. (Source: NASA's Jet Propulsion Laboratory)

The EEP is at the very foundation of modern physics and underpins Einstein's general theory of relativity. Many theories beyond general relativity and the standard model predict a violation of EEP at various levels. Different techniques were explored for improving the test of EEP in space including the use of superconducting detection of the differential motion of freely-flying test masses in low-Earth orbit; free-fall test masses in a high-altitude balloon; and use of cold atoms and atom interferometry. The QUITE experiment definition was initiated to employ the use of cold atoms and atom interferometry. The concept design developed would measure the differential acceleration of two different atomic species, laser cooled first to close to zero temperature in the atom interferometer configuration. In this experiment, the quantum wave nature of atomic particles is utilized; therefore, QUITE would also probe for connections between quantum-mechanical properties and gravity.

Figure 3.2.4. The Alpha Magnetic Spectrometer Research Facility. (Source: NASA)

Alpha Magnetic Spectrometer (AMS)

The Alpha Magnetic Spectrometer is a state-of-the-art particle physics detector. The purpose of the AMS is to study the universe and its origin by searching for antimatter and dark matter while performing precision measurements of cosmic rays composition and flux. The AMS was built, tested and is being operated by an international collaboration of 56 institutions from 16 countries and is sponsored by the United States Department of Energy. The experiment is located externally on the ISS and attached to the upper Payload Attached Point (S3) on the main truss. The core of the spectrometer is a large magnet and precision spectrometer to measure the sign of the charge of each particle traversing the instrument. The spectrometer is designed to collect data continuously producing a data stream of 10 gigabits per second, which, after processing, is reduced to approximately 13 megabits per second average of downlink bandwidth. As of July 2013, the AMS has measured over 35 billion particles.

Other Fundamental Symmetry Experiments Studied for Flight on the ISS

NASA also sponsored the definition of five other flight experiments before the reprioritization of ISS program objectives in 2004. They are listed below.

- Satellite Test of the Equivalence Principle, F. Everitt, Stanford University.
- Superconducting Microwave Oscillator Experiment, J. Lipa, Stanford University.
- Inverse Square Law Experiment in Space, H. Paik, University of Maryland.
- Test of Equivalence Principle in an Einstein Elevator, I. Shapiro, Harvard University.

Quantum Gases

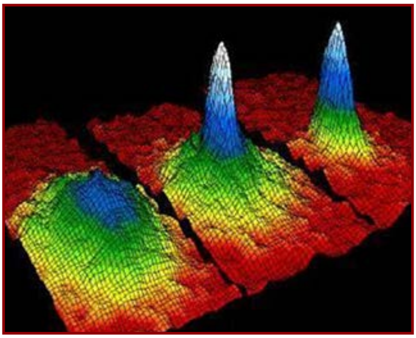


Figure 3.2.5. Emergence of a Bose-Einstein condensate. (Source: Eric Cornell, Joint Institute for Laboratory Astrophysics, Univ. of Colorado)

One of the exceptional achievements in science and technology in the last two decades is in the research area of cold atoms. The invention and development of laser cooling of neutral atoms to extremely low temperatures was recognized with a physics Nobel Prize to two U.S. scientists, S. Chu and W. D. Phillips, and a French researcher, Claude Cohen-Tannoudji, in 1997. Further cooling of the atoms resulted in generation of a Bose-Einstein condensate (BEC), a new dilute gas quantum state that was predicted by Einstein but only arguably observed in confined liquid helium before. The generation of dilute gas quantum degenerate states for both bosons and fermions opened up an entirely new frontier in quantum and material science research. Three U.S. scientists, W. Ketterle, C. E. Wieman, and E. A. Cornell, were awarded a physics Nobel Prize in 2001 for their contribution to the first demonstration of BEC generation. Three of these Nobel laureates were NASA fundamental physics program sponsored investigators.

Over the years, NASA has sponsored about 23 researchers in this sub-discipline to perform ground-based research and develop plans for performing measurements on the ISS.

Condensate Laboratory Aboard the ISS (CLASS) Concept Design

At the temperature of BEC, gravity can play a significant role in the cooling, trapping and dynamics of the ultra-cold atoms. Recognizing the potential benefits that microgravity research in this science area aboard the ISS might yield, the concept design of the CLASS was developed. CLASS was intended to provide researchers the capability to explore interactions in Bose Einstein Condensates of atoms at lower temperatures than achievable on the ground. The principal investigator for this experiment was Nobel laureate W. Phillips from the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland.

Matter Near Critical Phase Transitions

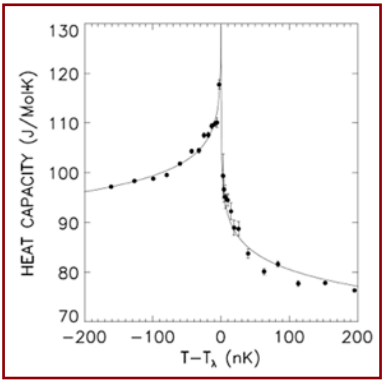


Figure 3.3.1. Heat capacity of superfluid helium in microgravity conditions. (Source: J. Nissen)

The condensed phase of simple gases provides a unique test bed for the predictions of fundamental theories. For a certain combination of temperature and pressure, determined by the molecular properties of the gas, the differences between the liquid and the vapor phases disappear. This state of the system is the critical point, in the neighborhood of which the fluid system exhibits the unusual properties of universality and scaling. Universality implies that the same parameters (critical exponents) characterize the system under many different conditions; scaling implies that the equations describing the system's behavior do not change their form when the length scale is altered. Critical points are found in many different materials including fluids, solids, alloys, fluid mixtures and magnets.

The physics of matter near critical points have been explored in detail in ground-based experiments. Fundamental theories have been developed to explain the unusual behavior of universality and scaling for matter near critical points. The special interest in this phenomenon is because the theoretical explanation, renormalization group (RG) theory, has implications for many diverse fundamental and applied research areas including weather modeling, metallurgy, oil field recovery, elementary particle physics, and cosmology. The region very close to the critical transition, where correction terms are small compared to critical anomalies, provides the best tests of RG theory. The ISS microgravity environment provides advantages for the study of matter near critical points since the density non-uniformity caused by Earth's gravity broadens the transition and limits how closely the critical point can be approached (Barmatz, 2007).

In total, about 80 investigators were supported in a period of over a decade for various studies in the critical phenomena area through 2004. Four experiments in this research area were successfully completed aboard the space shuttle, and a major low-temperature facility was developed to the near completeness. The four shuttle-based experiments are discussed in the following paragraphs.

Lambda Point Experiment (LPE)

LPE performed a very high-resolution measurement of the heat capacity of a golf ball-sized sample of liquid helium to within 2 nanokelvin (nK) of the critical point under microgravity conditions on the space shuttle in 1996. The principal investigator was Stanford University Professor John Lipa. The LPE verified that the critical point remains sharp down to the 1 nK level, demonstrated unambiguously that gravitational smearing could be removed by conducting the experiment in a microgravity environment and that very complex measurements can be performed in a space environment. The optimum value for the critical exponent characterizing the divergence of the heat capacity below the transition was found to be -0.01285, giving improved support for the RG theory of phase transitions. Additional information was also obtained related to the temperature dependence of the thermal conductivity just above the transition (Lipa, 1996).

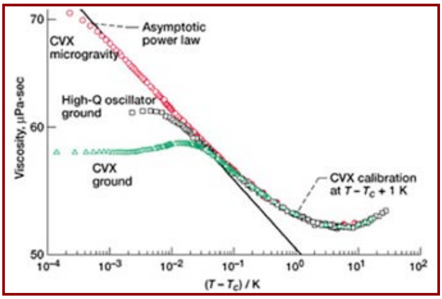


Figure 3.3.2 The chart shows ground-based and microgravity measurements of the viscosity of xenon near the critical point. In microgravity, the increase of viscosity is measured 100 times closer to the critical temperature (Tc) and much more accurately than on Earth. The asymptotic power law characterizes the universal behavior of viscosity in all pure fluids near the critical point. (Source: NASA's Glenn Research Center)

Critical Fluid Light-Scattering Equipment (ZENO)

The ZENO experiment flew as a payload on the space shuttle in 1994 and in 1996. The ZENO experiment provided new data, impossible to achieve through ground-based research, about the decay rates of critical-density fluctuations in a simple fluid (xenon) very near its liquid-vapor critical point.

The experiment employed laser light scattering and photon correlation spectroscopy to achieve its research objectives (Boukari, 1995). Related experiments are severely limited on Earth because of the presence of gravity. Gravity-related accelerations will cause large density gradients in the experiment sample, which is highly compressible near the critical point. ZENO's principal investigator was University of Maryland Professor Robert Gammon.

