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Stepping stones toward global space exploration

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ABSTRACT

Several nations are currently engaging in or planning for robotic and human space exploration programs that target the Moon, Mars and near-Earth asteroids. These ambitious plans to build new space infrastructures, transport systems and space probes will require international cooperation if they are to be sustainable and affordable. Partnerships must involve not only established space powers, but also emerging space nations and developing countries; the participation of these new space actors will provide a bottom-up support structure that will aid program continuity, generate more active members in the space community, and increase public awareness of space activities in both developed and developing countries. The integration of many stakeholders into a global space exploration program represents a crucial element securing political and programmatic stability. *How can the evolving space community learn to cooperate on a truly international level while engaging emerging space nations and developing countries in a meaningful way?* We propose a stepping stone approach toward a global space exploration program, featuring three major elements: (1) an international Earth-based field research program preparing for planetary exploration, (2) enhanced exploitation of the International Space Station (ISS) enabling exploration and (3) a worldwide CubeSat program supporting exploration. An international Earth-based field research program can serve as a truly global exploration testbed that allows both established and new space actors to gain valuable experience by working together to prepare for future planetary exploration missions. Securing greater exploitation of the ISS is a logical step during its prolonged lifetime; ISS experiments, partnerships and legal frameworks are valuable foundations for exploration beyond low Earth orbit. Cooperation involving small, low-cost missions could be a major stride toward exciting and meaningful participation from emerging space nations and developing countries. For each of these three proposed stepping stones, recommendations for coordination mechanisms are presented.

1. Introduction

Several nations are currently engaging in or planning for human and robotic space exploration programs that target the Moon, Mars and near-Earth asteroids. Given current budgetary constraints and the need for more sustainable space exploration programs, these ambitious plans to build new space infrastructures, transport systems and space probes will require international cooperation if they are to be successful. Indeed, monetary efficiency, program sustainability, political prestige and workforce stability are some of the mutual benefits that can arise from cooperative space exploration [1,2]. However, such partnerships must be based on shared objectives, clearly defined responsibilities, scientific support and other critical elements that make international space cooperation successful [2].

1.1. Overview of national and international space exploration activities

The United States (US) President Barack Obama took the National Aeronautics and Space Administration (NASA) in

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new directions with his Fiscal Year (FY) 2011 Budget Request. The latest plan includes new destinations for human space exploration such as near-Earth asteroids and focuses on technology development and creating opportunities for the commercial sector. NASA's Exploration Systems Mission Directorate is planning robotic precursor missions to the Moon, Mars and near-Earth asteroids to scout targets for future human activities as well as identify the hazards and resources that will determine the future course of human expansion beyond Low Earth Orbit (LEO).

The European Space Agency (ESA) is the main scientific user of the International Space Station (ISS) and has recently contributed a number of major infrastructure parts such as the *Columbus* laboratory, the Automatic Transfer Vehicle (ATV) and the *Cupola* observation module. The European Space Science Committee (ESSC) released in 2009 its *Science-Driven Scenario for Space Exploration*,[1] which defined overarching scientific goals for Europe's space exploration program. The Committee recognized Mars as Europe's main exploration target and clearly stated that Europe should position itself as a major actor in defining and leading a Mars sample return mission [3]. Indeed, the political dimensions of space exploration and its economic and strategic applications are now in the process of being acknowledged in Europe [4]. The EU and ESA jointly launched a consultation process with various stakeholder communities (e.g. science, industry, national agencies) in spring 2010 with three workshops that served as input to the second high-level conference on exploration held in October 2010 in Bruxelles.

Long-term cooperation between NASA and the European Space Agency (ESA) has been initiated through the Mars Exploration Joint Initiative (MEJI). The program provides a framework that will expand the collective capabilities of the two agencies as they jointly define and implement their scientific, technological and programmatic goals for Mars exploration. MEJI launch opportunities during the 2016–2020 timeframe should ultimately lead to a multi-element Mars sample return mission within the next decade [5].

