Microgravity Sci. Technol. (2011) 23:311–343
DOI 10.1007/s12217-010-9253-2

ORIGINAL ARTICLE

Summary of Recent Research Accomplishment Onboard the International Space Station—Within the United States Orbital Segment

Kenol Jules · Eric Istasse · Hilde Stenuit · Keiji Murakami · Izumi Yoshizaki · Perry Johnson-Green

Received: 4 June 2010 / Accepted: 3 December 2010 / Published online: 1 January 2011

Abstract November 20, 2010, marked a significant milestone in the annals of human endeavors in space since it was the twelfth anniversary of one of the most challenging and complex construction projects ever attempted by humans away from our planet: The construction of the International Space Stations. On November 20, 1998, the Zarya Control Module was launched. With this simple, almost unnoticed launch in the science community, the construction of a continuously staffed research platform, in Low Earth Orbit, was underway. This paper discusses the research that was performed by many occupants of this research platform during the year celebrating its twelfth anniversary. The main objectives of this paper are fourfold: (1) to discuss the integrated manner in which science planning/replanning and prioritization during the execution phase of an increment is carried out across the United States Orbital Segment since that segment is made of four independent space agencies; (2) to discuss and summarize the research that was performed during increments 16 and 17 (October 2007 to October 2008). The discussion for these two increments is primarily focused on the main objectives of each investigation and its associated hypotheses that were investigated. Whenever available and approved, preliminary research results are also discussed for each of the investigations performed during these two increments; (3) to compare the planned research portfolio for these two increments versus what was actually accomplished during the execution phase in order to discuss the challenges associated with planning and performing research in a space laboratory located over 240 miles up in space, away from the ground support team; (4) to briefly touch on the research portfolio of increments 18 and 19/20 as the International Space Station begins its next decade in Low Earth Orbit.

Keywords Microgravity · Spinal elongation · Nutrition · International space station · ISS · Bisphosphonates · Epstein–Barr · Extra vehicular activity · Integrated immune · Neurospat · Visual performance · Space adaption syndrome · Otolith · Space research · Deconditioning · Protein crystallization · Space motion sickness · Magnethorheological · Low earth orbit (LEO) · Life science · Fundamental biology · Materials science · Radiation · Human and environment interaction · Fluid physics · Space products and development · Education and earth observation · Research planning · Research execution · Research operations · Real time operations

K. Jules (✉)
NASA, Johnson Space Center, Mail Code OZ-4, 2101 NASA Parkway, Houston, TX 77058, USA
e-mail: kenol.jules-1@nasa.gov

E. Istasse · H. Stenuit
ESA, ESA Mission Science Office, ESTEC HME-GAC, Keplerlaan 1, Postbus 299, 2200 AG, Noordwijk, The Netherlands

K. Murakami · I. Yoshizaki
JAXA, Space Environment Utilization Center, 2-1-1, Sengen, Tsukuba, Ibaraki, 305-8505, Japan

P. Johnson-Green
CSA, John H. Chapman Space Centre, 6767 route de l’Aeroport, St. Hubert, QC J3Y 8Y9, Canada

Introduction

In the construction history of the International Space Station (ISS), there are a few flights or launches over its 10-year construction phase that stand out as significant milestones. Of course, November 20, 1998, marked the beginning of ISS construction with the Zarya Control Module launch. A few others are: (1) Expedition 1 (Increment 1) launch on October 31, 2000, which docked on November 2, 2000. With that docking, continuous human occupation of ISS began; (2) The USLAB, Destiny, launch on February 7, 2001, onboard the Space Transportation System (STS) 98. The arrival of that module marked the beginning of continuous space research on ISS; (3) ISS Harmony connecting module, Node 2, launch on October 23, 2007, marked the expansion of the United States Orbital Segment (USOS), the first science module (NASA's) until the arrival of the other two partners' science modules; (4) Columbus science module launch on February 7, 2008, onboard STS 122, brought the European scientific community's aspiration to fruition; (5) The Japanese Experiment Module (also called "Kibo")science module launch on May 31, 2008, onboard STS 124, connected the hope and dreams of the Japanese scientific community to ISS to complete the United States Orbital Segment (USOS) scientific modules. There are, of course, many other significant launches to ISS, but from a science outlook (these authors are, of course, biased), those were very significant launches to prepare and expand the scientific work volume of the USOS, to increase the research capability and throughput of the station in terms of new research facility capabilities and to support continuous human presence and research performance in space.

Background

With the launches of STS-122 on February 7, 2008, which delivered the European Columbus science module and STS-124 on May 31, which delivered the Japanese Kibo science module, the International Space Station became truly "International" with Europe and Japan joining the United States of America and Russia to perform space research on a continuous basis in a wide spectrum of science disciplines. With all the partners now onboard, ISS was ready to celebrate its tenth anniversary in Low Earth Orbit (LEO) on November 20, 2008.

With the end of Increment 17 on October 23, 2008 (1 month short of ISS tenth anniversary), continuous human presence on ISS reached a milestone of ninety five (95) continuous months in LEO. The many astronauts and cosmonauts, who lived onboard the station during that time span, spent their time building, maintaining the station as well as performing research on a daily basis. During those 95 months, the USOS Astronaut crew members logged more than 3,560 h of research time, while the Russian's Cosmonauts logged over 2,071 h during that time period. Of course, far more research time has been accumulated by experiments controlled remotely by investigators on the ground. The USOS Astronauts performed one hundred and forty five (145) new investigations inside the ISS during that time period. Amongst the 145 new investigations performed inside the ISS, many of them were operated across multiple Increments. The crew members also installed, activated and operated sixteen (16) research rack facilities that supported eight (8) science disciplines ranging from Materials science to Life Science. By the end of Increment 17 about 9560 kg of research rack mass were ferried to the station as well as 5607 kg of research mass (science hardware and science specimen/samples).

USOS Integrated Research Planning and Execution

With the addition of the European Space Agency (ESA) and the Japanese Aerospace Exploration Agency (JAXA) science modules, the USOS segment is now made up of four space agencies: the Canadian Space Agency (CSA), the European Space Agency (ESA), the Japanese Aerospace Exploration Agency (JAXA) and the National Aeronautics and Space Administration (NASA), spanning across three continents and four different time zones. With the partners now fully part of the ISS daily life, and each partner with different national research needs, every effort was made to coordinate research planning and execution across the USOS segment in an integrated manner for the benefit of all four agencies. One of the objectives of this paper is to briefly discuss the integrated manner in which ISS research planning, replanning, prioritization and execution of an increment is accomplished.

An increment is defined as a specific time period on ISS which combines different operations such as assembly, scientific research, maintenance, and other ISS systems and utilization operations. The duration of an increment is the time period from the undocking of the Russian Soyuz vehicle from the ISS to the undocking of the next Soyuz vehicle and can support one or more stages. The increment time period span is usually 6 months. The current ISS configuration requires two Soyuz vehicles to always be docked to ISS. An increment stage is a designated period defined by the ISS Program that begins and ends with a major activity on the ISS and is used for requirements documentation and planning purposes. It is usually referred to as the period of on-orbit configuration of the ISS after each flight which adds capability to the ISS vehicle.

USOS Integrated Research Planning

Research planning of an increment begins with a multilateral face to face meeting of the Multilateral Research Payload Working Group (MRPWG). The meeting is hosted semi-annually in an alternated manner by one of the USOS segment International Partners (IPs) countries. Currently, there are 15 IPs countries. The MRPWG is chaired by the NASA manager for Research Planning at the Johnson Space Center (JSC). The planning meeting for each increment begins more or less at Increment minus 19 months (I-19), meaning the first meeting to plan the increment takes place 19 months before the assigned crewmembers for that increment arrive on ISS. At that meeting, the MRPWG Chair discusses resources (e.g. how much mass can be ferried to/and from ISS for research use, research crew time availability, on-orbit facility availability and so on) allocation and distribution to each partner for the overall increment, based on other ISS activities that the crewmembers need to devote time to during their stay on ISS, such as daily maintenance work, repair work, construction work, crew health maintenance activities and so on.

Based on an agreed upon resources allocation formula for each Partner, crew time allocation, along with other resources, are given to each IP—that is how much crew time each IP will have to perform research during that increment. The amount of crew time available dictates how much research can be performed. However, there are other constraints that must be taking into account besides crew time, such as upmass (how much research mass that can be delivered to ISS by Shuttle, Progress, the European Autonomous Transfer Vehicle (ATV) and the Japanese H-II Transfer Vehicle (HTV) before and during the increment), how much mass can be accommodated on-orbit due to stowage capability or lack thereof, availability of on-orbit facilities to accommodate the needs of the proposed experiments such as cold stowage capability for the life science and fundamental biology experiments, and so on. Therefore, crew time is a very important factor, but it is only *one* of many constraints that must be taken into account in determining how much research gets done on a particular increment. In fact, since ISS has transitioned from a three-crew to a permanent six-crew rotation (May 2009), crew time dedicated to research performance is no longer a significant factor due to crew size increase, rather science samples return and the other constraints mentioned above are the critical ones and will get worst with the Shuttle slated for retirement within the fiscal year of 2011. These constraints will continue until the Commercial Orbital Transportation System (COTS) fully comes on-line and have vehicles that can provide large science samples return capability.

Currently, only the Space Shuttle provides samples return capability to earth for analysis (the Soyuz return module currently capability is almost non-existent compared to Shuttle). The other vehicles (HTV, ATV and Progress) discussed above currently have no return capability. From the COTS, only one vehicle so far plans to provide limited samples return capability. Once each IP receives its agency increment utilization resource allocation, each agency follows its own agency process to establish a list of experiments and the priority in which they need to be performed during the increment. The resource utilization requires to perform each agency research portfolio should be more or less within that agency allocated utilization resource box. Each agency submits its proposed research portfolio with its agency associated priority to the MRPWG Chair, who collects all of the agencies research portfolios and combines them into an integrated USOS research portfolio with associated priority. The overall goal is to maximize research within the USOS while remaining within an acceptable overall USOS research utilization allocation. The USOS integrated research portfolio (plan) for the Increment being planned is then presented to all IP agencies for concurrence before it can be transitioned to the implementation and operations phases. This is, in brief, the integrated planning process that is followed for the development of the integrated USOS research plan.

USOS Integrated Research Execution

Research execution or more commonly referred to as "real time operations" is defined as the time frame when the crew members assigned for the increment arrive onboard ISS to begin their tour of duty. For several increments now, that transition has been marked by Soyuz change-over—when a new Soyuz arrives, the "old" one departs ISS, usually within 10 days or so, that transition marks the beginning of a new increment as well as the end of the previous one.

A lot of planning and many products are generated by the research planning team and other support teams to be ready to start performing science once the crew arrives to begin the increment. Since this is a paper dealing with research performance, this section will focus only on the research team preparation for the research plan execution. Since research within the USOS segment (CSA, ESA, JAXA and NASA) shares common and limited utilization resources (e.g., crew time, onboard samples refrigeration facilities, upmass, downmass and so on), it makes sense to perform research within the USOS using an integrated approach in order to make the best use of the limited, shared, available resource, while maximizing overall science return for all. To accomplish that, a multilateral research board called Increment Research Team (IRT) was formed, whose specific task is to manage the overall research planning, prioritization and overall research decision during real time operations for all the four space agencies that make up the USOS. Also, the IRT leads increment replanning activities that might arise after the increment research plan has been concurred to by all international partners (IPs).

Replanning does occur from time to time due to the fact that Shuttle flights move in and out of an increment for a number of reasons associated with Shuttle flight schedules and operations. The IRT is specifically chartered to do the following: "The IRT has the responsibility for coordinating research activities during the near real-time, real-time and post increment assessment period. The IRT also has the responsibility to insure that all opportunities to increase science return are used optimally and done in an equable manner. Due to the nature of the multi-increment planning and execution activity on-going at any given time, the IRT could be carrying out these responsibilities for various increments concurrently" (Increment Research Team 2008). Each of the four USOS space agencies has one representative to the IRT. The representative is that agency ISS Increment Scientist (IS) for that specific increment. The ISS Lead Increment Scientist (LIS) Chairs the IRT. This board is where all research discussion begins, additional resource utilization is requested and discussed; integrated research planning and weekly on-orbit research prioritization are agreed to before proceeding with implementation. The IRT is also responsible to generate many products needed to support the research planning aspect of the increment in an integrated multilateral manner.

Research Accomplishment Within the USOS During the First 16 Increments

During the first 16 increments (increments 0 to 15), the USOS segment of ISS had only one operating science module, the USLAB "Destiny". During those 16 increments, the various crewmembers that staffed the USOS segment devoted 3,027 h of their time performing research. In addition to that, several thousand of hours were spent on research that was controlled directly from the ground (without crew involvement). During those 16 increments, the various USOS crewmembers performed a total of 122 new investigations in eight different disciplines. Additionally, 244 investigations were conducted across several increments (i.e., investigations continuing from one increment to the next). Taken into account both new experiments performed during each increment and those that continued across several increments, a total of 366 investigations were conducted on ISS during its first 16 increments. *Note*: new experiments are those that were started for the first time on a specific increment while the continuing ones are the ones that started on one increment and continued during other increments because they are long term investigation (for example, a life science investigation might require several Human Subjects, therefore it will continue on several increments until the desired number of Subjects are completed).

Figure 1 shows four pie charts that illustrate the investigations performed during those 16 increments in eight science disciplines. For a detailed discussion of how these science disciplines were selected and investigations categorized, the reader should consult (Jules 2008). The first chart (a) of Fig. 1 shows the research disciplines (e.g., Life Science), followed by the number of investigations performed in each disciplines (39, for Life Science), and the last number is the percentage (32% for Life Science) for each discipline within that category (i.e., New Experiments). The next two charts (b and c) of the same figure show the same information for the Continuing Experiments and the Combined categories. The combined category is the total of the two categories (new and continuing experiments) added together for each increment.