Critical Viscosity Experiment (CVX)

The Critical Viscosity Experiment (CVX) successfully flew on the space shuttle in 1997, 1999 and 2003. For the initial flight the instrument contained a novel viscometer built around a small nickel screen. An oscillating electric field made the screen oscillate between pairs of electrodes. Viscosity, which dampens the oscillations, can be calculated by measuring the screen motion and the force applied to the screen. The screen oscillations were set to be slow and small to ensure the fluid's delicate state near the critical point would not be disrupted. The data demonstrated that the viscosity increases as the critical point is approached and that it agrees with the theoretical prediction (Berg, 2009). CVX also measured low-frequency viscoelasticity in a pure fluid for the first time. Viscoelasticity is a partly elastic response to shear stress. It is common in polymers, foams, and other complex fluids, but has never been observed in a simple fluid such as xenon.

Because of the great success of CVX, the instrument was upgraded to allow measurements of the shear thinning of viscosity near the critical point of xenon for its second and third flights. CVX was the first experiment to measure shear thinning in a simple fluid (Berg, 2007). The quantitative understanding of shear thinning near the critical point achieved through CVX will lead to a better understanding of shear thinning in more complex fluids, such as polymers and emulsions, and may have broad applications in science and industry.

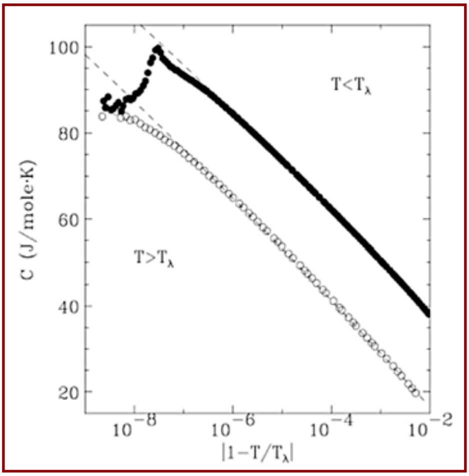


Figure 3.3.3. Confined Helium Experiment data show deviations from bulk values (dashed lines) as the critical point is approached. (Source: J. Nissen).

Confined Helium Experiment (CHeX)

The CHeX flew on the space shuttle in 1998. This experiment studied the confinement of a thin layer of liquid helium confined to a thin sheet. The principal investigator was Stanford University Professor John Lipa. CHeX studied the influence of boundaries on matter with particular focus on how finite size effects emerge as the sample size evaluated becomes comparable with the size over which the sample is correlated. By operating near the critical point of liquid helium in space, a macroscopic sample size of 57 microns could be used thereby reducing surface effects while magnifying the finite size effect. The results from CHeX were in good agreement with theoretical predictions and allowed an extension by several orders of magnitude in size compared to what had been accomplished through prior ground-based investigations (Lipa, 2000).

Low Temperature Microgravity Physics Facility (LTMPF) Plans and Hardware Development

Figure 3.3.4. LTMPF dewar system vacuum shell hardware.

Plans were developed for an ISS LTMPF to allow future related investigations following the successful shuttle experiments. The LTMPF would provide a 2 K environment for two separate instruments for a six-month duration as an ISS external payload mounted on the Japanese Experiment Module - Exposed Facility (JEM-EF). Many of the hardware elements were delivered and are in storage awaiting potential future use. A list of the planned investigations with this facility and their respective investigators is shown below.

- Critical Dynamics in Microgravity, R. Duncan, University of Missouri.
- Microgravity Scaling Theory Experiment, M. Barmatz, NASA's Jet Propulsion Laboratory (JPL).
- Boundary Effects on the Superfluid Transition, G. Ahlers, UCSB.
- Superfluid Universality Experiment, J. Lipa, Stanford University.
- Coexistence Boundary Experiment, Inseob Hahn, JPL.
- Enhanced Heat Capacity of Superfluid Helium in a Heat Flux, D. Goodstein, Caltech.
- Experiments Along Coexistence near Tricriticality, M. Larson, JPL.

Opportunities for Research on ISS

A series of ISS flight experiments have been initiated in the fundamental physics/physical sciences discipline. Recent investigations are a part of bartering arrangements with foreign space agencies to optimize use of research facilities and instruments on the ISS. Also as a part of the ISS 2014 initiative, NASA began development of the ISS experiment Cold Atom Laboratory (CAL) facility.

Complex Fluids and Soft Condensed Matter

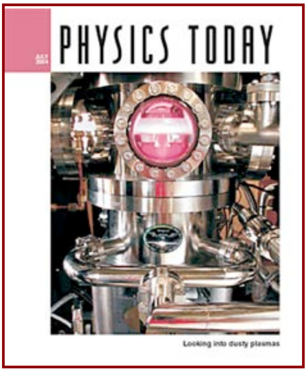


Figure 4.1. A 2004 Journal cover highlighting Dusty Plasma. (Source: Physics Today)

A number of Complex Fluids and Soft Condensed Matter related investigations utilizing the Fluid Integrated Rack (FIR) facility are ongoing. Many of these activities were described as part of the Complex Fluids discipline discussion earlier. A current focus is the research of "dusty plasmas". A dusty plasma occurs when micro-sized particles of solid matter are added to an ionized gas (plasma). Plasmas exhibit a rich variety of collective behavior because the electrons and ions are all electrically charged and apply forces upon one another resulting in collective interaction. As a result, plasmas exhibit processes like nonlinear waves, hydrodynamic flow instabilities, anomalous transport, and statistical fluctuations. All these phenomena become more pronounced when the micron-size particles of solid matter, called dust, are added to the mix. The dust particles accumulate a large, negative electric charge, about 10,000 electrons on a 5-micron sphere, by absorbing electrons from the surrounding plasma. Because they have large, negative charges, dust particles repel one another strongly, and they tend to arrange themselves spatially as do atoms in a crystal. By using video microscopy, experimenters can track the motion of individual particles and study phenomena such as phase transitions, viscoelasticity and the interaction of beams with matter.

Plasma Kristall (PK-4) Development

The PK-4 instrument is an ESA project that is scheduled to fly on the ISS in 2014. In contrast to previous rf instruments, PK-4 will use a dc-voltage to power a plasma discharge in a glass tube. Combined with laser manipulation and high-speed cameras, the instrument will allow the microscopic observation of motion in liquid-like structures. Experiments planned in PK-4 include measurement of non-

Gaussian statistics of particle motion, diffusion, viscosity, and beam motion in a liquid. U.S. principal investigator Professor John Goree at the University of Iowa is a member of ESA's Facility Science Team.

PlasmaLab

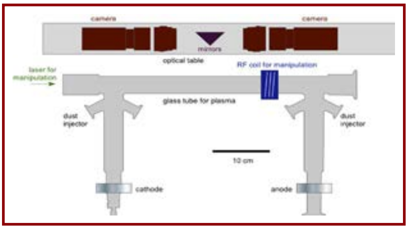


Fig. 4.1.1 Scientific package in the European Space Agency's Plasma Kristall instrument. (Source: J. Goree).

PlasmaLab is an ESA ISS experiment that will employ a dodecahedral-shaped chamber to enable study of a 3-D dusty plasma. Central objectives of this investigation are to develop an understanding of self-organization, study equilibrium and non-equilibrium phase transitions, phase separation, cooperative phenomena, and to extend the understanding of the plasma state of soft matter. U.S. principal investigators on the scientific team are University of Iowa professor John Goree, Auburn University professor Edward Thomas, Jr., and University of California at San Diego Dr. Marlene Rosenberg. Prototypes of the experiment hardware are under development in Germany to support a planned launch date of 2017.

Fundamental Forces and Symmetries

Experiments associated with fundamental forces and symmetries are designed to test our understanding of Einstein's general theory of relativity. Such experiments may also discover any additional weakly coupled, long-range interactions in physical law. The "classic" tests of Einstein's theory of gravity were astronomical in nature. The theory explained the anomalous precession of the perihelion of Mercury's orbit about the sun. His theory predicted the deflection of light passing close by the sun during a total eclipse, and it predicted the frequency shift (redshift) of light as it emerges from the gravitational field of stars. ISS provides the continued and routine access to space, which in conjunction with modern technologies, have opened a new frontier for testing gravitational theory through unprecedented measurement precision.

The ISS provides continued human research access to the space environment, which affords the following advantages for unprecedented investigations:

- Long-duration exposure to the orbital free-fall environment.
- Ease of measurement of changes of gravitational potential and relative motions.

- Study of very small accelerations on celestial bodies.
- Reduced atmospheric interference on the propagation of optical and radio signals.
- Ability to track and fit to theory very long time segments of body orbital motion.