A number of orbiter, lander and sample return missions are being prepared by Russia, Japan, China and India. Russia's *Phobos-Grunt* mission will be launched in 2012 to return samples from the Martian moon Phobos and Japan's *Hayabusa* spacecraft recently returned to Earth in June 2010 with a sample from the asteroid Itokawa. Several Lunar orbiter missions will be carried out in this decade, such as China's recently launched *Chang'e*-2 and India's planned *Chandrayaan*-2 (as a part of Russia's *Luna Resource*-1). Contact and in-situ robotic missions to the Moon are also envisaged for later in this decade, including Japan's *Selene*-2 (lander) and *Selene*-3 (sample-return), Europe's *Lunar Lander*, China's *Chang'e*-3 (lander) and *Chang'e*-4 (sample return), and Russia's *Luna Resource*-1 (Russian lander with Indian orbiter) and *Luna Resource*-2 (Russian lander, rover and retransmitting satellite) [6].

In addition to historical space powers such as the United States and Russia, newcomers including China and India are now pursuing or considering pursuing human space exploration. China launched its first human into space on *Shenzhou*-5 in 2003, followed by a two-person mission on *Shenzhou*-6 in 2005 and a three-person extravehicular activity (EVA) mission on *Shenzhou*-7 in 2008. In 2011, China will launch *Tiangong*-1, its first space lab module, followed by an unmanned *Shenzhou*-8 to dock with it. China recently began work on its inhabited space station aimed for completion around 2020. India's budget for pursuing human space exploration is currently under discussion.

1.2. Vision for a future global space exploration program

Despite these exciting advancements, international cooperation in space exploration (apart from the ISS) has focused on cooperation between the national programs of established space powers rather than a truly integrated global effort. Consequently, within the global space exploration community there remains a lack of common focus and roadmap as well as basic mechanisms for cooperation. Moreover, differences in the political priorities and budget cycles that shape the governments of established space powers, along with prohibitive technology transfer regulations such as the International Traffic in Arms Regulations (ITAR), still build barriers that must be overcome in the future.

Taking steps in the right direction, fourteen space agencies[2] produced in 2007 the report *Global Exploration Strategies (GES)—The Framework for Cooperation*.[3] The International Space Exploration Coordination Group (ISECG) currently implements and coordinates GES, helping to harmonize national plans and in particular architectures to advance human lunar exploration [7]. Other national and international working groups – including the International Lunar Exploration Working Group (ILEWG), the International Mars Exploration Working Group (IMEWG), the Lunar Exploration Analysis Group (LEAG) and the Mars Exploration Program Analysis Group (MEPAG) – are investigating cooperative mission scenarios for the Moon and Mars. The Committee on Space Research (COSPAR) and the International Academy of Astronautics (IAA) are among the capacity building organizations that promote the engagement of emerging space nations and developing countries in future space exploration plans.

One of the pillars of the United Nations Program on Space Applications for developing countries focuses on "basic space science, including astronomy and astrophysics, solar–terrestrial interactions, planetary and atmospheric studies and exobiology" [8]. All of those research topics are crucial to advance space exploration of the Earth–Moon–Mars space. A good understanding of the technology gathering basic science data is a precondition to achieve a higher level of independency of aspiring space

[1] http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=45509

[2] Australia, China, Canada, France, Germany, India, Italy, Japan, Russia, South Korea, Ukraine, the United Kingdom, and the United States and the European Space Agency.

[3] http://www.globalspaceexploration.org/

nations and transforming them into more active players [8]. A larger contingent of active players and stakeholders worldwide increases the potential of international cooperation for space exploration and thus political and programmatic commitment.

In this paper, we propose a stepping stone approach toward a future global space exploration program. Using this approach, the growing space community will learn to cooperate on a truly international level while also engaging emerging space powers and developing countries in a meaningful way [6]. The approach features three major stepping stones: (1) an international Earth-based field research program preparing for planetary exploration, (2) enhanced exploitation of the ISS enabling exploration and (3) a worldwide CubeSat program supporting exploration (Fig. 1).

An international Earth-based field research program preparing for planetary exploration will allow stakeholders from various cultures to advance related science and technology, while also gaining valuable practical experience from working together in the field. Securing enhanced exploitation of the ISS by involving a wider range of participants in the utilization of recently integrated facilities and a larger crew of six provides opportunities to advance our knowledge of living and working beyond LEO. Collaboration on small, low-cost missions through a worldwide CubeSat program can support primary exploration activities, while also enabling the participation of new space actors in a meaningful way. This stepping stone approach will ease cross-cultural barriers and the development of interfaces as well as foster standardization—all major prerequisites for a sustainable global space exploration program in the future.