Chart (d) of Fig. 1 is a breakdown of the third chart, chart (c), for the three categories under consideration. These charts clearly show that the majority of experiments were performed in the Life Science discipline, followed by Materials Science and Space Products development. The majority of experiments performed in the Life Science discipline was dominated by Human Subjects related experiments, while the Materials

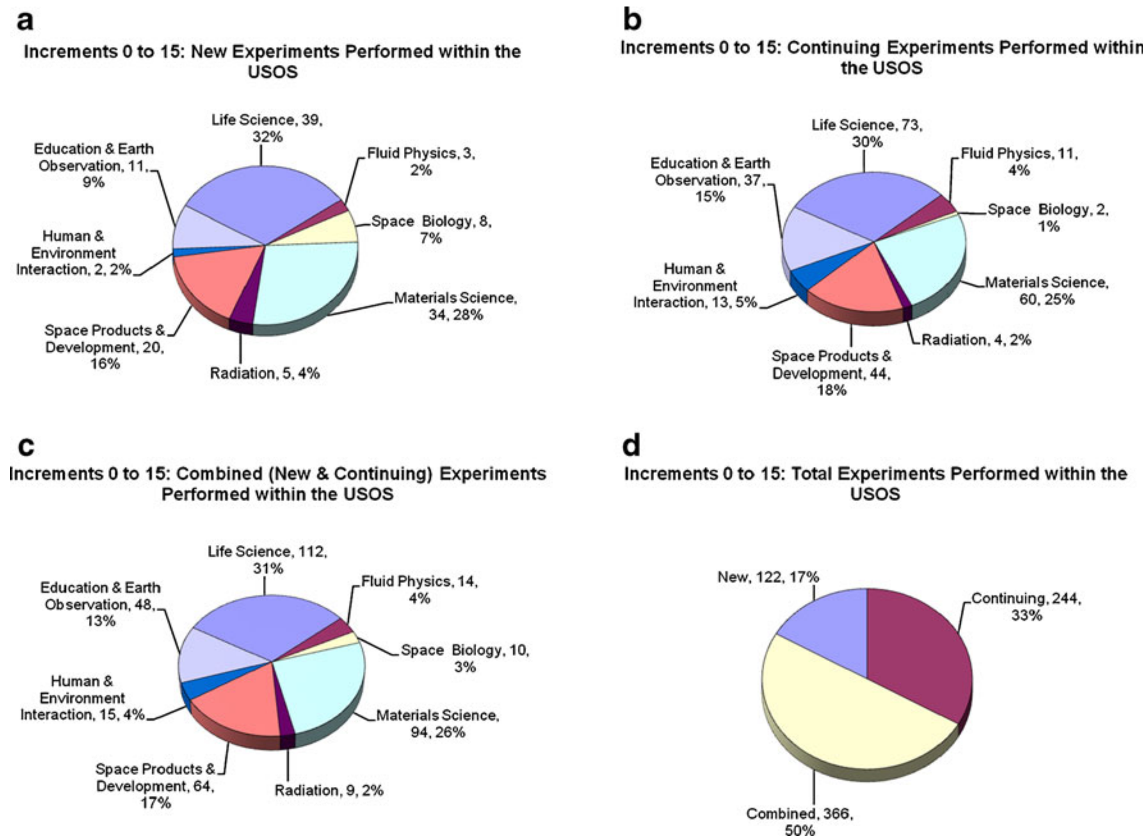

Fig. 1 Research performed in different disciplines on the international space station from increments 0 to 15

Science discipline was dominated mainly by Crystal Growth experiments. Most of the experiments in the Space Products and development were technologies demonstration related. Again, these results are for experiments performed within the USOS segment with only one science module attached to ISS, the USLAB. All of these experiments were performed by NASA, with only a few exceptions, performed by ESA and CSA in conjunction with NASA.

It must be pointed out; however, that ESA performed a lot of research in these eight science disciplines as well during those first 16 increments through joresearch collaboration with Roscosmos within the Russian Orbital Segment (ROS) of the ISS. The results of these experiments are not reported here since this paper focuses only on research accomplishment within the USOS segment.

Increment 16 Research Planning and Execution

The intent of Section USOS Integrated Research Planning and Execution was to briefly describe the overall ISS research planning process in a generic way, and also to describe the integrated research execution approach being used within the USOS with all the IP science modules onboard sharing limited resources amongst the four of them. This section will focus only on the research planning and execution for increment 16.

Increment 16 Research Planning

From the beginning, it was clear to everyone involved that Increment 16 was going to be one of the most challenging increments to plan, implement and execute. Every aspect of the increment was difficult, from the construction phase to finding crew time to perform research. From the vehicle traffic plan, there were three U.S Shuttle flights, four Russian Progress, one European Autonomous Transfer Vehicle (ATV) and the two Russian Soyuz swapped vehicles at the beginning of the increment and the arriving Soyuz at the end of the increment. There were two stage Extra Vehicular Activities (EVAs) planned just after the increment begins. Arriving and departing vehicles consume significant amount of crew time due to all the preparation required to finish unloading the vehicle of its cargo and then load the vehicle with return items or trash, dependent whether the vehicle will return to Earth or burn on reentry in the atmosphere. This is crew time not available to perform research or other activities.

Increment stage EVAs require significant crew time due to all the preparation requires for onboard crew training for the tasks that will be performed, for equipment check-out, EVA suits preparation and check-out, crew overnight camp-out and so on. Again, this is crew time not available to perform research or other activities. Increment 16 was probably the most critical increment in the construction phase of ISS in terms of research capability expansion and ISS assembly complete milestone since that was the increment which was to oversee the Harmony module attached to ISS—the building block for all the other Partners modules to be attached to ISS. Also, this was the increment in which the European science module, the Japanese logistic module and the Canadian Special Purpose Dexterous Manipulator (SPDM) became part of ISS.

In addition to all of these activities this increment was the one in which the new European Automated Transport Vehicle (ATV) made its first flight to ISS. A challenging increment: Yes, indeed. With all of these challenges, the research portfolio for the increment was more extensive than ever. Scientific investigations were planned by ESA, JAXA and NASA in eight science disciplines. The increment planning cycle was rather very steady. No significant change took place such as Shuttle flights moving in or out of the increment. The main problem was: *not* enough crew time available to perform the activities discussed above, in addition to all the system tasks, ISS daily/weekly maintenance required and science performance.

Figure 2 compares the original plan for the increment with what actually took place during the on-orbit implementation of the increment. As Fig. 2 shows, for the original plan, the 15S stage went exactly as was planned, however, all three other stages, 10A, 1E and 1J/A, were modified due to both ground and on-orbit situations. First, stage 10A increased from 63 days to 114 days. The reason of the stage extension, as it is apparently in Fig. 2, was due to the delay of the Shuttle 1E flight. The Shuttle flight delay was due to its External Tank (ET) fuel sensors failure, which required a few weeks of troubleshooting, testing and repairing. The 1E flight delay had some major impact on the overall increment since the European science module, Columbus, was to be delivered by that Shuttle. As a consequence, the original 1E stage was reduced from 63 days to only 36 days. Many of the Columbus commissioning work and science related activities rolled over into the next stage and even into the next increment. Also, in the original plan, only 1 stage EVA was planned, but with the 1E flight delay and an on-orbit anomaly associated

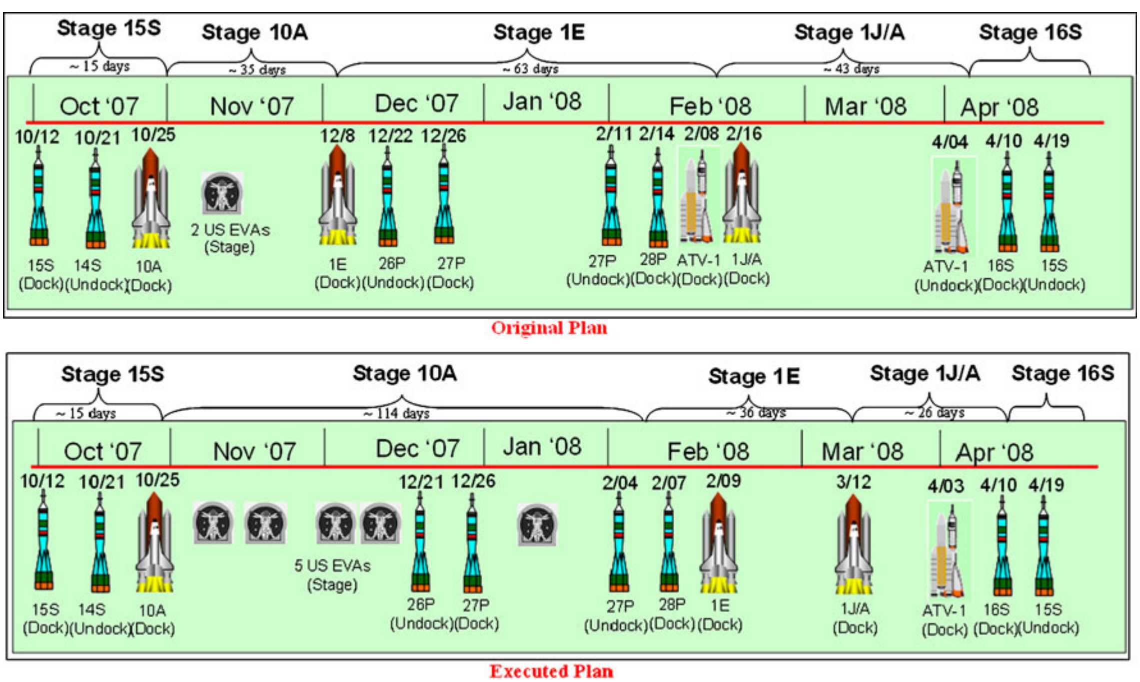

Fig. 2 Increment 16 flights/stages pre-planning vs. executed plan

with the Solar Array Rotary Joint (SARJ), which was needed for power generation, five stage EVAs were performed to take advantage of the long delay.

The EVAs were performed to attach the Pressurized Mating Adapter 2 (PMA-2) to Node 2 prior to relocating them to the US Laboratory Forward Position—thus, readying ISS to receive the European Space Agency's science module, Columbus, and later on, the Japanese Space Agency's science module, Japanese Experiment Module—Pressurized Module (JEM PM). Other objective of the additional EVAs was to investigate the SARJ on-orbit anomaly and replace the failed 1A solar array Bearing Motor Roll Ring Module. With the extension of the stage, more research was accomplished than was original planned as well. Second, as was said previously, stage 1E was reduced from 63 days to 36 days due to the flight delay, but also, the planned ATV docking activity during that stage did not occur. Third, as a consequence of the new date of flight 1E in February, which was more or less the time frame that was originally planned for flight 1J/A, flight 1J/A was, therefore, moved to March. Due to the delay with the ATV vehicle, its docking activity that was scheduled during the 1E stage did not occur not until the 1J/A stage and therefore the undocking activity previously planned during the 1J/A was rolled over to the next increment (increment 17).

In summary, the ET fuel sensors problem of the 1E flight for stage 1E caused a ripple effect throughout the rest of the increment as well as the next increment. It significantly affects crew rotations on-orbit duration stay for both 10A and 1E crewmembers, thereby research since some investigations (i.e., Life science/Human research) are directly tied to crew on-orbit duration (number of days a crew member remains in space), and some crewmembers were trained for specific investigations. It also affected some high priority commissioning work of the European Columbus Science module, which had to be rolled over into the next increment due to a very short 1E stage.

Increment 16 Research Execution

Beginning with increment 16, science planning and execution were done in an integrated manner for the USOS, as explained previously in Section USOS Integrated Research Planning and Execution, since the European Space Agency (ESA) science module was

Table 1 Investigations performed in different science disciplines during increment 16

Science disciplines	Increment 16 experiments		Comment
	New	Continuing	
Life science		NUTRITION	
		PMZ	
		EPSTEIN-BARR	
		MIDODRINE	
	Integrated immune	CCISS	
	Repository	SLEEP LONG	
	NLP VACCINE-1A	SLEEP SHORT	
	MDRV	SWAB	
	ELITE-S2	HPA	
		SLAMMD	
Fluid physics		CFE	
Space biology	MULIGEN-1		
	WAICO		
	CWRW		
Materials science	MISSE-6 (A & B)		
	INSPACE-2	BCAT-3	
	CSLM-2		
Radiation physics		STABILITY	
Space products & developments		LOCAD-PTS	
		MAUI	
		SPHERES	
	RIGEX	ANITA	
Human/environment interaction		Journals	
Education and earth observation		CSI-02 Resupply	
		CEO	
		EPO	

The list of investigations in this table does not include the exposed facilities investigations, located outside of the station

to be commissioned and activated during the 1E stage. With ESA coming onboard and JAXA science module commissioning and activation expected during increment 17, all the Partners were taking part jointly in the planning and execution process.

For increment 16, the USOS science complement requirement for on-orbit crew time was 81 h to complete all the planned investigations. Because increment 16 was very complex and heavily tilted toward commissioning tasks for the ESA science module and the preparation for the JAXA science module, not much on-orbit crew time was expected to be available for science activity. This is the reason the total planning crew time for both NASA and ESA science activities was only 81 h. However due to a very enthusiastic, efficient and fast pace working crew, a tremendous amount of science was accomplished. Never before had that much research performed during an increment which was heavily tilted toward construction activities for the two new science modules joining the station.

Table 1 shows the different investigations performed by the crew during the increment. The USOS crewmembers spent over 300 h doing science during the increment, while the original science requirement for the increment was a mere 81 h. Their science throughput, in terms of hours spent, was almost four times than planned. The crew members used their own free time, days off and weekends, as well as any spare time during working hours available to perform science. The result speaks for itself. The USOS crewmembers performed 18 investigations in Life Science, one in Fluid Physics, three in Materials Science (not counting MISSE-6, which was deployed outside the station), one in Human and Environment Interaction, three in Education and Earth Observation, three in fundamental biology, four in Space Products Development or Technology Demonstration and one in radiation. Overall, the USOS crewmembers performed 34 experiments in eight different disciplines. Below is a brief summary of the objectives, hypotheses of the phenomena investigated as well as a brief discussion of some preliminary results of the analyses whenever available for the science performed during increment 16.

Research Accomplishment During Increment 16

The main objective of this section is to give the reader an appreciation for the amount of research performed by the crewmembers during increment 16, and to briefly discuss some of these investigations objectives and expected results and/or potential science contribution to their respective science disciplines.

Life Science

In the area of Life Science, the following experiments were performed:

Nutrition

The primary objective of the Nutrition Status Assessment (NUTRITION) experiment was to test nutritional status before, during, and after long-duration spaceflight in order to understand the changes in nutrient status (i.e., folate, vitamin D, markers of oxidative damage), which will help researchers formulate better recommendations on how and when countermeasures may be necessary. This investigation allows better insight into countermeasure effectiveness. The result will define nutritional requirements for crew health during long duration space mission (Smith et al. 2008).

Repository

The objective of REPOSITORY was to develop a pre-, in- and post flight archive of human biological samples. This project collected blood and urine samples from ISS crewmembers for future scientific analysis. A “repository” is a storage bank that is used to maintain biological specimens over extended periods of time, under well-controlled conditions, for future use in approved research protocols. Biosamples and associated data are archived from long-duration spaceflight crewmembers for use as a resource for future spaceflight-related research. REPOSITORY allows the collection, processing, storage, maintenance, and ethical distribution of biosamples to meet goals of scientific and programmatic relevance to the space program. The samples are collected from crewmembers covering multiple ISS missions until the end of human presence on ISS. REPOSITORY will be a valuable resource and will provide research opportunities investigating patterns of physiological changes, analyses of components unknown at this time using techniques, methodologies and yet to be developed technologies or tools (NASA 2008).