Current fundamental forces and symmetries-related experiments under development for flight on the ISS are described in the following paragraphs.

US participation in Atomic Clock Ensemble in Space (ACES)

Figure 4.2.1. Schematic of ACES global time transfer comparison. (Source: Luigi Cacciapuoti, European Space Agency Atomic Clock Ensemble in Space project).

Four U.S. investigators have taken part in ESA's ACES project. ACES features the ISS operation of an atomic clock accurate to one part in 10^{16} for tests of fundamental physics and for providing high-accuracy comparisons of ground-based optical clocks through a microwave space-to-ground link. ACES is planned for installation on the ISS external payload facility of the Columbus module. Launch could occur as early as 2015 based on current development plans.

The scientific objectives of the ACES project are to utilize the ISS laboratory to:

- Demonstrate an atomic clock on the ISS accurate to one part in 10^{16}, measure the Earth's gravitational redshift to two parts in 10^6, and test relativistic effects in the frequency comparisons of moving clocks.
- Search for a time variation of the fine structure constant to better than one part in 10^{17} over a year period.
- Search for Lorentz transformation violations to the one part in 10^{10} level.
- Use ACES to perform time synchronization and time transfer experiments (both space to ground and ground to ground) and to allow comparison between ground clocks to a fractional frequency resolution of 1 part in 10^{17} after a few days of run time.

As part of the ACES collaborative investigation, microwave ground stations will be installed at a number of locations around the Earth so that global links to ACES can be maintained during each ISS orbit. At each ground station, ground clock signals will be linked up to the ISS ACES payload through microwave ground terminals. This will allow common view and non-common view clock comparison experiments. The link precision will be more than ten times better than the current Global Positioning System carrier phase time-frequency transfer scheme. Two microwave ground stations will be established in the U.S., one at the JPL in Pasadena, Calif., and the other at the NIST in Boulder, Colo.

Space Optical Clock (SOC) Collaboration

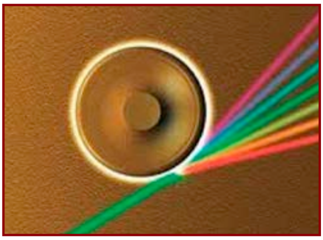


Figure 4.2.2.Schematic view of an optical frequency comb, a key element for the Space Optical Clock. (Source: K. Vahala)

Two U.S. investigators were selected for collaborative ground research supporting ESA's Space Optical Clock (SOC) project. The SOC project will develop and operate a high-performance optical clock with a predicted accuracy of one part in 10^{17}. It is planned for installation on the external payload facility of the Columbus Module on the ISS before the end of this decade. The scientific objectives of the SOC project are to utilize the ISS laboratory to:

- Demonstrate an optical clock on the ISS accurate to one part in 10^{17}, measure the Earth's gravitational redshift to two parts in 10^{7}, and test relativistic effects in the frequency comparisons of moving clocks.
- Perform a null measurement of the sun's gravitational redshift to two parts in 10^{7}.
- Use the SOC to perform differential geo potential measurements with 1 centimeter (cm) height resolution on the geoid; such measurements are based on the comparison of measurements with distant clocks located on ground.
- Use the SOC to perform time synchronization and time transfer experiments (both space to ground and ground to ground) and to allow comparison between ground clocks to a fractional frequency resolution of 1 part in 10^{18}.

The U.S. scientists are collaborating as a part of the international science team and are supporting the development of required technology, investigation of the clock system, and design studies of the hardware. In addition, the U.S. participants will perform research contributing to the overall scientific objectives, participate in time transfer and clock frequency comparison activities from the ISS clock to ground clocks, technology maturation activities, trade studies, and data analysis.

Quantum Weak Equivalence Principle (QWEP) Collaboration

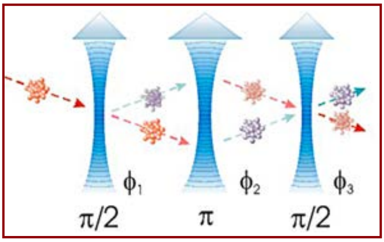


Figure 4.2.3 Schematic of atom interferometer for QWEP. (Source: Acta Astronautica, 67, 1059, 2010)

A team of U.S. investigators have taken part in ESA's Quantum Weak Equivalence Principle (QWEP) project. The QWEP project will perform an atom interferometry test of the Weak Equivalence Principle by measuring the differential acceleration experienced by two clouds of ultra-cold, rubidium atoms composed of different atomic isotopes. QWEP is planned for installation on the ISS Columbus Module as either an internal experiment or as an external payload in the 2020 timeframe.

The scientific objectives of the QWEP project are to utilize the ISS research laboratory to:

- Test the Weak Equivalence Principle using quantum particles to better than one part in 10^{14}.
- Validate the technology for a matter wave sensor in space through demonstration of differential atom interferometry and gravity gradiometer measurements.
- Investigate condensate properties in microgravity.
- Demonstrate atom interferometry with ultra-cold atom sources in space.

The U.S. investigators will participate on the international science team and support the assessment the QWEP measurements, develop required risk mitigation methods and corresponding technologies, investigate measurement methodologies, and support hardware design studies.

Quantum Gases and Cold Atom Laboratory (CAL)

CAL will provide a highly flexible Bose-Einstein condensation laboratory in space to carry out a variety of experimental studies of BEC and other quantum gases, atom lasers, and atom optics. CAL will have the performance capability comparable to a state-of-the-art ground experiment in terms of the number of atoms condensed, the ability to tune interactions and control trapping potentials and the diagnostic capability. The CAL payload is planned to fit into a double rack housing the physics package and a single rack accommodating laser system.

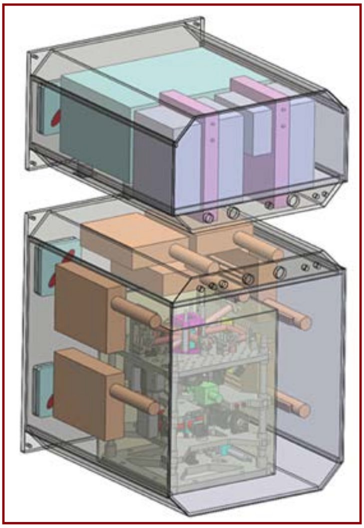


Figure 4.2.4. The planned Cold Atom Laboratory payload in a double rack housing the physics package and a single rack accommodating laser system. (Source: NASA's Jet Propulsion Laboratory Cold Atom Laboratory project)

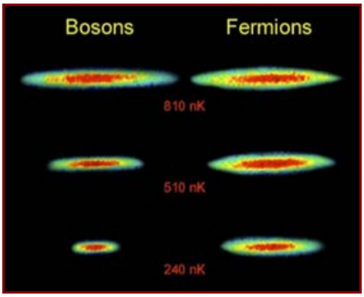


Figure 4.2.5. Difference between laser cooled fermions and bosons showing the effect of the Pauli Exclusion Principle in fermions. (Source: Kettelle et al, Nature 416, 211, 2002)

The payload anticipated mass is 82 Kg, and power required is 187 Watts. The experiment will be automated, limiting the need for crew interaction.

The first generation of Bose condensation experiments required large, well-equipped laboratories, staffed with teams of scientists often working around the clock. In contrast, the field has now matured to the point that low-power, rugged and portable BEC systems are commercially available and entirely automated. Such systems could be validated for space with relatively minor modifications. It should be stressed, however, that for many state-of-the art capabilities such as the ability to trap multiple species or load into an optical lattice (an array of potential wells formed by a standing, wave laser beam), the complexity of the system will increase dramatically. The CAL development schedule and budget include allowances for development of such capabilities.

The heart of the facility will be an "atom chip." This consists of micro fabricated wires patterned on a dielectric surface. For appropriate geometries of the wires, the magnetic field produced by a current through these wires produces exceptionally tightly confining magnetic traps. Because of this tight confinement, evaporative cooling proceeds very rapidly and efficiently, allowing condensates of a few hundred thousand atoms to be produced within seconds. In a microgravity environment, it is expected that this process will be more efficient, thus allowing larger condensates than a comparable system can achieve on the ground. The atom chip will be placed in an ultra-high vacuum chamber, along with one or more atomic sources. Rb, K, and Li are possible candidates.
Each may be incorporated, even if initial experiments only utilize one or two.

This flexibility will increase the range of experiments that may be explored for future payloads.

Because of the high efficiency of the atom chip approach, only modest laser powers (tens of milli Watts [mW]) are needed to prepare and detect the cold atoms. This will allow the laser system to be quite modest. Two laser frequencies are needed per species (a trapping/detection laser and a “repumper” laser). Each species is envisioned to have a single Extended Cavity Diode Laser modulated to provide the repumper frequency. An additional laser of modest power (<2mW) would be used for an optical lattice. The laser system baseline approach is to utilize a Commercial Off The Shelf (COTS) system.