Although the involvement of emerging space nations and developing countries will not necessarily be the primary driving force for a future global space exploration program led by established space powers, *they will make important contributions by providing a bottom-up support structure for ambitious space activities.* Indeed, given the long-term nature of space exploration, new space actors that do not have the required capabilities, resources or mandates at present will most likely develop them as the anticipated era of global space exploration unfolds. Actively engaging these new space actors in the early stages will therefore increase future interest and capacity in planned large-scale exploration endeavors. Their active participation will also help build up basic space technology capacity within their countries, thereby accelerating the transformation of these new space actors into more active members of the space community, for example by becoming hardware providers rather than just users of space data [8]. Finally, involving emerging space nations and developing countries will increase public awareness and engagement in space activities in both developed and developing worlds.

1.3. Established space powers, emerging space nations and developing countries

The three terms used in this paper to classify members of the space community – established space powers, emerging

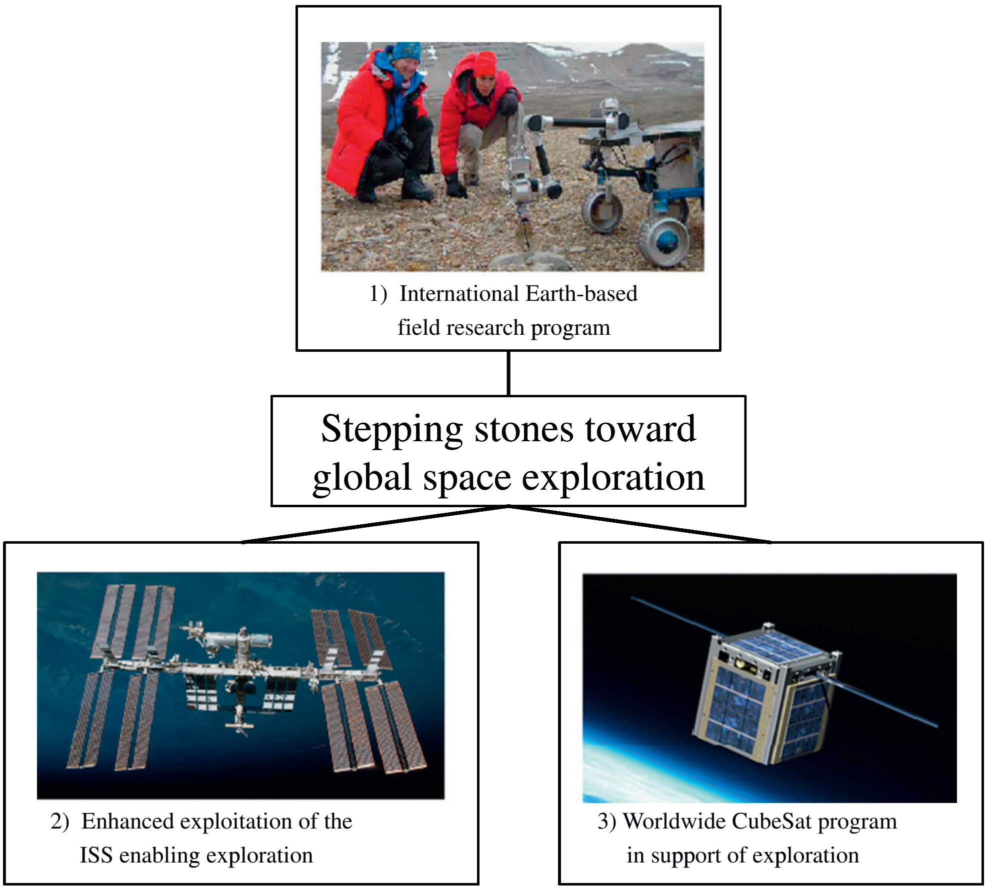

Fig. 1. Stepping stones toward global space exploration (images courtesy of NASA).

space nations, and developing countries – should not be thought of as distinct categories. Rather, these members exist along a continuum of space capabilities that range from low complexity with high dependence on foreign partnerships to high complexity with low dependence on foreign partnerships. Established space powers inhabit the latter end of the continuum and tend to drive the most ambitious space activities. They include the United States, Russia, Japan and Europe. China and India are nearing this end of the spectrum as they are engaged in ISECG and are beginning to make important contributions to space exploration. However, they have not yet reached the same level of past experience and capability as the established space powers.