Sleep

The main objectives of the Sleep-Wake Actigraphy and Light Exposure during Spaceflight (SLEEP) investigation was to test the hypothesis that space flight results in disruption of sleep for both short and long duration space missions and that this sleep disruption is associated with inappropriately timed (e.g., non-24 h) or insufficiently intense light exposure and that this sleep disruption and circadian misalignment will lead to subjective dissatisfaction with self-reported sleep quality and daytime alertness. To collect the needed data, the SLEEP experiment records/documents using wrist-worn Actiwatch activity-light recorders, the effects of short and long duration space flight on sleep–wake activity patterns; measure the ambulatory light-exposure of individual crew members in short and long duration space flight, using wrist-worn Actiwatch activity-light recorders; measure the effects of short and long duration space flight on crew members' subjective evaluation of the amount and quality of their sleep. Preliminary analyses for Shuttle Crewmembers suggest that astronauts obtain inadequate sleep during shuttle missions, especially on nights prior to mission critical EVAs. Prior ground-based research indicates that sleep loss, similar to that observed in the current study in-flight, produces substantial performance decrements (Czeisler et al. 2008).

CCISS

The objective of the Cerebrovascular Control on Return from the International Space Station (CCISS) was to quantify the changes that occur as a consequence of long-duration space travel that could compromise astronaut ability to maintain an upright posture and to perform physical exertion in the period immediately after return from space. Cerebrovascular responsiveness to changes in arterial blood pressure and arterial partial pressure of carbon dioxide (CO_2) was assessed. It is anticipated that the ability to regulate blood pressure through baroreflex control of blood vessel constriction will be impaired after space flight. Similarly, it is expected that brain blood flow will be more sensitive to changes in arterial blood CO_2 and thus will not be as tightly regulated after space flight. There are many patients with postural hypotension due to a wide range of factors including deconditioning resulting from bed rest or inactivity, and from disease states such as autonomic failure. It is hoped that the better understanding of mechanisms that will be gained from this investigation of long duration space flight crewmembers might benefit these individuals as well. The main long-term outcome of this investigation will be the development of appropriate countermeasures against dizziness or fainting when long-duration crewmembers return to earth (1-g condition). The side benefit of this research applies to the day-to-day lives of millions of elderly people in our society (Hughson et al. 2008).

Midodrine

The objective of the MIDODRINE investigation was to evaluate a new pharmacological countermeasure for protection from post flight orthostatic hypotension. Following exposure to spaceflight, upright posture can result in the inability to maintain adequate arterial pressure and cerebral perfusion (orthostatic or postural hypotension). This may result in presyncope (light-headedness) or syncope (loss of consciousness) during re-entry or egress. A significant number of astronauts experience post flight orthostatic hypotension and pre-syncope during upright posture. The severity of this problem increases with increasing length of exposure to weightlessness. About 20–30% of short-duration and 83% of long-duration crewmembers have this problem. It is expected that orthostatic hypotension will be severe on flights associated with exploration class missions. This experiment was designed to evaluate a new pharmacological countermeasure (Midodrine) for protection from post flight orthostatic hypotension. This experiment measured the efficacy of Midodrine taken in-flight, between time of ignition (TIG) and landing, in reducing the incidence and/or severity of orthostatic hypotension in returning astronauts. It is expected that use of Midodrine, an α-adrenergic agonist, will support standing arterial blood pressure and thereby reduce incidence of post flight orthostatic hypotension. Its efficacy will be evaluated with an expanded tilt test (Platts 2008).

Integrated Immune

The main objective of the INTEGRATED IMMUNE was to determine immune status, as it equilibrates over long duration space flight free from launch and landing influences. Stress, immune function and latent viral reactivation were all measured during both short and long duration space flight. In-flight data were compared to preflight baseline data and post-flight recovery data to ascertain immune alterations associated with the in-flight condition. It is known that the immune system is altered during space flight. Some specific aspects of spaceflight-associated immune-dysregulation will persist over the course of long-duration mission, while other aspects are associated with transient launch/landing stress and will resolve during longer missions. The determination of immune status during long-duration flight will allow an assessment of clinical risk related to immunity for exploration class missions. Also, a monitoring strategy will be developed that will allow the evaluation of potential immune-related countermeasures. Finally, the result will provide new insights into the mechanisms of immune dysregulation, physiological stress and latent viral reactivation (Sams et al. 2008).

EPSTEIN-BARR

The objective of the Spaceflight-Induced Reactivation of Latent Epstein–Barr Virus (EPSTEIN-BARR) experiment was to address fundamental questions on spaceflight and virus-specific immunity. It characterized Epstein–Barr virus (EBV) reactivation using serological and molecular techniques; determined virus specific T-lymphocyte immuno-competence, and measured stress hormones in plasma and urine. Previous flight studies have demonstrated that decreased cellular immunity can occur in space. These changes may be associated with increased risk of opportunistic infections such as those caused by herpes-viruses. Epstein–Barr virus (EBV), a member of the herpes-virus family, infects greater than 85% of the adult population. Since severe clinical symptoms have been associated with reactivation of EBV in patients with defective cellular immunity, EBV reactivation may have important health consequences during long-term space flights. This investigation hypothesized that the combined effects of weightlessness along with associated physical and psychological stress will decrease EBV-specific T-cell immunity and reactivate latent EBV in infected B-lymphocytes. This research will provide new insights into the mechanisms of EBV reactivation and shedding in space flight. In addition, this research may provide important information about the fundamental mechanisms underlying immunological changes which may lead to a better understanding of latent herpes-virus reactivation in humans living on Earth (Stowe et al. 2008).

MDRV

The objective of the Microbial Drug Resistance and Virulence (MDRV) investigation was to assess the ability of spaceflight to elicit alterations in virulence parameters. During long duration spaceflight, the virulence of pathogenic microbes will be enhanced and normally harmless microbes will become pathogenic. In addition, infections with these microbes will be more difficult to treat using conventional antibiotic or antifungal drugs. This investigation also allowed for testing a new hypothesis, specifically that the salt composition of the nutrient media plays a role in virulence in this organism. Information gained from this investigation will be beneficial in assessing microbiological risks and options for reducing those risks during crew missions. The result will ultimately provide significant insights into the molecular basis of microbial virulence. Once specific molecular targets are identified, there is the potential for vaccine development and other novel strategies for prevention and treatment of disease caused by these microbes both on the ground and during spaceflight. Finally, results from this experiment will help scientists more clearly understand measures that should be taken to reduce the risk of infection and contraction of disease while in space (Nickerson et al. 2008).

NLP Vaccine-1A

The objective of the National Laboratory Pathfinder (NLP) Vaccine-1A investigation was to verify what has previously been demonstrated in spaceflight studies that changes in bacterial and fungal growth rates and changes in drug resistance also apply to *Salmonella enterica*. NLP-Vaccine-1A begins a series of studies growing *Salmonella enterica* in space to affect its virulence (infection potential) to ultimately develop a vaccine for the prevention of infections from *Salmonella enterica*. The *Salmonella* grown in space experienced an increase in bacterial potency, also referred to as virulence, as observed in its affect on the model target organism, *C. elegans*. There is currently no vaccine available for the strains of Salmonella which cause diarrhea for public use in humans. This research may help develop vaccines against this life threatening organism (Hammond 2008).

PMZ

The primary objective of the Promethazine (PMZ) investigation was to establish dose–response relationship of PMZ before and during flight and estimate bioavailability of PMZ during flight. To compare and contrast the effect of flight-related variables (e.g. space motion sickness (SMS), mission duration, sleep medications, and crew activity schedules) and PMZ administration on sleep quality and efficiency. PMZ is currently used to treat space motion sickness (SMS) during Shuttle Missions. However, side effects associated with PMZ when used on Earth include dizziness, drowsiness, sedation, and impaired psychomotor performance, which could impact crew performance or mission operations.

Early anecdotal reports from crewmembers indicate that these central nervous system side effects of PMZ are absent or greatly attenuated in a weightless environment. Therefore systematic evaluation of PMZ bioavailability, effects on performance, side effects and efficacy in the treatment of SMS are essential for determining optimal dosage and route of administration of PMZ in-flight (Putcha 2008).

SWAB

The objective of the Surface, Water and Air Biocharacterization (SWAB) experiment was to examine the microbial environment of the station in order to assess the impact of the weightless environment on microbial growth. The result will assess and quantify the risks of pathogens to astronauts on long duration flight (Pierson et al. 2008).

HPA

The main objective of the investigation Hand Posture Analyzer (HPA) was to assess the performance of the upper limb, especially during grasp in a weightlessness environment. Accumulated evidence, based on information gathered on space flight missions and ground based models involving both humans and animals, clearly suggests that exposure to states of weightless conditions for varying duration induces certain physiological changes; they involve cardiovascular deconditioning, balance disorders, bone weakening, muscle hypotrophy, disturbed sleep patterns and decrease immune responses. This research investigated the performance degradation of the human upper limb muscle-skeletal apparatus and its morphological functional modifications during long term exposition to weightlessness and the role of gravity in the planning and execution hierarchy of reaching, grasping, manipulating and transporting objects in order to perform fatigue assessment and grip precision (Lacquaniti 2008).

ELITE-S2

The objective of the investigation Elaboratore Immagini Televisive for Space (ELITE-S2) was to study the connection between brain, visualization and motion in a weightless environment. It has previously shown that an internal model of Earth's gravity affects automatic motor control, but what is not known is whether it affects as well cognitive processes such as mental imagery. Can the lack of gravity be imagined? Is there a progressive adaptation of the gravity model to long-term weightless exposure? How do astronauts coordinate posture and movement in such environment? How are multiple degrees of motion organized to compensate inertial interactions and limit the required muscle effort to fracture the ankle? By recording and analyzing the three-dimensional motion of astronauts, the results of this investigation will yield a better understanding of basic mechanisms of motor control, and will be applied toward astronaut training and ergonomic design for future spacecraft components (Jules et al. 2007).

MOP

The objective of the in-flight questionnaire Motion Perception: Vestibular Adaptation to g-transition (MOP) was to gain specific insight in the process of vestibular adaptation to a gravity transition. The adaptation is assessed by rating motion perception as a result of body movements. The MOP investigation also correlates susceptibility to Space Adaptation Syndrome (SAS) with susceptibility to Sickness Induced by Centrifugation (SIC). In addition to in-flight questionnaires, extensive tests are performed on a ground centrifuge.

Low Back Pain

The objective of the LOW BACK PAIN: "Study of Lower Back Pain in Astronauts during Spaceflight" in-flight questionnaire investigation was to investigate the development of lower back pain in crewmembers during spaceflight and determining if there is a relationship to muscle atrophy.

ZAG

The objective of the Ambiguous Tilt and Translation Motion Cues After Space Flight (ZAG) investigation was to address the physiological basis for disorientation and tilt-translation disturbances reported by crewmembers when making head movements following re-entry into Earth's atmosphere, and to evaluate adverse operational implications of these disturbances. The first specific aim of the ZAG experiment was to examine the effects of stimulus frequency on adaptive changes in eye movements and motion perception during combined tilt and translation motion profiles.

Neocytolysis

The objective of Effects of Microgravity on the Haemopoietic System: "A study on Neocytolysis" (NEOCYTOLYSIS) investigation was to study and develop countermeasures against the symptomatic anaemia that has been detected from Astronauts upon returning from spaceflight. For decades, it has been repeatedly demonstrated that astronauts upon return to earth from spaceflight, even for short spaceflights, show a significant, symptomatic anaemia. A previously unsuspected physiologic process that selectively haemolyses the youngest circulating red blood cells under conditions of red cell excess, termed neocytolysis is responsible for this change. Based on simple pre-/post-flight blood draws, the NEOCYTOLYSIS investigation will probably lead to treatments of different types of anaemia, especially those related to renal failure or acute infections.

SLAMMD

The objective of the Space Linear Acceleration Mass Measurement Device (SLAMMD) investigation was to measure the on-orbit mass of the crewmembers by applying Newton's Second Law of Motion (force is equal to mass times acceleration). Two springs generate a known force against a crewmember mounted on an extension arm. The resulting acceleration of the subject, measured by an optical instrument which tracks the subject's position and time along the SLAMMD guide arm, is used to calculate the subject's mass.

Human and Environment Interaction

In the area of Human and Environment Interaction, the following experiment was performed.

JOURNALS

The objective of the Behavioral Issues Associated with Long Duration Space Expeditions: Review and Analysis of Astronaut Journals (JOURNALS) investigation was to obtain behavioral and human factors data relevant to the design of equipment and procedures to support adjustment and sustained human performance during long duration isolation and confinement. It is expected that the results will quantify the relative salience of behavioral issues on the station; identify specific factors that contribute to adjustment and sustained performance; and recommend guidelines for the design of procedures, equipment, and facilities for the lunar and planetary exploration. Also, the results will provide quantitative data on which to base decisions concerning the priority that should be placed on the various behavioral issues to prepare for lunar and planetary expeditions and to sustain human performance (Stuster 2008).

Radiation

In the area of Radiation, the following experiment was performed:

Stability

The objective of the investigation Stability of Pharmacotherapeutic and Nutritional Compounds (STABILITY) was to quantify the breakdown of key drugs and vitamins that were observed anecdotally on previous ISS missions due to the effect of radiation on complex organic molecules (e.g., vitamins). One (of four originally launched) identical package of pharmaceuticals and foods remains inside the ISS during the length of this increment, experiencing the internal environment. The result will help assess suitable countermeasure for developing more stable and reliable pharmaceutical and nutritional product for long duration mission (Putcha et al. 2008).

Fundamental Biology

In the area of Space Biology, the following experiments were performed:

Multigen-1

The objective of the Molecular and Plant Physiological Analyses of the Microgravity Effects on Multi-Generation Studies of Arabidopsis thaliana on the International Space Station (MULTIGEN-1) investigation focused both on seed production and bi-dimensional and tri-dimensional reconstructions of plant stem circumnutations and rosette leaf movements with *Arabidopsis thaliana* plant model. Unfortunately due to technical problems with the on-orbit hosting facility, not all the goals planned for MULTIGEN-1 were obtained, especially the production of second generation seeds.

WAICO

The objectives of the Waiving and Coiling of Arabidopsis roots: Interaction of circumnutation and gravitropism in 1-g and uncoupling at microgravity (WAICO) investigation were to understand the interaction of circumnutation and gravitropism, by observing the waiving and coiling of Arabidopsis thaliana wild type and an agravitropic mutant in two subsequent runs at different g-level stimuli. After a 2-week normal growth period of the plants, some functional issues were encountered with the facility automatic chemical fixation system, so the primary objective of the experiment could not be achieved. Plants were nevertheless returned to ground at cold temperature for detailed laboratory analysis, leading to interesting findings for the second WAICO science run planned in the near future.