When the decadal review was completed, there were no planned NASA investigations or collaborations with ESA in the fundamental physics research area. NASA has recently decided to develop the CAL for use on ISS in the 2017 timeframe. Taking the advantage of the absence of gravity, CAL promises access to the coldest spot in the universe—the space environment. The primary science objective for CAL is to utilize the cold temperature region to allow scientists to study ultra cold quantum gasses, collisions at the extreme low energy, and quantum interfaces and decoherence of macroscopic quantum clouds. CAL will be used for studying condensate expansion of clouds of atoms into extremely weak traps to achieve temperatures an order of magnitude below what has been achieved in terrestrial experiments. The facility will be used to study mixtures of Bose and Fermi gases at extremely low temperatures with tunable interaction strengths, to study quantum gases in optical lattices (arrays of potential wells formed by standing wave laser beams) of varying strength and dimensionality, and to study “atom lasers” and matter wave propagation in microgravity with long interaction times. CAL will be also a pathfinder experiment for future cold atom experiments in space including fore-mentioned QWEP.

Matter Near Critical Phase Transitions

The study of critical phenomena began over 180 years ago with observations of the supercritical phase and critical point of CO_2. Shortly thereafter, Van der Waals developed an equation of state and applied it to the liquid gas critical point. This equation was later extended to a wide range of critical points observed in solid systems. The concept of an order parameter by Landau successfully explained the singular behavior of the thermodynamic behavior in the early era of critical phenomena studies. As more precise experimental techniques were developed,

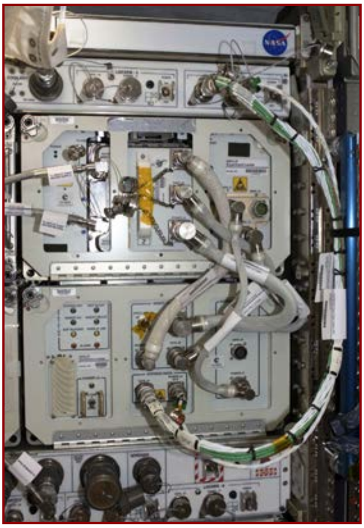


Figure 4.3.1. Picture of DEvice for the Study of Critical LIquids and Crystallization. (Source: Centre National d'Etudes Spatiales/NASA)

it became apparent the behavior of the real systems was inconsistent with the predictions of Landau's model. The concepts of scaling and universality were developed to better explain the critical phenomena observed. A key feature of a continuous phase transition in many physical systems in nature is scale-invariance in fluctuations of the order parameter, which implies continuity between large and small scale fluctuations associated with the transition. Scale-invariance occurs in many systems that are not completely understood such as the universe at the onset of the big bang as envisioned by cosmologist, the clustering of galaxies, massless fields in elementary particle physics, the distribution of earthquakes, and turbulence in fluids and plasmas. In each example cited, there is a wide range of scales over which some phenomena vary as a power-law of the scale. The RG theory is the most successful approach developed to date to derive and explore the relations between the characteristics of a system as viewed on different length scales. Many scientific investigations using liquid-gas critical point systems have been performed on the ground to test the theoretical predictions very close to the critical point. The predictions of the RG theory have been reasonably well validated. Nevertheless, the theory is based on assumptions that need to be validated based on more sophisticated experiments. Thus, it is important to test RG theory to the utmost precision achievable. Currently, there is one critical phenomena experiment ongoing on the ISS focused to validate assumptions supporting the RG theory.

DEvice for the Study of Critical LIquids and Crystallization Alice Like Insert (DECLIC-ALI)

NASA/CNES is studying the equilibration near the liquid gas critical point in microgravity utilizing the ALI of the DECLIC facility (Pont, 2011). The DECLIC-ALI will operate a number of experimental sequences throughout 2013. The U.S. objectives for this project are: to study the temperature and/or density equilibration behavior near the critical point in both the single and two-phase regions; to compare the temperature and density relaxation measurements with theoretical modeling predictions; to determine the coexistence curve of the sample fluid near the critical point; to determine the thermal diffusivity from the relaxation measurements; and compare the results with theoretical predictions.

The DECLIC facility is a joint Centre National d'Etudes Spatiales (CNES) NASA ISS research program. DECLIC uses the EXpedite the PRocessing of Experiments to the Space Station (EXPRESS) rack standard infrastructure. The ALI portion accommodates two fluid cells each filled with 0.6 cc of SF6 (Tc = 45.5 degC, Pc = 3.7 MPa, Pc = 0.742 g/cc) at the near critical density. The direct observation cell allows measurement of optical transmission, 90-degree scattering, that can give small angle light scattering pictures and transmit images with shadowgraphy. The second cell, interferometric observation cell, has an optical window and a mirror coating to measure interferograms using Twyman-Green Interferometry. It has four thermometers and two pressure sensors. The data sampling rates for temperature and pressure are at up to 2 kHz. The thermometers can be configured as heating elements also. The body of the two cells is made of copper alloy and the optical windows are all sapphire except for a 90-degree scattering window made of fused Silica. The modular sample cells are integrated within the ALI. The temperature-control stability of the ALI is better than 10 µK.

Recommended Future Research Program

This section describes the recommended fundamental physical science program to support the top four priorities of the 2011 Decadal Review. A critical element needed for successful accomplishment of the decadal priorities is sponsorship of a broad ground-based research program to nurture and develop the next generation flight experiments. The discussion focuses on facilities and experiments that can be developed in each priority area. A simple timeline is implied for each area by the order in which the experiments are described. The ultimate selection of what and when experiments are developed rests with NASA Headquarters through their peer review selection processes.

Complex Fluids and Soft Matter

The decadal review recommendations in this thrust area encompasses a broad program of which dusty plasmas is one element that is under consideration for the future ISS utilization. When it is realized for the implementation, the NASA Research Announcements (NRA) process would be used to select flight and ground-based investigators every three years throughout the life of the program.

Dusty Plasma Physics Facility (DPPF)

To initiate a sustaining program in the dusty plasmas area in the U.S., a unique U.S. DPPF needs to be developed. The DPPF will employ a different design than those of current European instruments to allow study of different kinds of science. For example, to study the transition from 3-D to 2-D physics, one of the manipulation capabilities on the first scientific payload will be temperature control of the electrodes to apply a desired thermophoretic force. By increasing the temperature gradient in the chamber, an experimenter will be able to progressively flatten a suspension of dust particles. To study nonlinear synchronization, another manipulation capability will be electrodes to drive waves that can be imaged with cameras. The cameras will be configured differently to allow stereoscopic imaging. This will allow an identification of the theoretically predicted, weak forces associated with wakefields. The DPPF configuration will be different from those

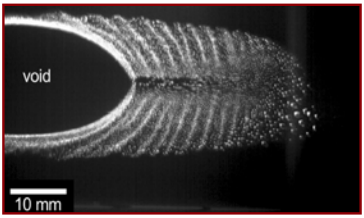


Fig. 5.1.1 Cross-sectional image of a suspension of polymer microspheres in a dusty plasma in a European Space Agency parabolic flight. (Arp, Goree and Piel PRE 2012). Features include a void that is due to a weak force called the 'ion drag force,' which is approximately one-tenth as strong as gravity under 1g conditions, wavefronts for a compressional sound wave, and small chains of microspheres that suggest a weak attractive force. (Source: J. Goree)

of PK-4 and PlasmaLab, which are designed to investigate other questions such as the effects of strong ion flows (PK-4) and observation of critical phenomena (PlasmaLab). The DPPF will be designed as a modular facility using EXPRESS rack lockers, allowing deployment of new instruments simply by exchanging out one or two lockers in the facility. The DPPF will be designed to operate autonomously with limited crew intervention.

It is envisioned that a total of four different instrument payloads will be flown in the DPPF. To generate a broad community of NASA researchers in this field, the NRA process would be used to select between 6 to 10 ground based investigators every three years, for a total of 10 flight investigators to complete their investigations on the ISS using the four different DPPF instrument inserts. Candidate examples of investigations include:

- Search for the predicted weak attractive forces between two dust particles in addition to the strong repulsive electric force.
- Study the transition between 2-D and 3-D physics using temperature-controlled electrodes.
- Study nonlinear dynamics of large plasmas.
- Perform an elegant test of the fluctuation theorem.