Developing countries are at the opposite end of the continuum from established space powers. The objectives of developing countries include establishing basic indigenous space capabilities and benefiting from satellite services. However, they lack the required resources as well as the technical and managerial expertise to successfully develop space hardware and operate satellites without significant foreign assistance. Thus, they are particularly interested in small satellite projects because they provide entry-level, hands-on technical experience and practical training [9,10]. Examples of developing countries include Azerbaijan, Croatia, Latvia, Malaysia, Nigeria, Peru, Romania and Tunisia—to name only a few.

Emerging space nations are more advanced than developing countries in terms of the autonomy and complexity of their space projects. They have executed a wider range of space projects (either independently or with the help of foreign partners) and currently benefit from the services provided by satellites they operate. However, they cannot be considered established space powers because they lack proven launch vehicles and have not yet played significant roles in exploration missions to other planetary bodies. One objective of emerging space nations is therefore to gain experience in more advanced space projects. Accordingly, they are often interested in establishing meaningful roles in international programs led by established space powers. Examples of emerging space nations range from South Korea to Brazil.

Clearly, differences exist in the objectives and interests of emerging space nations and developing countries. Mechanisms for engaging these two types of potential participants in global space exploration must reflect these differences. They must also aim to develop the political will that is critical for ensuring long-term funding for their participation. More detailed mechanisms are addressed in Section 3.

2. Stepping stones toward global space exploration

A stepping stone approach can pave the path toward a sustainable global space exploration program capable of conducting complex sample return and human exploration missions beyond LEO [11]. This paper focuses on three areas in particular that are actively being pursued on national, bilateral and multinational levels (see Table 1), but do not presently feature worldwide efforts involving all established space powers as well as emerging space nations and developing countries. In this paper, we elaborate on how these key areas can be expanded to serve as near-term international initiatives leading to a sustainable global space exploration program in the future.

Table 1
Potential near-term international initiatives for space exploration.

Initiatives	Potential specific missions	Participants
Preparation for planetary exploration beyond LEO	International Earth-based field research program	Current and emerging space nations, developing countries, private sector
Joint program for exploration research	Enhanced exploitation of the ISS enabling exploration	Current ISS partners and potential new partners
Cooperation on small, low-cost missions	Worldwide CubeSat program in support of exploration	Current and emerging space nations, developing countries, private sector

2.1. *International Earth-based field research program*

Human and robotic operations in space can be effectively prepared for on Earth, as terrestrial extreme environments often provide analogs to landing and operation sites on the Moon and Mars. Field research at such analog sites is currently being undertaken in collaboration with scientists, engineers, medical personnel and often journalists and students to cover the multidisciplinary aspects that are key in advancing and promoting planetary exploration. The importance of these efforts will grow in the coming decades, as increasingly ambitious space missions require more preparatory work in the field to maximize mission success and scientific return. Field expeditions and laboratory simulations not only test technologies, methodologies and protocols, but also serve as training bases for personnel and science and operations teams [12].

2.1.1. *A multidisciplinary endeavor in extreme environments*

Existing Earth-based field research programs preparing for planetary exploration range from narrow to broad in focus. They include investigating geological and geochemical contexts; demonstrating technologies, infrastructures and methodologies for current and future missions; evaluating crew operations and psychology through simulations; and training crews and support teams for ISS missions. Many space instruments augment their flight readiness level through tests at planetary analog regions on Earth. Lessons learned from sample collection, handling and in-situ analysis at these sites help to overcome contamination issues as well as improve instrument performance. Using Mars regolith analogs to test physical and chemical properties such as pH, redox potential, elemental composition, conductivity and organic content are part of the interdisciplinary preparation phase to search for organic molecules and life on Mars [13]. Artificial environments can also be used to test exploration concepts and further development of closed-loop systems for long-duration space exploration.

These research efforts of the planetary science community are often compatible with those of the Earth science community. Technologies required for scientific investigations at terrestrial extreme environments are often similar to those needed for operations on extraterrestrial bodies [14,12]. Thus, field research sites in extreme environments on Earth such as Antarctica provide a unique opportunity for collaboration between the planetary science and Earth science communities. By exploiting their synergies, it is possible to share field sites, equipment and data; jointly test related technologies, methodologies and protocols; cooperatively train science and operations teams; and mutually engage the public, media and educators in planetary science awareness [6]. Such cooperation will promote efficiency as well as sustainability for a global space exploration program.