CWRW

The Reverse Genetic Approach to Exploring Genes Responsible for Cell Wall Dynamics in Supporting Tissues of Arabidopsis under Microgravity Conditions and Role of Microtubule-Membrane-Cell Wall Continuum in Gravity Resistance in Plants (CWRW) investigation was actually two investigations (Cell Wall and Resist Wall) combined into one. The objective of the Cell Wall investigation was to study the molecular mechanism by which the cell wall (rigid outermost layer) construction in Arabidopsis thaliana (a small plant of the mustard family) is regulated by gravity. More specifically, the investigation was designed to test the hypothesis that the supporting tissues in plants are formed due to coordinated actions of a defined set of cell-wall related gene families and that their gene expressions are precisely regulated by gravity signal in such a way to adapt terrestrial atmospheric environment under 1 *g* gravity conditions.

The second part of the investigation sought to determine the involvement of the microtubule-plasma membrane-cell wall continuum in resistance of plants to gravitational force, thereby clarifying the mechanism of gravity resistance. The functions of cortical microtubules, the plasma membrane, and the cell wall are mutually dependent, and thus the structural or physiological continuum of microtubule-plasma membrane-cell wall is responsible for plant resistance to the gravitational force.

The results of these investigations were to support future plans to cultivate plants on long-duration missions to the Moon and Mars. Unfortunately, due to hydration problems associated with the on-orbit facility where these two experiments were being performed, not all the goals planned were achieved. The rosette leaves of six seedlings were harvested and fixed in either RNALater or in formaldehyde in KFT container. Although rosette leaves of MG-wild plants were recovered, but no specimen for analysis of inflorescence stem was obtained. Characterization of the mRNA expression profile in the rosette leaves is in progress as well as the characterization of immune-histochemical localization of GUS proteins and cell wall components, including specific polysaccharides and cell wall proteins.

Fluid Physics

In the area of Fluid Physics, the following experiment was performed:

CFE

The objective of The Capillary Flow Experiment (CFE) was to advance the development of design method to exploit wetting characteristics and system geometry to manage liquid inventories aboard spacecraft. Two aspects were investigated for this experiment: (1) CFE Vane Gap 1 and (2) CFE Contact Line.

CFE Vane Gap 1 The CFE Vane Gap 1 experiment probed a critical wetting phenomenon that occurs as a result of subtle changes in container shape. Surface tension and viscosity affect the rate the fluid moves, but not the fact that it moves; the latter is determined only by the fluid wetting properties and the container shape. Since it cannot be predicted when the 'critical vane wetting' takes place analytically—and that's a problem because such constructs are common in large fuel tanks—the CFE Vane Gap 1 was designed in part to verify such numerical predictions experimentally. The CFE Vane Gap 1 experiment investigated a critical geometric wetting phenomenon using a right cylinder with elliptic cross section and a single central vane that does not contact the container walls.

(2) CFE Contact Line The primary objective of the Contact Line was direct comparison of the extremes in contact line boundary condition, free and pinned. The moving contact line boundary condition is critical to modeling the dynamics of large inventories possessing capillary surfaces in low-gravity environments. The contact line controls the interface shape, stability, and dynamics of capillary systems in low-g. The CFE-Contact Line investigation provided a direct measure of the extremes in behavior expected from an assumption of either the free or pinned contact line condition.

The CFE investigation has direct application to many systems onboard a spacecraft such as storable liquid fuels and cryogens, life support systems (e.g., water processing system), phase change thermal system, daily fluid management and, probably, bio-fluid transport phenomenon. Results of this investigation will shed light on understanding better the fundamental capillary phenomena, which will help minimize system failure and enhance system reliability and performance and add robustness to the system design. Results obtained so far helped develop spontaneous capillary flow model to predict 3-D geometric effects on complex containers for passive management of fluid onboard spacecraft as well as for modeling passive phase separations, transport, and interphase stability for a variety of system disturbances, container types, wetting and fluid properties (Weislogel et al. 2008).

Materials Science

In the area of Materials Science, the following experiments were performed:

MISSE-6

The objective of the Materials on the International Space Station Experiment-6 (MISSE-6) was to expose current and future generation space solar cells materials to the space environment and to provide validation data for these technologies. This experiment was deployed outside the ISS in order to assess the impact of the space environment (vacuum, solar radiation, atomic oxygen and micrometeorites) on the samples. Two hundred advanced space materials samples were attached to thermal blanket to test the effect of space exposure on them, which was determined by comparing pre and post flight laboratory characterization test data. Excellent agreement was found between on-orbit and ground test data. The data obtained indicated that the materials samples performed nominally with no indication of degradation (Walters 2008).

BCAT-3

The primary objective of the Binary Colloidal Alloy Test-3 (BCAT-3) was to study mixtures of polymers and colloids that, depending on their composition, either remain homogeneous indefinitely, or immediately start separating into two phases, like salad dressing left to sit. The results obtained so far from the ISS show surprising rates for phase separation kinetics in a low gravity environment and these rates were observed for weeks. Surface crystals did not form in the low gravity environment where conditions were different (Weitz et al. 2008).

INSPACE-2

The objective of the Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions (INSPACE-2) investigation was to obtain fundamental data of the complex properties of a class of smart materials known as Magnetorheological (MR) fluids. These fluids exhibit a rapid transition from a liquid- to solid-like state upon the application of a magnetic field. An important feature of these fluids over conventional mechanical devices is their ability to achieve a wide range of viscosities in a small fraction of time. These rapid, reversible changes in viscosity can be used to effectively control vibrations in applications dealing with actuation, damping, and robotics. Basically, this investigation sought to understand the “gel point” or rheological cross-linking transition of MR suspensions in microgravity and the behavior of structures around this point (incipient structure). The fluctuations of these chains can also be used to estimate the microrheological response of the MR fluid. Additionally, measurements of the chain fluctuations in the final gelled material provide an estimate of the storage modulus of the suspension.

Preliminary results for the pulsed field phase showed fascinating column buckling. Investigation of the dynamics of this buckling instability is important for the understanding of the solid like behavior of the MR structures, since knowledge of their elastic properties can be extrapolated to well known theories for elastic solids. The novel morphology and dynamics observed so far from the data points to a markedly different behavior of MR fluids in microgravity. Understanding this behavior is vital to determining the performance of MR fluids for space applications.

Results of this investigation can impact a wide area of applications such as microfluidic devices using tunable suspensions, robotics, clutches, engine mounts, aircraft landing gears and seismic dampers as well as break systems and seat suspension. Preliminary results obtained so far suggest that effect of gravity on magnetic emulsions aggregates involves surface effects; columns grew initially as on ground; coarse structures took on “interesting” shapes and dynamics and results showed wetting/dewetting during pulses (ejection of small aggregates) (Furst et al. 2008).

CSLM-2

The objective of the Coarsening in Solid-Liquid Mixtures-2 (CSLM-2) investigation was to support the development and accuracy of theoretical models of the Oswald Ripening (coarsening) process. The CSLM-2 investigation sought to determine the coarsening rate of various volume fraction samples without the phenomena of convection and sedimentation influencing the arrangement of particles in the two-phase mixture. During coarsening, the small particles of tin shrink by losing atoms to the larger tin particles within the liquid matrix.

Results obtained from this investigation will determine the factors controlling the morphology of solid-liquid mixtures during coarsening. The steady state dependence of the rate constant, particle size distribution and particle spatial distribution on the volume fraction of the coarsening phase will be determined for a two phase eutectic mixture. This research has direct applications to metal alloy manufacturing on Earth, including materials critical for aerospace applications. The results will provide predictive capability to custom design alloy systems with the desired traits. The results will be used in design codes to improve manufacturing capabilities (Voorhees 2008).

Space Products and Development or Technologies Development

In the area of Space Products and Development or Technologies Development, the following experiments were performed:

LOCAD-PTS

The objectives of the Lab-On-a-Chip Application Development—Portable Test System (LOCAD-PTS) were to conduct a general survey of endotoxin within the USOS cabin environment and to verify that reagents onboard were clean. The ISS remains a unique opportunity to gather data, pre-flight and in-flight, and test procedures to monitor forward contamination that will support the human exploration of the Moon and Mars. While many techniques are available today for rapid bio-molecular analysis, few, if any, have been tested and verified to function in microgravity and in a space mission environment.

Prior to this investigation, there was no on-board analysis of endotoxin on ISS surfaces and the levels were simply unknown. Extensive and highly valuable microbiological analysis has been performed on returned samples, but not yet onboard. Given that much can happen to samples between sample collection on ISS and analysis in a lab on Earth (e.g. cell death, growth, contamination), the approach of LOCAD has been to transfer the site of analysis from Earth to space, and let the crew be the scientists; especially important for exploration missions, when samples analysis will have to be done in-situ.

The results obtained by this investigation will have relevance to exploration missions by helping determine appropriate forward contamination requirements for human space exploration of the lunar and Martian surfaces (Maule et al. 2008).

SPHERES

The objectives of the Synchronized Position Hold, Engage, Reorient, Experiment Satellites (SPHERES) investigation were twofold: to demonstrate docking and formation flight inside the USOS for single and/or multiple satellites.

For satellites docking: the objectives were (a) to demonstrate autonomous docking to a tumbling (nutating) target in the presence of simulated sensor and actuator faults. Mature the algorithms by demonstrating an integrated system (integrate estimation, control, autonomy, and artificial intelligence algorithms) in a representative environment. (b) To demonstrate the use of safe docking trajectories which guarantee that uncontrolled contact between two satellites will not occur in the case of failures in the actuators. (c) To demonstrate the ability to autonomously assemble large space structures by docking together modules of similar masses using only one actuating module (a tug), which reconfigures its control parameters after each docking operation. Mature the reconfiguration algorithms by integrating autonomy (Mass-ID) and path-planning to basic estimation and control. (d) And finally, to research close proximity operations for tasks such as satellite inspection (without actual docking), maintenance, and repair.

For formation flight: the objectives were (a) to Investigate different control algorithms to create formation flight systems usable for separated space telescopes or space-based radar, including algorithms for plane coverage, plane precession, and fuel balancing. (b) To demonstrate formations relevant to the Terrestrial Planet Finder mission and other space-based optical telescopes (e.g., the Stellar Imager). (c) To demonstrate and mature path planning algorithms for changing formation configurations autonomously while avoiding collisions and any uncontrollable obstacles, and maintaining mission constraints such as restricted pointing (e.g. sun avoidance).

These maneuvers need to be performed for cases relevant to both precision flying formations (e.g., space telescopes) and fractionated spacecraft which do not require precise formation but require high availability of the multi-satellite system.

The following results have been obtained or successful demonstrated so far:

1. On-line path planning demonstration of docking to a fixed target, including obstacle avoidance (multiple space firsts)
2. 1 kHz closed loop ΔV control demonstrations

3. Demonstrated control of two docked spacecraft with joint thruster firing (space first)
4. Performed a "mesh" inspection simulation visual-based navigation.
5. Fractionated spacecraft and formation flight demonstrations of:
   - Formation initialization.
   - Formation scatter (space first)
6. Docking to a tumbling target: simulated docking to an uncooperative target rotating at a constant speed with the docking port in the same plane as the rotation.
7. Plume impingement demonstrations: first ever demonstration where a spacecraft is allowed to drift on purpose in order to demonstrate the effects of plume impingement as the chaser craft approaches and slows down.
8. Safe docking: demonstration of advanced docking trajectories designed to prevent uncontrolled collision between two spacecraft in the presence of thruster failures (stuck off)
9. On-line path planning: autonomous docking to an obstacle with a target pointing away from the chaser, including path update before berthing

The results obtained from this applied research will have significant impact on future space missions, assembly of inter-planetary stacks and of space telescopes to name a few applications (Miller et al. 2008).

MAUI

The objective of the Maui Analysis of Upper Atmospheric Injections (MAUI) investigation was to better understand the interaction of engine firings in the upper atmosphere by measuring the visible and near infrared emissions of the thruster plume. The main task was to measure plumes from the shuttle Primary Reaction Control System (PRCS) and the Vernier Reaction Control System (VRCS) for a controlled sequence of burns. A secondary goal was to investigate the ionospheric effects caused by large Orbiter Maneuvering System (OMS) burns using ground-based optical and radar systems. Earlier Shuttle missions indicated a rich variety of effects emanating from the interaction of engine exhaust with the upper atmosphere in the shuttle low earth orbit (200–400 km).

The GLO-2 instrument on STS-63 in February 1995 observed spectral emissions from molecules excited by the hyper-thermal interaction of the exhaust with the tenuous upper atmosphere. The exhaust from the monomethyl hydrazine and nitrogen tetroxide bipropellant reaction exits the shuttle at a speed of 3 km/s and interacts with the atmosphere that is moving at about 7.5 km relative to the shuttle (pseudo "atmospheric wind"). Depending upon the angle of attack of the exhaust, the available energy of collision varies and different excited molecules can be produced and emit at characteristic frequencies.

The results of the MAUI burn observation experiments will be used to improve sensors and plume models for space surveillance (Winick 2008).

RIGEX

The main objective of the Rigidizable Inflatable Get-Away-Special Experiment (RIGEX) investigation was to demonstrate the use of rigidizable/inflatable technology in the Shuttle Cargo Bay. Current payloads are often limited in size due to limited launch vehicle dimensions. For this experiment, the deployment and structural characteristics of three test specimens when deployed in a zero-gravity space environment were investigated. The overall goal was to demonstrate the feasibility of using rigidizable/inflatable materials to create lightweight space structures which can then be used for a variety of remote sensing applications. The objective was to successfully heat and inflate three 20 in. long carbon fiber tubes in the microgravity environment and then measure their structural characteristics and physical deployed configuration. Three separate but identical tube deployments were conducted as part of the experiment. An additional objective was to return the inflated tubes to the laboratory for post-flight characterization. Results obtained from this investigation will help alleviate size limitations for future missions (Cobb 2008).

Education and Earth Observation

In the area of Education and Earth Observation, the following experiments were performed:

CEO

The Crew Earth Observations (CEO) investigation objective was to obtain quantifiable data sets, via on-orbit photographies, that document changes in cities; Asian deltas; climate variability as indicated by water levels in lakes in South America, Africa, Australia, North America and the Middle East; the health of Pacific ocean coral reefs; ecological preserve sites; aerosols; and the extent of glaciers and ice packs. Crewmember takes a number of photos of designated targets each week during that crewmember's stay onboard the station.

One hundred and seventy three sites were identified to document changes. In addition, dynamic Earth processes such as large-scale flooding and droughts, tropical storms, extensive areas of fires and smoke, and volcanic eruptions were transient phenomena that were also requested to be documented as they were taken place. Since Increment 1, over 308,000 images of the Earth have been taken from the ISS. Increment 16 crewmembers added 19,890 additional Earth images to that growing number of images cataloging the changing face of our planet (Runco et al. 2008).