Fundamental Forces and Symmetries

The gravitational interaction is by far the weakest of the four known fundamental forces of nature. Yet, by virtue of its universal attraction it is the dominant force at long ranges and plays a central role in both forming the structure and governing the motion of planets, stars, galaxies, and exotic objects such as neutron stars and black holes. Gravity also gives "shape" to the universe itself and guides its dynamical evolution. The geometry of spatial relations among objects and the timekeeping of our most precise atomic clocks are intimately tied to the properties of the gravitational field(s). It is important to know if Einstein's tensor field of gravity is acting alone in establishing nature's arena or if other fields such as the scalar field also contribute to this function. And if there are other new long-range, very weakly coupled force fields still to be found, their slight modifications of the apparent gravitational interaction and its consequent effects on the orbits of celestial bodies, clocks, rulers, and other experimental devices, will be one of the most likely routes to the discovery of "new physics."

To generate a broad community of NASA researchers in this field, the NRA process is employed and the selection of between 6 to 10 ground-based investigators occurs every three years for the approximate 15-year life of the program. In addition, flight investigators will be selected every three years for the investigations described in the following paragraphs.

Quantum Tests of Equivalence Principle and Space-Time (QTEST)

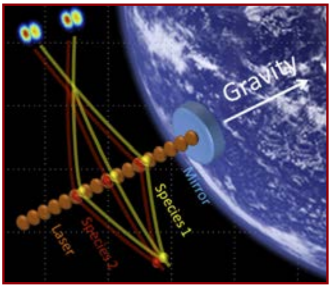


Figure 5.2.1. Concept of the Quantum Tests of Equivalence Principle and Space-Time. (Source: H. Mueller)

EEP is one of the most fundamental physics laws to be tested. This is not only because it is one of the pillars of modern physics, but also because a breakdown of any modern physic's law or symmetry often implies a breakdown in EEP. QTEST is essentially the same concept of QUITE and QWEP, that is, two different laser-cooled atomic species will be used as free-fall test masses, and atom interferometry will be used for differential acceleration measurements.

There have been significant advancements in experiment design, technological development and science analysis since the QUITE proposal many years ago. Continuous academic research has resulted in new and improved approaches to atom interferometry. The atom interferometer technology and many of its critical components have also significantly matured. There is also a new understanding of the associated physics and interpretation of the measurements. In particular, emphasis is now focusing on the quantum matter wave aspect of the EEP test. In this context, the experiment is not just testing two falling objects, but two quantum wave functions. The physics and phenomena of the matter wave under gravity are subjects of discussion and debate. It is a quite intriguing possibility that such an experimental test system may provide a means to probe the connection between the quantum system and gravity.

To achieve this goal, a Large Momentum Transfer atom interferometer will be used for the QTEST approach. It will use two rubidium isotopes to provide the needed symmetry in the highly precise differential measurements. Dual ultra-cold atom sources will be used as well since a majority of the systematic errors can be reduced by using colder and smaller atomic clouds. Symmetric Bloch diffraction will be used to form and complete the atom interferometer sequence to improve the symmetry of the measurement system and reduce potential systematic errors.

The autonomous QTEST payload would be located in the Active Rack Isolation Systems (ARIS) rack near the center of the ISS structure. This location would provide a reduced acceleration environment especially at lower frequencies. Other environment control implementation would be included within the payload.

Microgravity Facility for Optical Reference Comb Experiments in Space (MicrogFORCES)

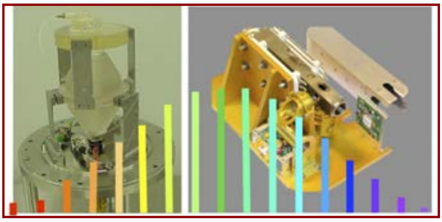


Figure 5.2.2. Microgravity Facility for Optical Reference Comb Experiments in Space uses a combination of highly stabilized resonator cavities and a compact atomic clock linked by a self-referenced frequency comb. (Source: Folkner et al, NASA's Jet Propulsion Laboratory)

Precision measurements require ultra-stable frequency reference sources and a benign laboratory environment. Space provides a very pristine environment for performing ultra-high precision measurements. In addition, a space-based platform can provide access to large variations of gravity-related accelerations, the void of space, and global Earth coverage. These attributes make the ISS an ideal platform for fundamental physics tests and high-precision global measurements and services. A microgFORCES on the ISS would allow groundbreaking investigations in fundamental physics. microgFORCES would also be an ideal platform to demonstrate new high-impact technologies and to provide global metrology services. The ISS envisioned payload would consist of a self-referenced optical frequency comb that is stabilized to a set of extremely stable optical reference cavities and referenced to a trapped ion atomic clock. The key science and technology objectives of microgFORCES facility are: 1) to demonstrate a stabilized optical reference in space at a 10-16 level; 2) to perform the fundamental physics tests of Lorentz symmetry in a migrogravity environment with the anticipated goal of improving current correlation by two orders of magnitude; and 3) to establish an ISS capability to enable high performance global clock comparisons and time transfer. This facility could also provide an opportunity for U.S. scientists to collaborate with the ISS planned ESA SOC project. Collaboration would provide an opportunity for maturing and validating a number of high-precision measurement techniques that are of great interest to NASA and the Department of Defense.

Space Optical Clock (SOC) NASA Sub-system

U.S. researchers possess the expertise required for many of the SOC sub-systems planned by ESA for development and operation on the ISS. A NASA contribution could elevate NASA to a near-equal partner to ESA in this ambitious scientific pursuit of testing the range of validity of Einstein's theories of relativity and would allow U.S. scientists to be participants in the discovery of any transformational changes to the collective "view the world" that may come about because of measurements taken in space. NASA could play a key role with ESA by developing the stabilized clock laser and the optical link portions of this experiment. Additional recommended NASA contributions are for the development of an optical frequency comb or one or both of the atom interferometer physics packages.

Quantum Weak Equivalence Principle (QWEP) NASA Sub-system

In the budget-constrained environment, it would be beneficial for NASA to collaborate with ESA on the planned QWEP project. ESA would benefit from the ability to coordinate with the leading expertise in the U.S. in atom interferometer development, and U.S. scientists would be able to achieve nearly all of the planned science objectives of QTEST. Such a partnership could include NASA developing a major subsystem for the ESA QWEP project as well as jointly participating in the QWEP investigations and resulting science data analysis and interpretation.

Relativistic Gravity Experiment At L2 (REGAL2)

The REGAL2 will perform a precise test of many of the laws of fundamental physics through measuring the different time dilations of high-precision clocks located in the weak gravity environment near the Earth-Moon L2 and on Earth. The key technologies required for REGAL2 are essential for future plans to develop optical communication capability in space. Through gravitational time dilation, a clock located at a significant distance from a massive body, like the Earth, runs faster than one located within the gravitational environment of the Earth. In low-Earth orbit, the gravitational potential is reduced by a few percent as compared to the Earth. At the L2, approximately 300,000 km from Earth, the gravity potential is essentially zero. This difference will allow for improved tests of Einstein's predictions. This experiment could improve the precision accuracy of current Einstein's gravitational redshift measurements by a factor of more than 1,000 and would enable a high-precision test of Einstein's equivalence principle. Any confirmed violation would be a major scientific discovery. REGAL2 is envisioned to consist of an optical atomic clock accurate to a few parts in 1017 and a frequency-stabilized laser as the optical local oscillator. The clock would be referenced to an atomic frequency based on trapped and laser-cooled atomic species. The experiment would also feature a laser transponder to provide a high-performance frequency link to a second precision clock located on the ground. The key technologies required for REGAL2 are also essential for future plans to develop optical communication in space. A synergistic development of this technology may be undertaken with this endeavor.

Quantum Gases

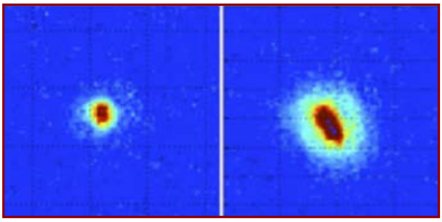


Figure 5.3. Cloud of atoms are controlled against gravity (left) and allowed to freely expand (right). (Source: R. Thompson, NASA's Jet Propulsion Laboratory)

It is important to look at the tiny building blocks of matter and how they manifest the fundamental laws of physics. Atoms are the smallest systems available for study of many of the basic principles of the universe in a laboratory setting. New study techniques allow the use of laser light to cool and probe the properties of individual atoms as a starting point. By carefully working with individual atoms, one can observe the smallest pieces of matter leading to a better understanding of the complex behavior of large systems. Furthermore, conducting these types of experiments in space allows us to remove the variables associated with the influence of gravity and manipulate matter freely without having to counteract the accelerations associated with specimens "falling" within the experimental devices. By observing the behavior of atoms completely under the experimenter's control, one has the opportunity to explore experimental regimes that could lead to new insights and perhaps unexpected observations. Experimentation in a microgravity environment allows the study of clouds of atoms cooled by laser light to very near absolute zero, freely floating without the forces that would contain them on Earth. Further, the ISS microgravity environment will allow for longer observation times and higher precision measurements of an atom nearly at rest.