2.1.2. *Existing Earth-based field research programs*

Programs exist worldwide that use Earth-based sites to prepare for planetary exploration, as shown in Table 2 and summarized in this section. Many of these programs include bilateral or multinational cooperation. However, these common efforts should be united through a global, cross-disciplinary program that supports space exploration missions beyond LEO.

AMASE: The Arctic Mars Analog Svalbard Expedition (AMASE)[4] conducts Mars-related field research on the Arctic island of Svalbard, the only place known on Earth with carbonate deposits identical to those of the Martian meteorite ALH84001. Through AMASE, a multinational team of researchers from Europe and the United States has tested a variety of exploration instruments for Mars missions such as ESA's ExoMars and NASA's Mars Science Laboratory.

ASTEP: NASA's Astrobiology Science and Technology for Exploring Planets (ASTEP)[5] is a science-driven exploration program supporting the development of new technologies, instrumentation and operational schemes for exploring extreme environments. Research conducted through ASTEP field campaigns aims at further understanding of the limits and adaptability of life as well as lower risks of exploration activities on other planetary bodies.

CAREX: Initiated by the European Commission (EC) through its "Framework 7", the Coordination Action for Research Activities on life in Extreme Environments (CAREX)[6] has two main objectives: strengthen the European network of scientists researching life in extreme environments and coordinate and set scientific priorities. CAREX endorses cross-sector interests in microbes, plants, and animals in diverse extreme environments including outer space.

CARN: The Canadian Space Agency (CSA) established the Canadian Analog Research Network (CARN) to coordinate and facilitate the use of three Moon/Mars analog sites in Canada for scientific exploration research. CARN includes the McGill Arctic Research Station, Haughton-Mars Project (HMP) and Pavilion Lake Research Project (PLRP) [15].

CEEF: Japan's Institute for Environmental Science (IES) established the Closed Ecological Experiment Facilities (CEEF) to research potential closed environment concepts. CEEF currently consists of three buildings: the Closed Geo-Hydrosphere Experiment, Closed Animal Breeding and Habitation Experiment and Closed Plantation Experiment. Results from CEEF are expected to contribute to the development of closed-loop systems for future Moon/Mars bases [16,17].

Concordia Station: Concordia Station is a permanently inhabited research facility in Antarctica for conducting scientific research in the fields of glaciology, atmospheric sciences, astronomy and astrophysics, Earth sciences, technology and human biology and medicine. Given the similarities between Antarctic research stations and future planetary outposts, ESA uses Concordia Station for experiments and simulations relevant for future human space exploration [18].

Desert RATS: Desert Research and Technology Studies (Desert RATS)[7] is an annual field test led by NASA in collaboration with non-NASA research partners in remote parts of Arizona and California. The program assesses preliminary exploration concepts for surface operations including rovers, EVAs and ground support.

HMP: The Haughton-Mars Project (HMP)[8] was established in 1997 on Devon Island in the Canadian High Arctic and is now part of CARN. HMP serves as a Mars analog that supports the development of new technologies and operational frameworks in preparation for future human and robotic exploration of Mars and other planetary bodies.

ILEWG: The International Lunar Exploration Working Group (ILEWG)[9] has a task group that organizes and coordinates field campaigns at the Mars Desert Research Station, Eifel Volcanic Park, Rio Tinto and other sites in collaboration with ESA, NASA, and other partners in academia and industry. The goals of ILEWG field campaigns include testing instrumentation, rovers, landers, EVA technologies and habitats; performing field research in geology, sample analysis and exobiology; studying human factors and crew aspects; and public outreach and student training.