EPO

The objective of the Educational Payload Operations (EPO) was to help students discover how familiar objects may perform differently in the low gravity environment onboard the ISS. An additional objective was to provide students and educators with a look at what it takes to work and live onboard the International Space Station. A total of four such activities were performed by the crewmembers during the increment. a) Sanitation on Station: described how crewmembers keep the ISS sanitary. b) ISS Living Area Tour: gave a video tour of ISS, while describing the living area onboard the station. c) Newton's Laws and Rotation: discussed Newton's Laws and rotation in microgravity. d) INSPACE: the crewmember described the INSPACE investigation's hypothesis/objectives and showed the facility in which it was being performed, expected results and potential applications of the expected results.

CGBA

The Commercial Generic Bioprocessing Apparatus (CGBA) Science Insert-02 (CSI-02 Resuply) was a collection of small education experiments and ecosystem habitats that were housed and processed within the CGBA-5. The primary objective of the CSI-02 was education. During Increment 16 CSI-02 contained 4 experiments utilized by students, but also provided scientific value to the life science community. The experiments conducted for CSI-02 were designed primarily to meet education objectives relating to science, technology, engineering and math. However, to the maximum extent possible, meaningful scientific research was conducted to generate new knowledge into gravity-dependent biological processes and to support future plans for human space exploration.

Each experiment was designed to be easily reproducible in the classroom providing hands-on experience to the students. One experiment examined seed germination in microgravity. A second experiment examined crystal formation using silicate (compounds containing silicon, oxygen and one or more metals). The third experiment utilized Yeast cells to examine the specific genes that give cells a survival advantage or disadvantage in the microgravity environment. The last experiment examined cell differentiation and gene expression in plant cells grown in space.

CSI-02 potentially impacted over 500,000 students ranging from elementary to high school all over the world. Reports from teachers indicated the kits and involvement in analyzing the spaceflight images sent to classrooms were a great success with students. The objectives of the seed germination experiment were not met due to lack of germination. Corrective measure is to launch a pre-assembled Petri Dish containing seeds sown on ground.

The principal objective of Cell Culture experiment was to evaluate whether cells of a monocotyledonous and a dicotyledonous plant could develop normally from the transitional stage into normal somatic embryos under space (microgravity) conditions. A first glance at the returned samples indicated this to be true in spite of some contamination in one of the Opticells. Histological and genetic analyses are on-going. The Yeast experiment examined the global effects of spaceflight on microbial gene expression. Hence, this study was aimed to determine the contribution and relative importance of every gene in the genome to cell survival during space flight. The availability of survival data on all yeast strains should greatly facilitate the comparison to mammalian gene analogues. Pathways analyzed included, but were not limited to, radiation repair pathways, and pathways implicated by earlier data as mediating effects of microgravity on mammalian cells. Analysis is on-going. The silicate crystals (Silicate Garden) experiment sought to shed light on the growth mechanisms of crystalline fibers, utilizing a combination of data gathered from real-time images downlinked from space and data collected from the specimens themselves once they return to Earth. Analysis is still on-going. Reports from teachers indicated that over 4,000 students participated in that experiment (Stodieck 2008).

Exposed Facilities

During increment 16 two external ESA research facilities were mounted on the Columbus modules external frame. They were commonly referred to as "Exposed Facilities" because they were exposed to the external environment or space. The research complement contained in these two facilities was non-crew tended, and therefore was controlled remotely from ground. These two facilities were the Sun Monitoring on the External Payload Facility of Columbus (SOLAR) and the European Technology Exposure Facility (EuTEF).

The SOLAR platform was deployed for a 2-year mission. It was located on the Columbus External Payload Facility zenith position (i.e. pointing away from the Earth). The SOLAR research platform consisted of three spectrometer instruments complementing each other to allow measurements of the solar spectral irradiance throughout virtually the whole electromagnetic spectrum—from 17 nm to 100 μm—in which 99% of the solar energy is emitted. The three complementary solar science instruments were: SOVIM, "*Solar Variable and Irradiance Monitor*", SOLSPEC "*Solar SPECtral Irradiance measurements*" and SOL-ACES "*Solar Auto-Calibrating Extreme UV/UV Spectrophotometers*". While SOVIM and SOLSPEC are upgraded versions of instruments that have already accomplished several space missions, SOL-ACES is a newly developed instrument.

The European Technology Exposure Facility (EuTEF) houses experiments requiring exposure to the space environment. The experiments and facility infrastructure were accommodated on the Columbus External Payload Adaptor (CEPA), consisting of an adapter plate, the Active Flight Releasable Attachment Mechanism and the connectors and harness. The experiments were mounted either directly on the Adapter plate or a mechanical support structure that elevates them for optimum exposure to the direction of flight or pointing away from the Earth. EuTEF is a programmable, fully automated, multi-user facility with modular and flexible accommodation for a variety of technology payloads.

The deployed configuration of EuTEF during this increment housed nine different instruments. The suite of experiments consists of: MEDET "*Material Exposure and Degradation Experiment*"; DOSTEL, "*Radiation Measurements*"; TRIBOLAB, "*Test bed for the tribology properties of materials in space*"; EXPOSE, "*Photobiology and Exobiology*"; DEBIE-2, "*micro-meteoroid and orbital debris detector*"; FIPEX, "*Atomic oxygen detector*"; PLEGPAY, "*Plasma Electron Gun payload for plasma discharge in orbit*"; EuTEMP, an experiment candidate to measure EuTEF's thermal environment during un-powered transport during ascent and descent phases to/from ISS; finally EVC, "*Earth Viewing Camera*".

In addition to these two exposed facilities, MISSE-6, a materials science experiment from NASA was also deployed on the Columbus external frame.

Research Planning and Execution During Increment 17

This section focuses on the research planning and execution for increment 17

Increment 17 Research Planning

Increment 17 science complement planning was no different than previous increments in terms of changes that happened during the planning cycle due to vehicles traffic schedule and additional EVAs needed to address on-orbit developing anomalies. Figure 3 shows the original plan for the increment, top panel of the graphic. The increment had three stages: 16S, 1J and ULF-2 stages, with approximate number of days for each stage (for example, approximately 153 days for the 1J stage). The increment had two station Shuttle flights, three Progress cargo flights and the normal Soyuz exchange flights. (The Shuttle Hubble Space Telescope (HST) flight was not a station flight, but a flight dedicated to the repair of the Hubble Space Telescope.) There were two EVAs at the latter half of the increment. Mid-way in the planning cycle, some changes were made to accommodate the vehicles traffic schedule. The 1J Shuttle and the Progress 31P flights were moved from the April and August time frame to May and September, respectively. In addition, the Shuttle ULF-2 flight was removed from the increment and the two EVAs were reduced to one at an earlier date, see middle panel of the graphic in Fig. 3. One consequence of these changes was that the 16S stage increases in duration as well as the 1J stage, while the ULF-2 stage was completely eliminated.

By the time the increment entered its real time phase or execution phase two additional changes were made to the plan. First, the Progress 31P flight was removed and 30P was moved to the September spot. Second, the ATV-1 vehicle undocking that was supposed to take place during increment 16, but was delayed, was added for early September in this increment. Therefore, ATV-1 was on-orbit during much of increment 17. In addition to these two changes, the 1J Shuttle flight was delayed by a few days, and one more EVA was added to the plan to inspect the docked Soyuz vehicle in order to understand the reason why the last Soyuz re-entry and landing, at the end of increment 16, did not go as planned. Additionally, the Shuttle repaired mission of

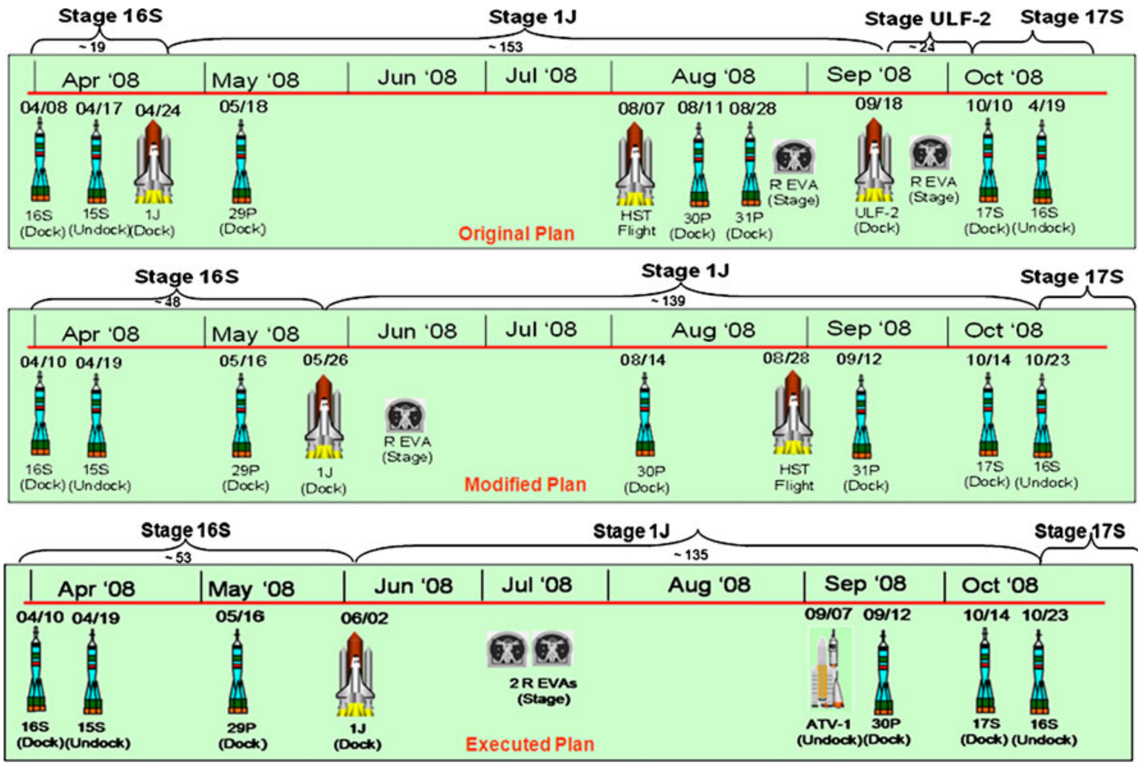

Fig. 3 Increment 17 flights/stages pre-planning vs. executed plan

the Hubble Space Telescope was removed from this increment, see bottom panel of graphic in Fig. 3.

The overall impact of these changes was that the experiments that were supposed to be delivered by the ULF-2 Shuttle flight and operated during the ULF-2 stage had to be removed from the science complement. Since crew rotation was also affected, because of the flight deletion, any Human research investigation that was linked to such crew rotation had to be deleted. The same was true for any experiment that was supposed to be delivered by the Progress 31P flight and operated during the increment. Additionally, the two back to back EVAs that were now scheduled impacted significantly the research activities since significant amount of crew time was required for the crew to be trained on-orbit, to plan, prepare and execute the EVAs (it takes about 80–100 h of crew time per EVA—of course, depending of the EVA). These two EVAs, however required much more crew time than any previous EVA because the entire station had to be configured into unmanned configuration, which means that all the modules had to be sealed (except for the Russian module) because there was no crew inside the station during the EVA. Two crew members were outside working on the Soyuz vehicle and the other one was isolated inside the Soyuz vehicle.

To configure the station into unmanned configuration and isolated the other crew member inside the docked Soyuz vehicle required significant amount of crew time, when taking into consideration the current size of the station. Consequently, no research could be performed during that time frame. Also, with the ATV-1 undocked activity added in the increment, science activity got impacted since it required about 31 h of crew time to perform ATV-1 transfer activity, unloading and loading, before its undocking. Again, science was impacted. However, the deletion of the ULF-2 flight from the increment offered opportunity to do some research since the crew preparation work required for the arriving vehicle was postponed.

Increment 17 Research Execution

The main activity that affected science execution, in addition to the activities discussed in the previous section, was the completion of the JAXA JEM Pressurized Module (PM) commissioning and activation in order to get that module ready to support the JAXA science complement for this increment. For increment 17, the ISS program allocation, in terms of crew time availability, given to perform science was 165 h. However, during the integrated planning activity, where all activities that required crew time are accounted for, only 147 h of science activities were accommodated. The science complement required 165 h of crew time to complete the high priority investigations. Additionally, another 200 h of crew time were needed for science activities that could not be accommodated due to lack of crew time. That category was called “reserve experiments”. Those were investigations that were available to be performed in case some crew time became available due to deletion of other planned activities during the execution phase.

Table 2 shows the different investigations performed by the crew during the increment. The crew devoted a total of 202 h performing science during the increment. Out of these 202 h, 154 h were used to performed science as part of crew daily scheduled activities. Again, when the integrated crew time on-orbit plan was formulated before the start of the increment, only 147 h were possible to be accommodated, but the crew used 154 h on-orbit. In addition to the 154 h, the crew spent 52 h of crew weekend (days off and late afternoons) to perform additional science. Finally, whenever the crew was ahead on non-science activities and finished them ahead of time, the crew used the extra time to perform an additional of 14 h of science, using a concept called “Task list”. It is a list with activities for crew to choose from, if the crew chooses to, whenever crew is ahead of the daily activities. Due to a very motivated crewmember, eager to perform science, and a very supporting ground team, a lot of science was accomplished during this increment as well.

It is worth noting that this was a one-person crewmember for the USOS segment and that it was the first increment science was being performed in all three science modules (USLAB, Columbus and JEM PM) within the USOS. In addition to science activities, daily maintenance, outfitting and commissioning activities were performed for both Columbus and the JEM modules by the crew.

During this increment, 13 investigations were performed in Life Science, three in Fluid Physics, one in Space Biology, three in Materials Science, seven in Space Products and Development, one in Human and Environment Interaction and nine in Education and

Table 2 Investigations performed in different science disciplines during increment 17

Science disciplines	Increment 17 experiments		Comment
	New	Continuing	
Life science		NUTRITION	
		Repository	
	NLP VACCINE-1B	EPSTEIN-BARR	
	3D SPACE	MIDODRINE	
	SOLO	Integrated immune	
		SLEEP LONG	
		SLEEP SHORT	
		NLP VACCINE-1A	
		ELITE-S2	
		SLAMMD	
		UltraSound	
Fluid physics	GEOFLOW		
	SHERE		
	Marangoni-EXP		
Space biology		CWRW	
Materials science	BCAT-4	BCAT-3	
		MISSE-6 (A & B)	
		CSLM-2	
Radiation physics	Area PADLES	STABILITY	
Space products & developments		LOCAD-PTS	
	SEITE	MAUI	
	HDTV	SPHERES	
	Commercial	ANITA	
Human/environment interaction		Journals	
Education and earth observation	JAXA EPO (5)	CEO	
		CSI-02	
		EarthKAM	
		NASA EPO	

The list of investigations in this table does not include the exposed facilities investigations, located outside of the station

Earth Observation. Overall 37 investigations were performed in the disciplines mentioned above during the increment, see Table 2. (Note that the exposed facilities investigations are not taken into account here.)