NASA recognizes the unique features of the ISS microgravity research environment. To capitalize on this opportunity and provide the opportunity to the broad science community to engage and take advantage of the new capability, NASA plans to develop a state-of-the-art, ultra cold atom laboratory ISS facility. To engage academic scientists, the competitive NRA will be employed. To generate a broader interest and invite more creative ideas, the NRA will solicit flight and ground research proposals. Currently, two rounds of CAL-related NRA competitions are planned.

Cold Atom Laboratory 2 (CAL2)

NASA planning includes the future upgrade of the CAL facility design. The CAL2 design upgrade would provide a more flexible and capable facility for studying atom interference with the quantum gases.

The combined objectives of CAL and CAL2 are to provide the capability to perform science related to cold atoms and a technology maturation path to dedicated cold atom experiments such as QTEST. To address cold atom science, the facility will provide various types of bosons, various types of fermions, and also interactions between bosons and fermions at high resolution. In the case of bosons, one can study the competition between long-range spatial order commensurate with the optical lattice and order in momentum space as in a Bose–Einstein condensate. In the case of cold fermions, the possibility for pairing and the conditions under which superfluidity can occur in the presence of an optical lattice are possible investigation topics. Fermions in optical lattices, which interact via repulsive interactions, are expected to show a very rich phase diagram in the microgravity environment. While similar phenomena occur in crystalline materials where the electrons of the solid experience the periodic lattice of the crystalline arrangements of the ions, the studies of systems of such ultra cold atoms in optical lattices offer unprecedented control of the microscopic parameters. When combined with quantum simulations, the opportunity is provided to test the theoretical framework and understanding of a very broad range of phenomena. The marriage of quantum degenerate fermions with BECs promises exciting discoveries about basic quantum mechanical interactions ranging from extremely weak to quite strong correlations. The non-interacting limit can be used to refine the understanding of the implications of the Pauli exclusion principle. The mixture of quantum degenerate fermions with BECs may also demonstrate effects similar to those in the strongly interacting 4He–3He liquid. Studies of the effects of interaction based spatial phase separations will yield a more complete level of understanding and lead to improved experimental technique to increase the understanding of quantum degenerate systems.

Macro Mechanical Quantum System Experiments

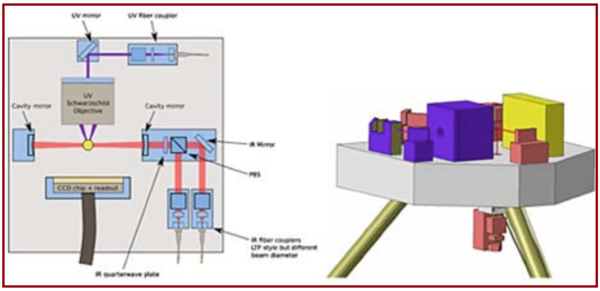


Figure 5.3.2 Optical bench for the proposed DECoherence In Double-Slit Experiments. (Source: NASA's Jet Propulsion Laboratory).

The ISS offers the opportunity for investigations of micromechanical quantum systems. Ground based laboratory approaches have demonstrated the ability to cool micromechanical systems to the regime where the quantum phenomena can be observed. A macroscopic quantum system can also be used for studying quantum phenomena at the boundary between the microscopic and atomic scale world in which quantum physics dominate. In addition, several researchers have hypothesized that gravity may play an important role through gravity-induced quantum decoherence. Study of such systems in a microgravity environment provides the opportunity to improve our understanding of gravity and quantum systems and clarify the links between them.

Micromechanical quantum systems have been usefully demonstrated in opto-mechanic resonators where interaction with light is used for bringing the system down to extremely low temperature and for detection of small motions of the mechanical system. Using opto-mechanically-coupled quantum systems in the microgravity environment of space will enable observation of the coupling between gravity and macroscopic particles (approximately 1,010 atoms) acting as quantum systems. Experiments in space can also test the physics of entanglement and decoherence over long baselines in an almost dissipation-free environment.

Matter Near Critical Phase Transitions

The condensed-matter state is prevalent everywhere we look in the universe. While most of the volume of the universe is nearly an absolute vacuum, this vast expanse of space is punctuated with dense matter at many length scales, from the sun and our solar system to galaxies and galactic clusters. Human access to the space environment offers a unique opportunity to enhance our understanding of principles responsible for formation of the condensed matter state. The space environment is required when the experimental region of interest cannot be reached in ground-based studies, or gravity-related accelerations cause sample inhomogeneity that will reduce the resolution in ground-based experiments by orders of magnitude. Investigations related to this research topic will concentrate on exploring model systems possessing extraordinary properties such as liquid-gas phase transition.

DECLIC-ALI-R and DECLIC ALI-2

Figure.5.4.1. Pictured is a DEvice for the Study of Critical LIquids and Crystallization Alice Like Insert sample cell. (Source: Y. Garrabos)

Results from the currently operating ISS DECLIC-ALI investigation indicate that the critical density was missed by about two percent because of the inability to adjust the fluid content in orbit. To fully meet the proposed CNES/NASA investigations on DECLIC-ALI, a refurbished cell can be developed (ALI-R) to ensure that the critical density can be reached. This represents a low-cost, high pay-off investigation. To take advantage of the full capability of the DECLIC facility to perform critical phenomena experiments, a new instrument, DECLIC-ALI-2, can be developed. This instrument can be designed to address questions raised by current DECLIC-ALI and ALI-R investigations or could be used to investigate topics such as finite size effects, dynamical effects and/or heat transfer effects near the critical point.

Lessons Learned

Experiments conducted on the ISS require an understanding of natural and induced environments present. These environments include microgravity, vibration, radiation, vacuum, and thermal extremes. Depending on the particular experiment, each of the environments must be considered in the design of the experiment. Section 7 provides a general summary of the microgravity, vibration and radiation environments an experimenter will encounter on the ISS. Vacuum and thermal environments are dependent upon the location of the experiment. Internally mounted experiments within the pressurized volume of the ISS will experience very controlled pressure and temperature environments. However, experiments mounted externally will be subject to the low-Earth orbit, vacuum environment and to thermal cycles associated with each orbital pass around the earth. ISS offers several external locations on U.S., Japanese and European sites for the mounting of unpressurized experiments. Each of the locations provide different opportunities to take advantage of the natural environments present for fundamental physics research and intermediate disciplines.

ISS Facilities and How to Use Them

The ISS provides world-class facilities for in-orbit research. This section provides a brief summary about U.S. and foreign facilities available. Research facilities are located internally and externally providing access to all low-Earth-orbit environments for experimentation. More complete ISS research facilities information is available at the NASA website http://www.nasa.gov/mission_pages/station/research/experiments.

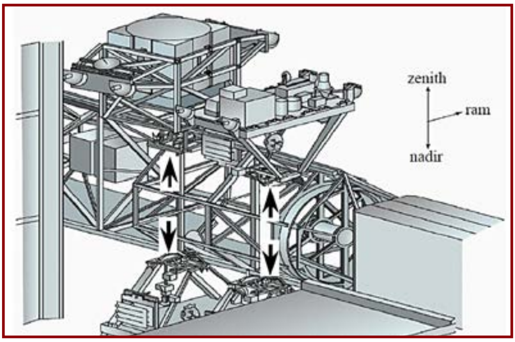
U.S. Experiment Support Facilities

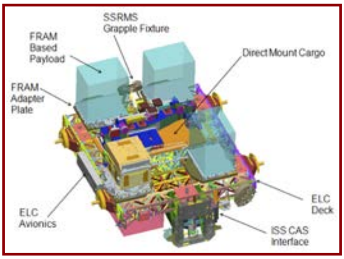
The internal pressurized U.S. laboratory facilities of potential interest for experiments related to fundamental include the FIR, the Combustion Integrated Rack, the Material Science Research Rack (MSRR), Microgravity Acceleration Measurements System (MAMS), Space Acceleration Measurement System (SAMS) the Window Observational Research Facility, and the Microgravity Science Glovebox (MSG). In addition, the ISS features eight EXPRESS racks that feature a standard design architecture and outfitting scheme to allow for ease of experiment integration. In


CGBA
MAMS
SAMS
MSG
ExPRESS Rack (1-8)
MSRR

Figure 7.1.1. U.S. International Space Station Internal facilities available for in-orbit research. (Source: NASA)

conjunction with the internal facilities, there are multiple external Express Logistics Carrier (ELC) experiment site locations available. External experiment design requirements are unique to each site location and need to be considered as a part of the experiment design.