MARS: The Mars Analog Research Station (MARS)[10] program is a global effort led by the Mars Society. MARS currently operates two simulated Mars habitats, the Flashline Mars Arctic Research Station (F-MARS) on Devon Island and the Mars Desert Research Stations (MDRS) in Utah. There are intentions to establish two more habitats, Euro-Mars in Iceland and Mars-Oz in Australia. At MARS facilities, scientists conduct experiments in psychology, geology and biology for further understanding of how to live and work on Mars. Simulated deployments last roughly two weeks and participants must wear simulated spacesuits and communicate with time lags equivalent to Earth–Mars radio message

[4] http://amase.ciw.edu
[5] http://astrobiology.nasa.gov/astep
[6] http://www.carex-eu.org
[7] http://www.nasa.gov/exploration/analogs/desert_rats.html
[8] http://www.marsonearth.org
[9] http://sci.esa.int/ilewg
[10] http://www.marssociety.org/portal/groups/AnalogsTF/index_html

Table 2
Current and planned Earth-based field research programs

Initiatives (Founded)	Lead entities	Supporting entities	Locations	Descriptions
Current Analog Programs				
AMASE (2003)	Hans Amundsen (Europe)	Various	Svalbard (Arctic)	Conducting astrobiology research and instrument testing at a Mars analog field site
ASTEP (2001)	NASA (United States)	Various	Various extreme environments	Scientific research and technology demonstrations for understanding of the limits and adaptability of life
CAREX (2008–2010)	British Antarctic Survey, ESF (Europe)	CAREX Core Partners	Various extreme environments	Coordinating scientists and setting scientific priorities for research of life in extreme environment in Europe
CARN (2005)	CSA (Canada)	Various	Canada	Coordinating the use of Canadian Moon and Mars analog field sites for exploration research
CEEF (1990s)	IES (Japan)	N/A	Rokkasho (Japan)	Closed environment facilities that may help develop closed-loop systems for Lunar and Martian bases
Concordia (2005)	IPEV (France), PNRA (Italy)	ESA (Europe)	Antarctica	Researching glaciology, atmospheric sciences, astronomy, Earth sciences and human biology
Desert RATS (1998)	NASA (United States)	N/A	California, Arizona (United States)	Conducting annual field campaigns to test preliminary concepts for surface operations on extraterrestrial bodies
HMP (1997)	Mars Institute (United States, Canada)	SETI (United States)	Devon Island (Canada)	Using field research sites at the Haughton impact structure as terrestrial analogs for Mars
ILEWG (1995)	ESA (Europe), NASA (United States)	National space agencies	Utah (United States), Rio Tinto (Spain) and others	Testing technologies, performing field research, studying human factors and conducting education and outreach activities
MARS (2000)	Mars Society (United States)	Various	Devon Island (Canada), Utah (United States)	Long duration psychology, geology and biology field tests for understanding how to live and work on Mars
PLRP (2004)	CSA (Canada), NASA (United States)	N/A	British Columbia (Canada)	Researching the origins of freshwater microbilites, which can be applied to the search for life beyond Earth
PISCES (2007)	JUSTSAP (Japan, United States)	Canada, Europe	Hawaii (United States)	Field research campaigns and education and outreach activities promoting living and working in space
TNA-1 (2009)	Europlanet (Europe)	European Community	Spain, Russia, Tunisia, Svalbard, Morocco	Facilitating access for Europeans to certain Earth-based field sites to conduct planetary research
Proposed Analog Programs				
IAN	CSA (Canada)	Various	Canada	International expansion of CARN
PISA	United States, Japan	Various	Hawaii (United States)	International expansion of PISCES

delays. MDRS is also a societal endeavor that engages public applicants.

PLRP: The Pavillion Lake Research Project[11] was established in 2004 and is now part of CARN. PLRP is a science and exploration effort focused on furthering knowledge on the origins of freshwater microbilites in the Pavillion Lake in British Columbia, Canada. This multidisciplinary research effort is relevant to both Earth science and astrobiology communities because it can be applied to the study of the development of life on Earth as well as the search for life beyond Earth.

PISCES: The Pacific International Space Center for Exploration Systems (PISCES) is a research and education center dedicated to the development of new technologies and concepts needed to sustain life on the Moon and beyond. It was established by the Japan-US Science, Technology and Space Application Program (JUSTSAP) and is based at the University of Hawaii at Hilo. When fully developed, PISCES will consist of field sites, including a simulated Lunar outpost, and various laboratories and classrooms [19]. In 2008, a PISCES field site was used to assemble scientists from the United States, Canada, Germany and Switzerland to perform the first International Lunar Analog Test. Future campaigns involving more international partners and a wider variety of systems and instrumentation tests are planned for 2010 and beyond [20].