Research Accomplishment During Increment 17

The main objective of this section is to give the reader an appreciation for the amount of research performed by the crew member during increment 17 and to briefly discuss some of those investigations objectives, expected results and potential impact of those results to their respective science disciplines.

Life Science

Since there were many life science investigations from increment 16, which continued during increment 17, they will not be discussed here again since the previous discussion applied here as well. The following investigations continued from increment 16: Nutrition, Repository, SLEEP, Integrated Immune, Epstein–Barr virus, Midodrine, NLP Vaccine-1A and ELITE-S2. Only the new investigations in life science during this increment will be discussed below. Although Vaccine-1B could be regarded as a new investigation, its objective is similar to NLP Vaccine-1A, and the expected results and impact also similar. Therefore, it will not be discussed here either.

In the area of Life Science, the following experiments were performed:

3D Space

The objective of the Mental Representation of Spatial Cues during Flight (3D SPACE) investigation was to accurately characterize perception and localization of objects in the weightlessness environment. Such paradigms are prerequisites for spatial orientation and reliable performance of motor tasks in spaceflight conditions. Humans have indeed mental representations of their environment based on sensory information and experience. It is hypothesized that objects' depth and distance perception could be altered in weightlessness because of the absence of gravitational reference and ambiguous perspective cues. Depth perception and the role of perspective cues are addressed using geometric illusions. Finally, distance perception is analyzed using both standard psychophysics tests and natural tridimensional scenes generated in virtual reality.

SOLO

(2) The objective of Sodium Loading in Microgravity (SOLO) investigation was to study the mechanisms of fluid and salt retention in the body during long-duration space flight. It is known that reduced gravity condition leads to an activation of sodium retaining hormones even at normal sodium intake levels and causes positive sodium balances. Average and high sodium intake in microgravity exacerbates the rise in bone resorption in space and can therefore result in dramatic effects during extended exposure to spaceflight. SOLO is a metabolically controlled study whose objectives are capitalizing on previous studies performed during the EuroMIR missions in 1994 and 1997, and recent bedrest studies.

Human and Environment Interaction

Journal continued during increment 17 from increment 16. See relevant section above for discussion on the Journal investigation in the increment 16 section.

Radiation

One experiment in this discipline, which continued from increment 16, was the investigation called STABILITY. The reader should refer to the increment 16 discussion above for information regarding this investigation.

In the area of Radiation, the following experiment was performed:

Area PADLES

The objective of the Passive Dosimeter for Life Science Experiment in ISS (Area PADLES) investigation was to monitor passive radiation inside the newly attached JAXA science module to ISS, JEM Pressurized Section (PS), using plastic plate and thermoluminescence dosimeter (TLD). PADLES measures the radiation environment inside the JEM PS science module in 12 locations. Area PADLES dosimeters will be exchanged every 6 months and returned to ground for analysis. The results obtained will be used to assess shielding effects of the JEM PM wall thickness and to validate and calibrate radiation simulation codes. Overall, the results will contribute toward technology improvement of human spaceflights.

Fundamental Biology

CWRW was the only investigation in fundamental biology from increment 16 which continued during increment 17. Refer to increment 16 for any discussion regarding this investigation.

Fluid Physics

In the area of Fluid Physics, the following experiments were performed:

GEOFLOW

The objective of the Simulation of Geophysical Fluid Flow under Microgravity (GEOFLOW) investigation was to study viscous incompressible fluid between two concentric spheres rotating around a common axis under the influence of a simulated central force field. This is of importance for astrophysical and geophysical problems, such as global scale flow in the atmosphere, the oceans, and in the liquid nucleus of planets.

Marangoni EXP

The objective of the Marangoni experiment (Marangoni EXP) was to obtain experimental data of the critical condition, at which Marangoni flow transitions from steady to oscillatory flow, for various ratios of height to diameter of the liquid bridge. Marangoni convection is a surface-tension-driven flow. A liquid bridge of silicone oil (5 or 10 cSt) was formed into a pair of disks. Convection was induced by imposing the temperature difference between the disks. Due to the fluid instability, the flow transitions from laminar to oscillatory, chaos, and then to turbulence flow as the driving force increases.

Flow transition conditions and temperature fields are recorded for precise analysis of the processes that took place. The critical condition was successfully obtained for various aspect ratios of the liquid bridge. The results obtained confirmed that the origin of the instability in the liquid bridge is indeed the hydrothermal wave. The results will contribute to the Fluid Science field, especially in the area of interfacial hydrodynamics and micro-hydrodynamics. They will contribute as well to higher/better quality crystal growth and to energy transport with higher efficiency.

SHERE

The objective of the Shear History Extensional Rheology Experiment (SHERE) experiment was to study the effects of a pre-shear history on the transient extensional viscosity in a uniaxial stretching flow for dilute polymer solutions. Access to an extended reduced gravity environment also allowed the subsequent relaxation behavior to be measured after cessation of the extensional deformation. The preshearing is followed with exponential axial stretching of the fluid with well-defined kinematics (exponentially increasing elongation profile). During this stretch, key quantities on the elongating polymer bridge: tensile force, midpoint radius and fluid filament profile evolution are measured. Based on the data collected, rheological parameters of the polymer solution are calculated for the fluid characterization and flow modeling.

Understanding and quantifying the extensional rheology of complex fluids will improve and allow better control of earth-based manufacturing processes and to understand the flow and quantify the rheological properties of biofluids. This investigation allows for the first time to obtain accurate measurements of the extensional viscosity for less elastic fluids such as polymer solutions, suspensions and liquid crystalline materials without sagging of the fluid under a gravitational body force. The effects of a controlled pre-deformation history on the extensional viscosity of dilute polymer solutions have been studied in 1g on Earth and the current reduced gravity results are in good agreement with ground-based observations.

The data obtained will allow designers of both space- and ground-based material processes to use improved constitutive models in numerical simulations of complex two- and three-dimensional fluid flows.

Materials Science

BCAT-3 and CSLM-2 continued during this increment from the previous one. Also, new samples were flown to begin BCAT-4. The objective of BCAT-4 is similar to BCAT-3, except that the samples concentrations are different. Refer to previous discussion of this investigation above, if needed. In addition to BCAT-3 and CSLM-2, MISSE-6 continued as well during this increment.

Space Products and Development or Technology Development

During this increment, the following investigations continued from the previous increment: SPHERES, MAUI and LOCAD. Refer to increment 16 for any discussion regarding these investigations since their objectives and expected results remain the same.

In the area of Space Products and Development or Technology Demonstration, the following experiments were performed:

SEITE

The objective of the Shuttle Exhaust Ion Turbulence Experiment (SEITE) investigation was to study plasma turbulence driven by rocket exhaust in the ionosphere using space based sensors by providing direct measurements of exhaust flow sources, in situ observations of density and electric field disturbances, and developing quantitative models of plasma turbulence that degrades tracking and imaging radars. Instruments that measure electric fields, plasma waves, plasma densities, and magnetic fields will detect plasma turbulence produced by the Shuttle Orbital Maneuvering System (OMS) engine exhaust.

Commercial

The objective of the payload "Commercial" was to film a Television advertisement for a Japanese product within the JAXA science module for a Japanese company to be used in Japan.

HDTV

The purpose of the High Definition Television (HDTV) activity was to check the newly arrived HDTV Japanese system before actual usage. The Japanese HDTV system transmits High Definition (HD) images to ground in real time from the station. Prior to utilization operations, the hardware needed to be tested in order to check the system and to verify procedures of real-time downlink as a technology demonstration.

Education and Earth Observation

During this increment, the following investigations continued from the previous increment: CEO, CSI-02 Resuply and NASA-EPOs. Refer to increment 16 for any discussion regarding these investigations since their objectives and expected results remain the same.

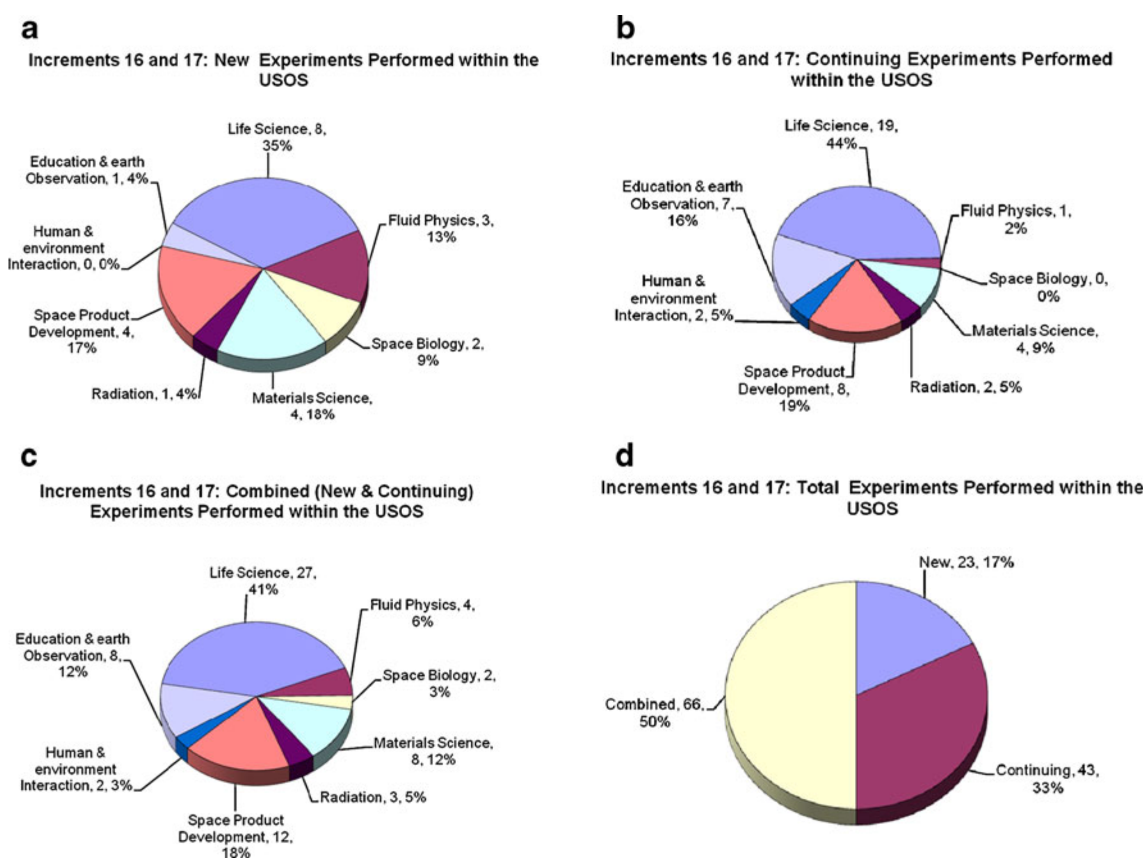

Fig. 4 Research performed in different disciplines on the international space station during increments 16 and 17

In Education and Earth Observation, the following experiments were performed:

EarthKAM

The objective of the Earth Knowledge Acquired by Middle School Students (EarthKAM) was to provide students and educators the opportunity to participate in a space mission and develop teamwork, communication, and problem-solving skills; to engage teams of students, educators, and researchers in collaborative investigations using remotely sensed data; to incorporate the active use of Web-based tools and resources in support of the learning process. EarthKAM integrated Earth images with inquiry-based learning to enhance curricula in support of national and state education standards. The objective of the image gathering sessions was to provide a functional camera/data transfer system responsive to the targeting requests of middle school students. Images from space provide a unique and powerful way for students to explore and learn about Earth.

EarthKAM has accumulated a wealth of images, showing wide diversity or regions and physical features, from every continent except Antarctica. Teachers and students learn how to work with these images, use EarthKAM's Web site to search for, access, and download the images, link the images with local educational priorities, and use the images as starting points and resources for student investigations. Each school adapts EarthKAM to their curriculum based on local opportunities and priorities. For the increment 17 EarthKAM session, 60 schools participated and a total of 1040 images were collected over 4-days and 12-h of active operation in the Node 2 Nadir Hatch window. Of the combined total of 1040 images, 681 were captured using the 50 mm f/1.4 lens and 359 were captured through the 180 mmf/2.8 lens. The addition of the 1040 images now brings the ISS EarthKAM total raw image count to 27,327 images. A total of 32,060 images have been downlinked by the STS and ISS missions.

EPO

JAXA Education Payload Observation (EPO) included educational activities, artistic, and cultural activities.

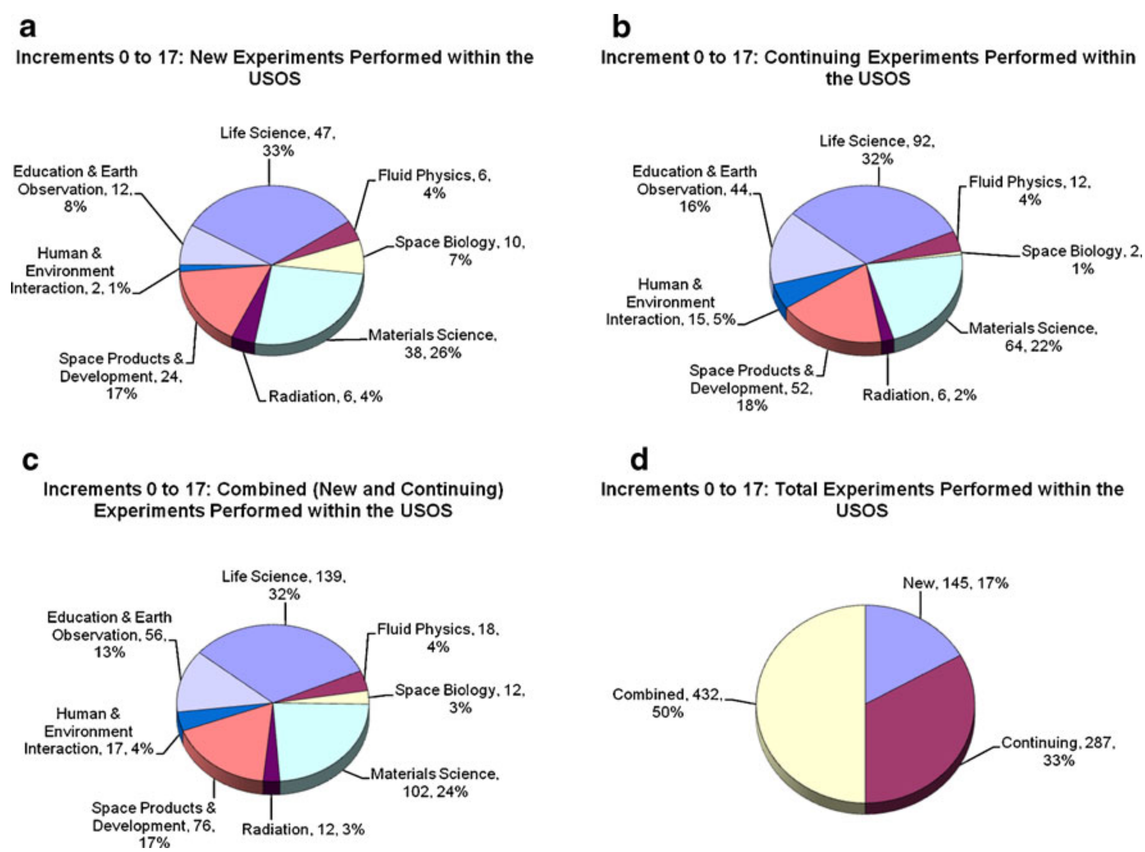

Fig. 5 Research performed in different disciplines on the international space station from increments 0 to 17

JAXA implements these activities to enlighten the general public about microgravity utilization and human space flight. JAXA realizes that ISS/JEM is useful not only to Japanese scientists and engineers but also to writers, poets, teachers, and artists. Therefore, JAXA designed specific activities to be performed on the ISS in cooperation with Japanese universities specializing in Arts.