ELC (1-5)

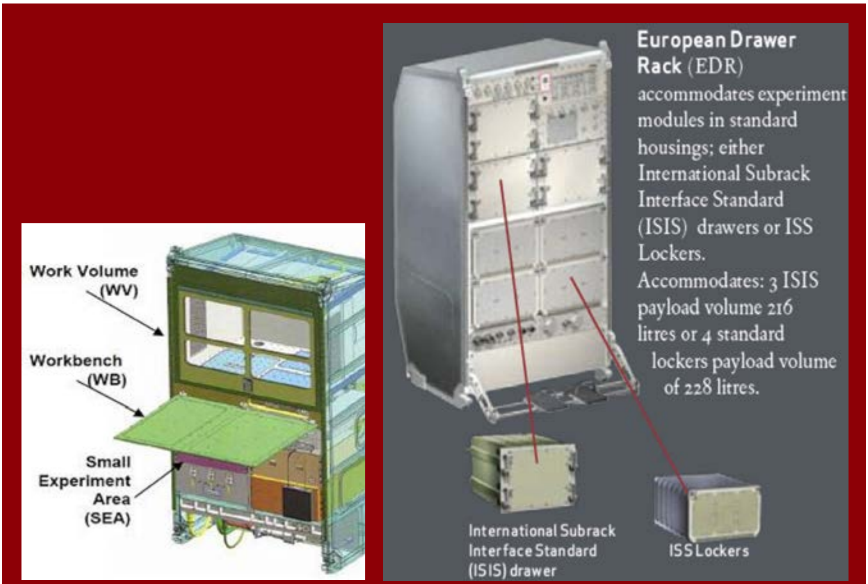
Figure 7.1.2. U.S. External facilities available for in-orbit research (several palates are available with multiple experiment sites/pallet). Credit: NASA)

ESA and Japanese Aerospace Exploration Agency (JAXA) Research Support Facilities

ESA and JAXA facilities that are available for fundamental physics research include the Fluid Science Lab (FSL), the European Drawer Rack (EDR), the Ryutal (Fluids) rack, the Kobairo (Gradient Heating Furnace), the Multipurpose Small Payload Rack (MSPR), the Space Environment Data Acquisition facility, and the Superconducting Submillimeter-wave Limb-Emission Sounder. ESA and JAXA also provide external mounting locations for unpressurized payloads.

Ryutai

FSL

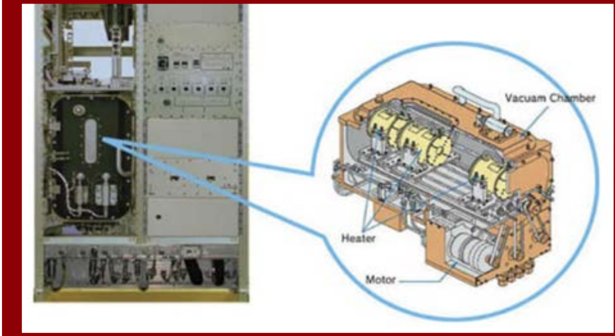


European Drawer Rack (EDR) accommodates experiment modules in standard housings; either International Subrack Interface Standard (ISIS) drawers or ISS Lockers.

Accommodates: 3 ISIS payload volume 216 litres or 4 standard lockers payload volume of 228 litres.

MSPR

EDR



Kobairo

Figure 7.2.1. The European Space Agency and Japanese Aerospace Exploration Agency ISS internal facilities for in-orbit research. (Source: JAXA/ESA)

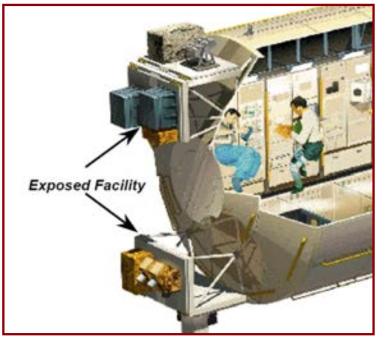


Figure 7.2.2. The European Space Agency's external facilities for in-orbit research. (Source: ESA)

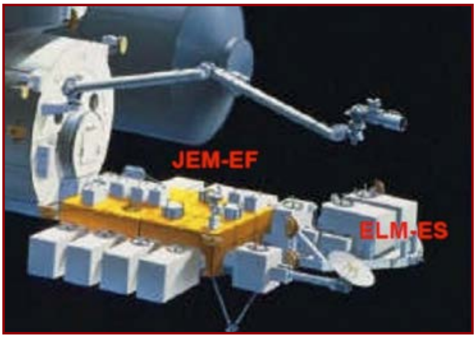


Figure 7.2.3. Japanese Experiment Module - External Facility and the Experiment Logistics Module - Exposed Section. (Source: JAXA)

Developing and Flying Research to ISS

Conducting an Experiment on the ISS: Review of the Unique Conditions of ISS

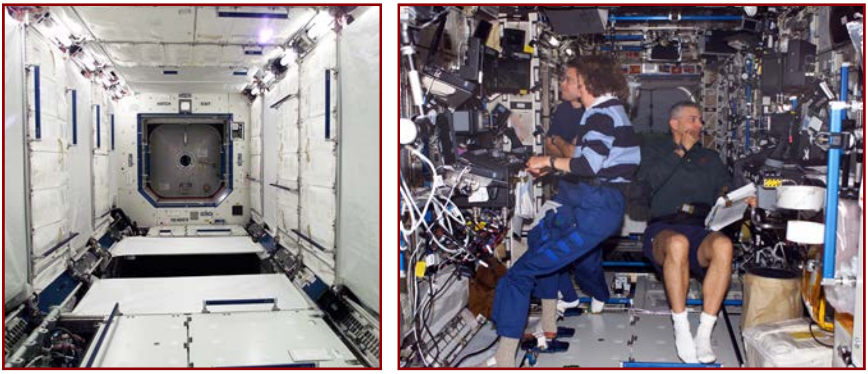


Figure 8.1. The International Space Station U.S. Lab's interior (initial ISS laboratory installation and in operation). (Source: NASA)

Environmental Conditions on the ISS: Microgravity

The ISS orbit has a normal 450 km altitude and 51.6 degree inclination. One orbital period around the Earth is approximately 90 minutes. In Earth orbit, the microgravity environment is attributed to the ISS free-fall condition with all parts of the ISS continuously falling together through space as it orbits the Earth. The term microgravity (µg) is used to describe the space environment because absolute zero gravity (g) is not achievable in practice. An orbiting ISS experiences both atmospheric drag and solar radiation pressure. These forces produce the effect of small gravity equivalent accelerations and push heavier objects toward the front end of the moving ISS. If the ISS is rotated for a docking maneuver for example, small centrifugal forces can also be created. Tidal forces, also called gravity gradient forces, are present in the orbiting ISS because of small differences in the forces of gravity over the extended object. The presence of the small tidal forces has been demonstrated through in-orbit inspection of a spherical bubble. The shape of a spherical bubble is elongated toward and away from the direction to the

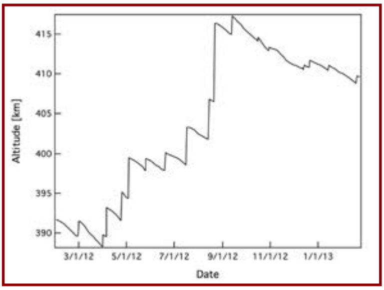


Figure 8.1.1 The chart shows altitude of the International Space Station orbit variation over a year. (Source: NASA's Jet Propulsion Laboratory)

Earth. In the orbiting ISS, these small effects are reduced to the level of a 10^{-6} g. Within a small region, very near the center of mass of the spacecraft, a level of 10^{-7} g can be achieved.

Environmental Conditions on the ISS: Vibration

The vibration environment of an in-orbit spacecraft can be broken into three main regimes: quasi-steady, vibratory, and transient. For instance, the ISS definition for quasi-steady vibrations includes disturbances at frequencies below 0.01 Hz. The sources of the disturbances are atmospheric drag, gravity gradient and rotational effects. The quasi-steady acceleration environment of ISS is less than 1 μg rms as averaged through the entire frequency range up to 0.01 Hz. The ISS requirements specify minimum time intervals of 30 continuous days of “microgravity mode” operation, with cumulative time of not less than 180 days per year.