JAXA performed five Education Payload Operations (EPOs) in various areas within the JEM PM module: (a) Aquasphere, whose objective was to make artistic shape of water sphere using vibration; (b) Ink Ball, whose objective was to make marbling painting on water sphere using ink; (c) Art, whose objective was to photograph the inside of the JEM, space and Earth using the HDTV camera; (d) Microgravity Clay, whose objective was to make figuring of the human body using clay; (e) Photographing the Moon, whose objective was to take photos of the Moon through the ISS windows.

Exposed Facility

Both facilities that were deployed as "exposed facilities" during increment 16 continued to house the same set of investigations during increment 17. Likewise, MISSE-6 continued, as an external investigation on the Columbus external frame during this increment. Again, none of these investigations were crew tended.

A Quick Look: Past, Present and Future

In this paper, brief highlights of the overall science performed during the first 16 increments of continuous

Table 3 Investigations performed in different science disciplines during increment 18

Science disciplines	Increment 18 experiments		Comment
	New	Continuing	
Life science		3D SPACE	
		ZAG	
		MOP	
	Bisphosphonates	MUS	
	OTOLITH	Midodrine	
	Digital Holter ECG	CCISS	
	NLP Cells-1	SOLO	
	BISE	SLEEP	
	Visual performance	Nutrition	
		Repository	
		Integrated immune	
		NLP Vaccine-2	
		NLP Vaccine-3	
Fluid physics		GEOFLOW	
		SHERE	
		Marangoni-EXP	
Space biology	DOME Gene		
	Rad Gene & LOH		
	ROALD		
Materials science	Ice crystal	BCAT-3	
	Facet	BCAT-4	
	PCDF-Protein	INSPACE-2	
Radiation physics	DOSIS/DOBIES	Area PADLES	
		Stability	
Combustion	SPICE		
	MDCA/FLEX		
Space products & developments	ENose	LOCAD-PTS	
	Commercial (2)	MAUI	
	PSSC	SEITE	
	SIMPLEX	SPHERES	
Human/environment interaction		Journals	
Education and earth observation	Photosynth	CEO	
	VLE-I	EarthKAM	
	JAXA EPO (3)	NASA EPO	
	ESA EPO (1)	CSI-02 and 03	

The list of investigations in this table does not include the exposed facilities investigations, located outside of the station

human presence on the ISS were presented (from increments 0 to 15). A breakdown of investigations based on eight science disciplines, which accounted for all of the investigations performed within the USOS (when only the US science module was on-orbit), were presented and discussed, Fig. 1.

Table 4 Investigations performed in different science disciplines for increments 19/20

Science disciplines	Increment 19/20 experiments		Comment
	New	Continuing	
Life science	Biological rythms	3D SPACE	
	CARD	Bisphosphonates	
	EKE	CCISS	
	Integrated cardiovascular	Integrated immune	
	Neurospat	MUS	
	Spin	Nutrition	
	Thermolab	Otolith	
	VO2max	Repository	
	EDOS	SLEEP	
	MDS	SOLO	
	Spinal elongation	SWAB	
	Reaction self test	ZAG	
		BISE	
		Holter	
		SLAMMD	
		NLP Vaccine-5	
Fluid physics	SODI (3)	Marangoni-EXP	
	FOAM STABILITY		
	DECLIC		
Space biology	Lada-VPU-PR		
	Space seed		
	Microbe-1	RadSilk	
	Yeast B1/B2	DOME GENE	
Materials science	MISSE-6A/B	Facet	
		PCDF-Protein	
		BCAT-4	
		PCG	
		INSPACE-2	
		Ice crystal	
Radiation	RADI-N	Area PADLES	
		ALTEA DOSI	
		DOSIS/Dobies	
Combustion		MDCA-FLEX	
		SPICE	
Space products & developments	HTV Environment Monitor	ENose	
	Commercial (2)	LOCAD-PTS	
	ANDE-2	MAUI	
	DRAGONSat	SEITE	
	DTN	SPHERES	
	Avatar	SIMPLEX	
		SNFM	
Human/environment interaction			
Education and earth observation	ESA EPO (3)	JAXA EPO (3)	
	CSI-03	CEO	
	EPO-Kit-D	NASA EPO Demos	
	LES-II	Try Zero-g	
	IRIS		
	Photosynth		

The list of investigations in this table does not include the exposed facilities investigations, located outside of the station

Tables 1 and 2 show the science disciplines and associated investigations that were performed during increments 16 and 17 with the participation of all the international partners' science modules being part of the USOS. During these two increments, a total of 23 new investigations were performed, while 43 others continued from one increment to the next, which netted a combined of 66 investigations in total, Fig. 4. Out of these 66 investigations, 41% was in Life science, 18% in Space product and development or Technology demonstration, 12% in Materials science and Earth observation and Education, 6% in Fluid physics, followed by Radiation, and the other disciplines between 2–3%. Again, the trend is the same as was previously discussed for Fig. 1 for increments 0 to 15, where Life science, Materials science and Space product and development dominated the other science disciplines.

Figure 5 shows the cumulative results for all the science performed from increments 0 to 17. Up to Increment 17, a total of 145 new experiments were performed within the USOS, while 287 continued across several increments during these 18 increments, which netted a grand total of 432 combined investigations performed.

Tables 3 and 4 show the investigations that were performed during Increments 18 and 19/20. These investigations listed in these two tables are for information only since they were not discussed in this paper. Figure 6 shows that 62 new investigations and 72 continuing ones were performed during increments 18 and 19/20, for a total of 134 investigations performed. Figure 7 shows that a total of 207 new investigations were performed from increments 0 to 20, while 360 investigations continued across several of those increments, that netted a grand total of 567 investigations performed so far on the ISS from increments 0 to 20. Both Figs. 6 and 7 show a breakdown of the different science disciplines investigations distribution from increments 0 to 20, including percentage and number of new and continuing investigations for each science discipline.

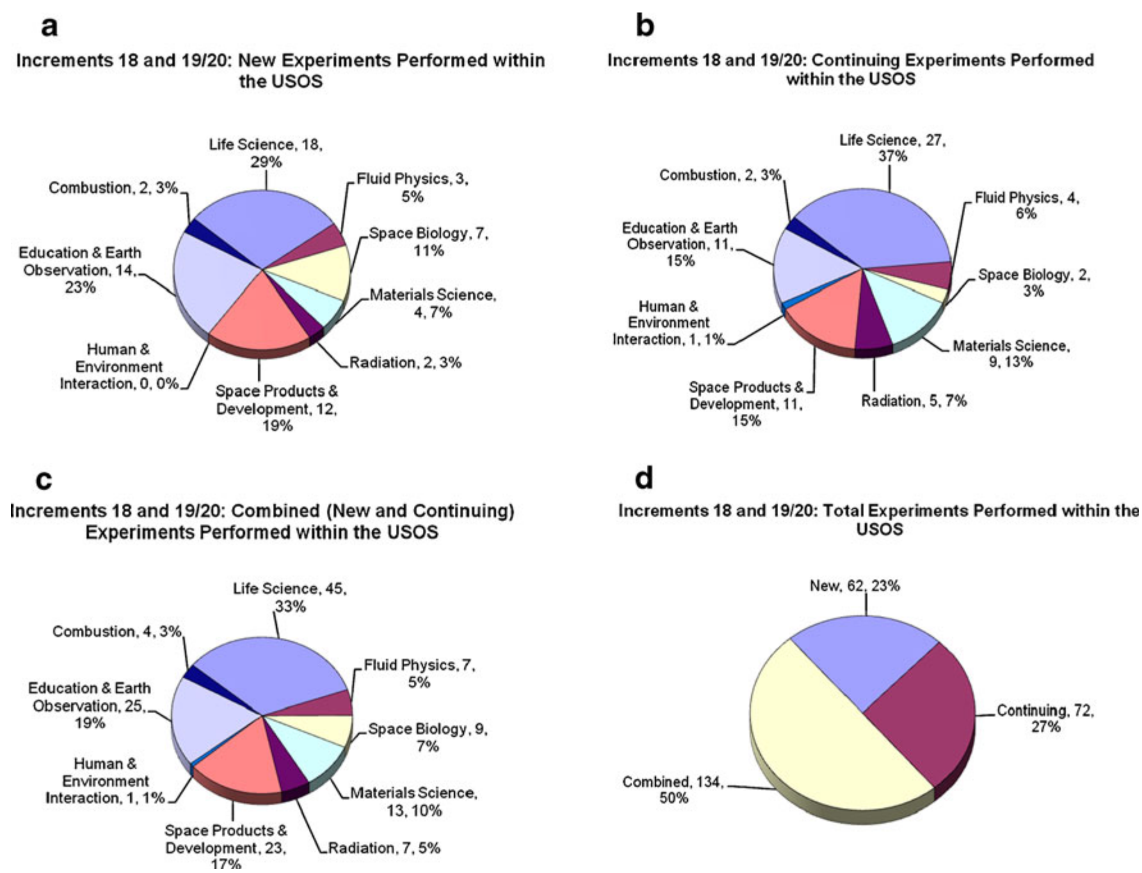

Fig. 6 Research performed in different disciplines on the international space station during increments 18 and 19/20

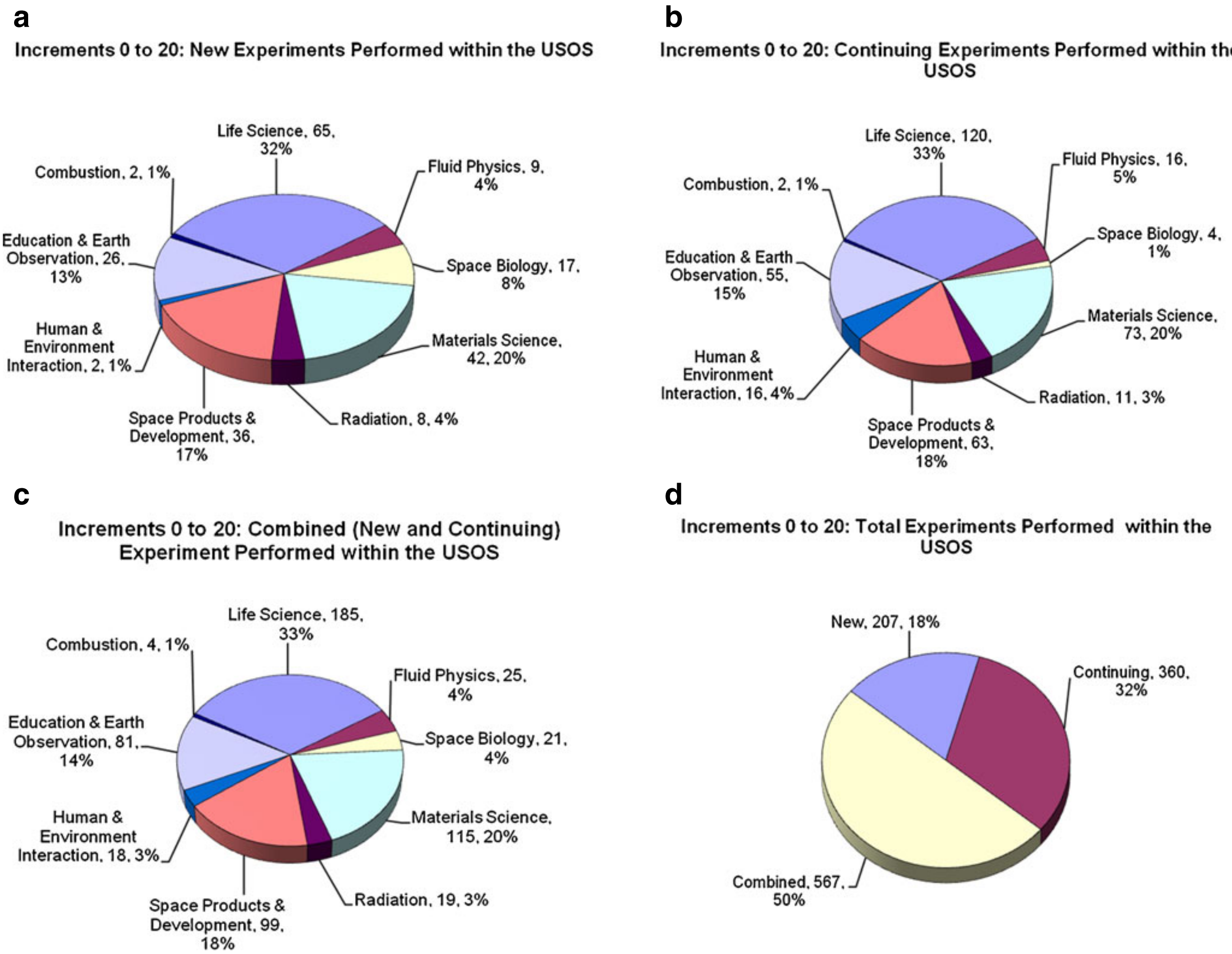

Fig. 7 Research performed in different disciplines on the international space station from increments 0 to 20

Conclusion

Both increments 16 and 17 were very challenging and complex with numerous ISS assembly tasks and science modules and research facilities commissioning, a record numbers of visiting vehicles and several stage EVAs, but yet the crewmembers performed all required science and more. The main purpose of this paper was to make the science community aware of the many investigations that are being conducted on a daily basis on the International Space Station by the many crewmembers since that scientific outpost has been continuously staffed for the last 10 years. Research has been performed in a wide spectrum of science disciplines and yielded many important results that are changing or improving our understanding of some of the phenomena and theories in these fields. It was shown that a total of 207 new experiments and 360 continuing ones had been performed by the end of increment 20, for a grand total of 567 experiments performed within the USOS, With all the ISS partners science modules onboard now and the station permanently staffs with a six-crewmember (since May 2009), versus a three-crewmember in the past, the prospect for ISS as a meaningful science research platform is, indeed, very bright.

Acronym Definition

ANDE	*Atmospheric Neutral Density Experiment*
ANITA	*Analyzing Interferometer for Ambient Air*
ATV	*Autonomous Transfer Vehicle*

BCAT-3	*Binary Colloidal Alloy Test 3*
BISE	*Body in the Space Environment*
BISPHOSPHONATES	*Bisphosphonates as a Countermeasure to Space Flight Induced Bone Loss*
CARD	*Long-term microgravity: A model for Investigating Mechanism of Heart Disease with New Portable Equipment*
CCISS	*Cardiovascular and Cerebrovascular Control on Return from ISS*
CEO	*Crew Earth Observation*
CEO	*Crew Earth Observations*
CEPA	*Columbus External Payload Adapter*
CERISE	*RNA interference and protein phosphorylation in space environment using the nematode Caenorhabditis elegans*
CETSOL	*Columnar-to-Equiaxed Transition in Solidification Processing*
CFE	*Capillary Flow Experiment*
CGBA	*Commercial Generic Bioprocessing Apparatus*
CSA	*Canadian Space Agency*
CSI	*Commercial Generic Bioprocessing Apparatus Science Insert*
CSLM-2	*Coarsening in Solid Liquid Mixtures 2*
CWRW	*Cell Wall and Resist Wall*
DECLIC	*DEvice for the study of Critical Liquids and Crystallization*
DNT	*Delay Tolerant Networking*
Dome Gene	*Dome Gene Experiment*
DOSIS/DOBIES	*Dose Distribution inside ISS/Dosimetry for Biological Experiments in Space*
DRAGONSAT	*Dual RF Astrodynamic GPS Orbital Navigator Satellite*
EarthKAM	*Earth Knowledge Acquired by Middle School Students*
ECG	*Electrocardiogram*
EDOS	*Early Detection of Osteoporosis in Space*
EKE	*Assessment of Endurance Capacity by Gas Exchange and Heat Rate Kinetics during Physical Training*
ELITE-S2	*Elaboratore Immagini Televise 2nd Generation*
ENERGY	*Astronaut's Energy Requirements for long-term Spaceflight*
ENOSE	*Electronic Nose*
EPO	*Education Payload Operations*
EPSTEIN-BARR	*Space Flight Induced Reactivation of Latent Epstein-Barr Virus*
ERB	*Erasmus Recording Binocular*
ESA	*European Space Agency*
ET	*External Tank*
EuTEF	*European Technology Exposure Facility*
EVA	*Extra Vehicular Activity*
EVC	*Earth Viewing Camera*
FACET	*Investigation of Mechanism of Faceted Cellular Array Growth*
FASES	*Fundamental and Applied Studies of Emulsion Stability*
FOAM	*Foam Stability*
GENARA	*Gravity Regulated Genes in Arabidopsis thaliana*
GEOFLOW	*Simulation of Geophysical Fluid Flow under Microgravity*
GRAVI	*Threshold Acceleration for Gravisensing*
HDTV	*High Definition Television*
HPA	*Hand Posture Analyzer*
HQPC	*High Quality Protein Crystallization Experiment Onboard JEM*
ICE Crystal	*The Study of Microgravity Effect on Pattern Formation of Dendritic Crystal by Method of in-situ Observation*
INSPACE	*Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions 2*

Integrated Immune	*Validation of Procedures for Monitoring Crewmember Immune Function*
IP	*International Partner*
IRT	*Increment Research Team*
IS	*Increment Scientist*
ISS	*International Space Station*
JAXA	*Japanese Aerospace Exploration Agency*
JEM PM	*Japanese Experiment Module—Pressurized Module*
JEM PS	*Japanese Experiment Module Pressurized Section*
JEM	*Japanese Experiment Module*
JOURNALS	*Behavioral Issues Associated with Isolation and Confinement: Review and Analysis of ISS Crew Journals*
JSC	*Johnson Space Flight Center*
Lada-VPU-PR	*Lada vegetable Production Unit Plants, Protocols, Procedures and Requirements*
LBP	*Low Back Pain*
LEO	*Low Earth Orbit*
LES	*Lessons from Space*
LIS	*Lead Increment Scientist*
LOCAD-PTS	*Lab-on-a-Chip Application Development—Portable Test System*
LOH Rad Gene	*Detection of Changes in LOH Profile of TK Mutants of Human Cultured Cells (LOH)—Gene Expression of PS3—Regulated Genes in Mammalian Cultured Cells after Exposure to Space Environment*
MAMS	*Microgravity Acceleration Measurement System*
MAUI	*Maui Analysis of Upper Atmospheric Injections*
MAUI	*Maui Analysis of Upper Atmospheric Injections*
MDCA/FLEX	*Multi-user Droplet Combustion Apparatus/ Fundamental Studies in Droplet Combustion and Flame Extinguishment in Microgravity*
MDRV	*Microbial Drug Resistance Virulence*
MDS	*Mice Drawer System*
MEDET	
MIDODRINE	*Test of Midodrine as a Countermeasure Against Post-flight Orthostatic Hypotension*
MISSE	*Materials on the International Space Station Experiment*
MOP	*Motion Perception: Vestibular Adaptation to G-Transitions*
MR	*Magnethorheological*
MSL	*Materials Science Laboratory*
MULTIGEN	*Molecular and Plant Physiological Analyses of the Microgravity Effects on Multigeneration Studies of Arabidopsis Thaliana*
MUS	*Low Back Pain Study in Microgravity*
NASA	*National Aeronautics and Space Administration*
NEURORAD	*Biological Effects of Space Radiation and Microgravity on Mammalian Cells*
NEUROSPAT	*The Effect of Gravitational Context on EEG Dynamics: A Study of Spatial Cognition, Novelty Processing and Sensorimotor Integration*
NLP	*National Lab Pathfinder*
NUTRITION	*Nutritional Status Assessment*
OMS	*Orbital Maneuvering System*
OTOLITH	*Otolith Assessment during Postflight Re-adaptation*
PADIAC	*Pathway Different Activators*
PADLES	*Passive Dosimeter for Life science Experiments in Space*
PCDF	*Protein Crystallization Diagnostics Facility*
PCG	*Protein Crystal Growth*
Photosynth	*Photosynth three dimensional modeling of ISS interior and exterior*

PLEGPAY	
PMA	*Pressurized Mating Adapter*
PMT	*Photocatalyst Material Test*
PMZ	*Bioavailability and Performance Effects of Promethazine During Space Flight*
PRCS	*Primary Reaction Control System*
PSSC	*Pico-Satellite Solar Cell Experiment*
RAD SILK	*Integrated Assessment of Long-term Cosmic Radiation through Biological Responses of the Silkworm, Bombyx mori, in Space*
RIGEX	*Rigidizable Inflatable Get-Away-Special Experiment*
ROALD	*Role of Apoptosis in Lymphocyte Depression*
ROS	*Russian Orbital Segment*
RPWG	*Research Planning Working Group*
SAMPLE	*Study of Microbial Communities Exposed to Weightlessness*
SAMS	*Space Acceleration Measurement System*
SARJ	*Solar Array Rotary Joint*
SAS	*Space Adaption Syndrome*
SEITE	*Shuttle Exhaust Ion Turbulence Experiment*
SHERE	*Shear History Extensional Rheology Experiment*
SIMPEX	*Shuttle Ionospheric Modification with Pulsed Localized Exhaust Experiments*
SLAMMD	*Space Linear Acceleration Mass Measurement Device*
SLEEP	*Sleep-Wake Actigraphy and Light Exposure During Spaceflight*
SMS	*Space Motion Sickness*
SNFM	*Serial Network Flow Monitor*
SODI	*Selectable Optical Diagnostics Instrument—Influence of Vibration on Diffusion of Liquid*
SOLACES	*Solar Auto-calibrating Extreme UV-Spectrometer*
SOLAR	*Sun Monitoring on the External Payload Facility of Columbus*
SOLO	*Sodium Loading in Microgravity*
SOLSPEC	*Solar Spectral Irradiance Measurements*
SOVIM	*Solar Variable and Irradiance Monitor*
SPACEDRUMS	*Space Dynamically responding Ultrasonic Matrix System*
SPDM	*Special Purpose Dexterous Manipulator*
SPHERES	*Synchronized Position Hold, Engage, Reorient, Experimental Satellites*
SPICE	*Smoke Point in Co-flow Experiment*
SPIN	*Validation of Centrifugation as a Countermeasure for Otolith Deconditioning during Spaceflight*
SPINAL ELONGATION	*Spinal Elongation and its Effects on Seated Height in a Microgravity Environment*
STABILITY	*Stability of Pharmacotherapeutic and Nutritional Compounds*
STABILITY	*Stability of Pharmacotherapeutic and Nutritional Compounds*
STP-H2-ANDE	*Space Test Program-H2-Atmospheric Neutral Density Experiment*
STS	*Space Transportation System*
SWAB	*Surface, Water and Air Biocharacterization—A Comprehensive Characterization of Microorganisms and Allergens in Spacecraft Environment*
THERMOLAB	*Thermoregulation in Humans during Long-term Spaceflight*
TIG	*Time of Ignition*
TRIPLELUX	*Gene, Immune and Cellular Responses to Single and Combined Spaceflight Conditions*
ULF	*Utilization Flight*
USOS	*United States Orbital Segment*
VCAM	*Vehicle Cabin Air Monitor*

Visual Performance	*Human Factors Assessment of Vibration Effect on Visual Performance during Launch*
VLE-I	*Video Lesson European Space Agency*
VO2max	*Evaluation of Maximal Oxygen Uptake and Submaximal Estimates of VO2max Before, During and After Long Duration International Space Station Missions*
VRCS	*Vernier Reaction Control System*
WAICO	*Waving and Coiling of Arabidopsis Roots at Different g-levels*
YEAST	*The Influence of Microgravity on Cellular Adhesion: Biofilm Formation and Invasive Growth in the Model Eukaryote Saccharomyces Cerevisiae*
ZAG	*Ambiguous Tilt and Translation Motion Cues After Space Flight*

Acknowledgements The authors would like to express their sincere thanks to the USOS Expedition 16 crew members: Commander and USOS Science Officer Peggy Whitson and Flight Engineers Daniel Tani, Leo Eyharts, Garrett Reisman and Clay Anderson and to the Expedition 17 USOS Science Officer Greg Chamitoff. Every one of them performed a tremendously amount of research during the two increments discussed in this paper. And, of course, many thanks go to all of the other Astronauts who spent time conducting research on the ISS during the last 10 years and specially those who unselfishly gave their weekends and off duty days to perform Saturday/Voluntary/Weekend science (additional research performed in addition to the daily scheduled research activity) for the benefit of the science community. Thanks. The authors would like to thank as well Mr. Roger Weiss for the upmass manifest data provided for all of the increments discussed in this paper.

References

Cobb, R.: Rigidizable Inflatable Get-Away-Special Experiment (RIGEX). Increment 16 30 day Science Report, NASA Internal (2008)

Czeisler, C.A., et al.: Sleep-wake actigraphy and light exposure during spaceflight (SLEEP). Increment 16 Science Report, NASA Internal (2008)

Furst, E., et al.: Investigating the structure of paramagnetic aggregates from colloidal emulsions (INSPACE), Increment 16 30-day Report, NASA Internal (2008)

Hammond, T.: National laboratory pathfinder Vaccine-1A. Increment 16 30 day Science Report, NASA Internal (2008)

Hughson, R., et al.: Cardiovascular and cerebrovascular control on return from ISS (CCISS). Increment 16 30 day Science Report, NASA Internal (2008)

Increment Research Team (IRT) Charter, RPWG-001, NASA Internal (2008)

Jules, K.: Summary of the science performed onboard the international space station during increments 12 and 13. Acta. AstroNaut. **63**(Special Issue), 38–52 (2008)

Jules, K., et al.: Elaboratore immagini televisive for space (ELITE-S2). Increment 16 Science Symposium, NASA Internal (2007)

Lacquaniti, F.: Hand Posture Analyzer (HPA). Increment 16 30 day Science Report, NASA Internal (2008)

Maule, J., et al.: Lab on-a-Chip Application Development—Portable Test System (LOCAD-PTS). Increment 16 30 day Science Report, NASA Internal (2008)

Miller, D.W., et al.: Synchronized Position Hold, Engage, Reorient, Experiment Satellites (SPHERES). Increment 16 30 day Science Report, NASA Internal (2008)

NASA Biological Sample Repository—Increment 16 30 day Science Report. NASA Internal (2008)

Nickerson, C., et al.: Microbial Drug Resistance and Virulence (MDRV). Increment 16 30 day Science Report, NASA Internal (2008)

Pierson, D., et al.: Surface, Water and Air Biocharacterization—A Comprehensive Characterization of Microorganisms and Allergens in Spacecraft Environment (SWAB). Increment 16 30 day Science Report, NASA Internal (2008)

Platts, S.: Test of midodrine as a countermeasure against postflight orthostatic hypotension (Midodrine). Increment 16 30 day Science Report, NASA Internal (2008)

Putcha, L.: Bioavailability and performance effects of promethazine during spaceflight (PMZ). Increment 16 30 day Science Report (2008)

Putcha, L., et al.: Stability of pharmacotherapeutic and nutritional compounds (Stability). Increment 16 30 days Science Report, NASA Internal (2008)

Runco, S.K., et al.: Crew Earth Observation (CEO). Increment 16 30 day Science Report, NASA Internal (2008)

Sams, C., et al.: Validation of procedures for monitoring crewmember immune function (Integrated Immune). Increment 16 30 day Science Report, NASA Internal (2008)

Smith, S.M., et al.: Nutrition status assessment (Nutrition). Increment 16 30 day Science Report, NASA Internal (2008)

Stodieck, L.: Commercial Generic Bioprocessing Apparatus Science Insert-02 (CGBA-CSI-02 Resuply). Increment 16 30 day Science Report, NASA Internal (2008)

Stowe, R.P., et al.: Spaceflight-induced reactivation of latent Epstein-barr virus. Increment 16 30 day Science Report, NASA Internal (2008)

Stuster, J.: Behavioral Issues Associated with Long duration Space Expeditions: Review and Analysis of Astronaut Journals (Journals). Increment 16 30 day Science Report, NASA Internal (2008)

Voorhees, P.W.: Coarsening in Solid-Liquid Mixtures-2 (CSLM-2). Increment 16 30 day Science Report, NASA Internal (2008)

Walters, R.J.: Materials on the International Space Station Experiment (MISSE). Increment 16 30 day Science Report, NASA Internal (2008)
Weislogel, M., et al.: Capillary Flow Experiment (CFE). Increment 16 30 day Science Report, NASA Internal (2008)
Weitz, D.A., et al.: Binary colloid alloy test-3 (BCAT-3). Increment 16 30 day Science Report, NASA Internal (2008)
Winick, J.: Maui Analysis of Upper Atmospheric Injections (MAUI). Increment 16 30 day Science Report, NASA Internal (2008)