The vibratory regime is in the frequency range of 0.01 to 300 Hz. Typical sources of the disturbance are routine crew activity, thruster firings, fans, and pumps. The ISS requirements on the vibratory acceleration limits are defined over a set of frequency intervals. In the low-frequency regime ($f < 0.1$ Hz), the limit is less than 1.6 μg. In frequency range, $0.1 \text{ Hz} < f < 100 \text{ Hz}$, the limit is less than 1.6 μg. The acceleration limit is less than 1,600 μg in the frequency range between 100 Hz and 300 Hz. The transient disturbances are of relatively short duration and are identifiable events. Examples of transient events are docking, operation of airlock valves and routing maintenance. The transient acceleration limits of ISS are an instantaneous limit of 1,000 μg, and an integrated impulse limit of 10 μg-sec per axis over any 10 second interval. The actual vibration environment of the ISS has been monitored under the NASA Glenn acceleration measurement program (http://microgravity.grc.nasa.gov). It is important to point out that the ISS vibration level is much worse than levels that can be easily achieved in a laboratory on the ground. Extra care has to be given when one designs a space experiment requiring more stringent vibration requirements. Recognizing this concern, the ISS provides accommodations for experiments sensitive to vibration disturbances. For vibration-sensitive experiments, ISS offers an ARIS. The ARIS facility provides the ability to predict and prevent the potential impacting effects of ISS-induced vibrations on experiments mounted within the ARIS rack. Stringent in-orbit tests of ARIS determined that sensitive experiments installed within an ARIS rack would be isolated and protected from vibration and acceleration related motions.

Environment Conditions on the ISS: Radiation Environment

There are three major sources of charged particles in the ISS space environment: galactic cosmic rays, solar energetic particles and trapped particles in the Van Allen Belt. Galactic cosmic rays are generally isotropic with energies up to hundreds of gigaelectronvolts. Solar energetic particles or solar particle events are names for this very energetic process. These terms are also used to describe the potentially damaging situation that occurs when very strong magnetic fields in the solar photosphere reach a critical instability. A third term used in a similar manner is a solar proton event since protons are the most abundant comprising more than 90 percent of the subatomic particles. For the typical ISS low-Earth orbit, these solar particles are shielded by the Earth's magnetic field and are of limited concern. However, should a major solar particle event occur, crew procedures are in place to mitigate associated risks. Trapped particles relevant to the ISS orbit are mostly protons. The main problems associated with the trapped particles is the electrostatic charging effects to the ISS when it passes through the auroral zone and "single event" upset phenomena that can impact electronic devices caused by a single passing energetic particle. The typical impacts of charged particles on experiments are noise pick-up in data acquisition electronics and/or direct heating effects impacting heat sensitive measurements. NASA is prepared to provide experiment design guidance to limit either or both of these issues.

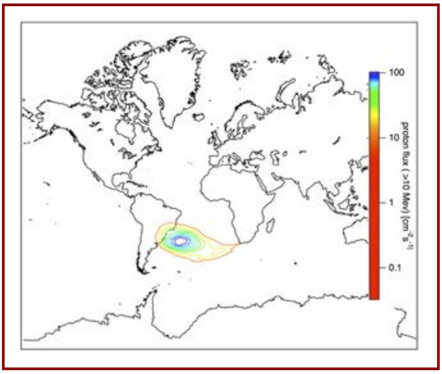


Figure 8.1.2. Trapped proton flux map at 380 km. (Source: SPENVIS)

On account of the orbital inclination of the ISS, it passes through the South Atlantic Anomaly (SAA) on a routine basis. The SAA contains a large flux of protons because of the off-axis, off-centered magnetic field of the Earth. It is expected that 50 percent of ISS orbits will pass through the SAA. The proton dose rates experienced during an orbital pass through the SAA exceed 10 protons/cm2sec for approximately 10 minutes of the 90-minute orbit.

What Should Principal Investigators Know About Conducting Research on the ISS?

Supporting research in science and technology is an important part of NASA's overall mission. NASA solicits research through the release of NASA Research Announcements (NRA), which cover a wide range of scientific disciplines. All NRA solicitations are facilitated through the web-based NASA Solicitation and Proposal Integrated Review and Evaluation System (NSPIRES) http://nspires.nasaprs.com/external/. Registering with NSPIRES allows investigators to stay informed of newly released NRAs and enables submission of proposals. NSPIRES supports the entire lifecycle of NASA research solicitations and awards, from the release of new research calls through the peer review and selection process.

In planning the scope of their proposal, investigators should be aware of available resources and the general direction guiding NASA research selection. NASA places high priority on recommendations from the 2011 National Research Council's NRC Decadal Survey, which placed emphasis on hypothesis-driven spaceflight research. In addition, principal investigators (PI) should be aware that spaceflight experiments may be limited by a combination of power, crew time, or volume constraints. Launch and/or landing scrubs are not uncommon, and alternative implementation scenarios should be considered in order to reduce the risk from these scrubs. Preliminary investigations using ground-based simulators may be necessary to optimize procedures before spaceflight. Also, many experiments require unique hardware to meet the needs of the spaceflight experiment. To understand previous spaceflight studies, prospective PIs should familiarize themselves with the NASA ISS Program Science Office database, which discusses research previously conducted on the ISS, including that of the International Partners. A detailed catalog of previous, current, and proposed experiments, facilities, and results, including investigator information, research summaries, operations, hardware information, and related publications is available at www.nasa.gov/iss-science through the NASA ISS Program Office. Additionally, details pertaining to research previously supported by the Space Life and Physical Sciences Research and Applications Division of NASA's Human Exploration and Operations Mission Directorate can be located in the Space Life & Physical Sciences Research and Applications Division Task Book in a searchable online database format at: https://taskbook.nasaprs.com/Publication/welcome.cfm.

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Acronyms

ACES	Atomic Clock Ensemble in Space
AMS	Alpha Magnetic Spectrometer
ARIS	Active Rack Isolation System
BEC	Bose-Einstein Condensate
CAL	Cold Atom Laboratory
CAL2	Cold Atom Laboratory 2
CHeX	Confined Helium Experiment
CLASS	Condensate Laboratory Aboard the ISS
CNES	Centre National d'Etudes Spatiales
CVX	Critical Viscosity Experiment
DECLIC-ALI	Device for the Study of Critical Liquids and Crystallization Alice Like Insert
DPPF	Dusty Plasma Physics Facility
EDR	European Drawer Rack
EEP	Einstein's Equivalence Principle
ELC	Express Logistics Carrier
ESA	European Space Agency
EXPRESS	Expedite the Processing of Experiments to the Space Station
FIR	Fluid Integrated Rack
FSL	Fluid Science Lab
GRADFLEX	Gradient Driven Fluctuations Experiment
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JEM-EF	Japanese Experiment Module – Exposed Facility
JPL	NASA's Jet Propulsion Laboratory
LPE	Lambda Point Experiment
LTMPF	Low Temperature Microgravity Physics Facility
MAMS	Microgravity Acceleration Measurements System
MSG	Microgravity Science Glovebox
MSPR	Multipurpose Small Payload Rack
MSRR	Material Science Research Rack
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NRA	NASA Research Announcements
PARCS	Primary Atomic Reference Clock in Space
QTEST	Quantum Tests of Equivalence Principle and Space-Time
QUITE	Quantum Interferometer Test of Equivalence
QWEP	Quantum Weak Equivalence Principle
RACE	Rubidium Atomic Clock Experiments
REGAL2	Relativistic Gravity Experiment At L2
RG	Renormalization Group
SAA	South Atlantic Anomaly
SAMS	Space Acceleration Measurement System
SOC	Space Optical Clock
VOC	Volatile Organic Compounds
ZENO	Critical Fluid Light-Scattering Equipment

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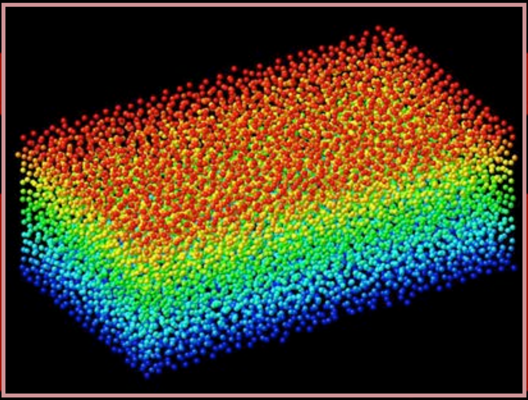

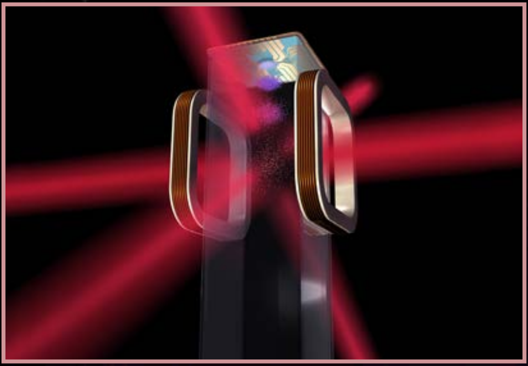

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