TNA-1: The TransNational Access (TNA) program[12] is part of the Europlanet Research Infrastructure, an initiative funded through the EC's "Framework 7" and aimed at engaging Europe's planetary science community in collaborative research. One of the program's areas, TNA-1, funds

[11] http://www.pavilionlake.com

[12] http://www.isa.au.dk/networks/euroPlanet/index.html

European scientists to perform planetary research at selected sites in Spain, Tunisia, Svalbard, Morocco and Russia that are analogous to environments on Mars, Europa and Titan.

Other: China has identified the Eastern Xinjiang Gobi Desert as its Lunar analog site and intends to use this domestic resource to test space exploration technologies and methodologies [21]. Russia primarily uses closed labs or simulators for such tests, though it also makes limited use of field sites such as the Vostok Lake and Deception Island in Antarctica as well as the Kamchatka Peninsula and Popigai Impact Structure in Russia.

The Earth-based field research programs described above are currently used to prepare for planetary exploration beyond LEO. Several of these programs have strong synergies with Earth science programs [14]. The exploitation of these synergies is critical, as it promotes sustainability for future space exploration programs (Section 3.1 elaborates further on this concept). In addition to Earth-based field research programs in support of space exploration, several programs have been established that focus in particular on human performance aspects [22]. Among them are:

NEEMO: NASA's Extreme Environment Mission Operations (NEEMO)[13] is a program that trains astronauts, scientists, engineers and other individuals for future ISS missions. NEEMO trainees live in an underwater facility, Aquarius, for one to two weeks while simulating EVAs, testing exploration concepts and researching medical issues that may arise during spaceflight.

Mars500: This program involves six crewmembers that are currently simulating a round trip mission to Mars (250 days to Mars, 30 days on the Martian surface and 240 days back to Earth). Since 3 June 2010, the Mars500 crew has lived and worked in a sealed facility in Moscow investigating the psychological and medical aspects of long-duration space missions. Efforts to reproduce a real trip to Mars include limiting supplies and imposing an artificial 20-min delay in communications each way. Mars500 is being conducted under the auspices of the Russian Institute for Biomedical Problems (IBMP) with extensive participation by ESA [23].

2.1.3. Planned Earth-based field research programs

IAN: The International Analog Network (IAN) is the proposed international expansion of CARN to include more analog sites throughout Canada and to make them available to any researcher in a participating country [24].

PISA: Similar to the transformation of CARN into IAN, the Pacific International Space Alliance (PISA) is the proposed international expansion of PISCES. PISA intends to engage governments, universities, industry and non-governmental organizations in PISCES related activities and will use ISECG policies to guide its program [25].

Antarctic Stations: Antarctica and extraterrestrial bodies such as the Moon or Mars share several similarities, including the lack of indigenous populations and existence of extreme conditions where humans require life support technologies to survive. They also represent international arenas where nations are driven by scientific interests to compete and cooperate with each other. Thus, future planetary outposts may profit from infrastructure, research and legal expertise that have been developed at Antarctic stations (ESA is already making use of Concordia Station as a high fidelity analog site). The Scientific Committee on Antarctic Research (SCAR)[14] coordinates scientific research in Antarctica and provides international, independent scientific advice to other bodies. Thirty-one countries that pursue active scientific research programs in Antarctica have joined SCAR as full members. Governance frameworks for future planetary bases could be modeled after SCAR as well as other current in-situ exploration and operations schemes.

The many existing and planned Earth-based field research programs illustrate the importance of these activities as a means of preparing for planetary exploration. These programs provide foundations upon which a united, multidisciplinary research program may be initiated under the auspices of research foundations, academic institutions and national space agencies of both developed and emerging space nations. Mechanisms for launching into this next phase of cooperation are discussed in Section 3.1.

2.2. International scientific exploitation of the ISS enabling exploration

In 1984, US President Reagan directed NASA to build a permanently occupied space station and to seek other nations to join in the program. This presidential invitation led to a series of formal agreements between the station's original partners (Europe, Canada, Japan, and the United States) with Russia being added as a partner later in 1993. After a series of redesigns and negotiations, the 1998 Intergovernmental Agreement (IGA) was established, laying out the fundamental obligations of the ISS program and a framework for long-term cooperation amongst the partners. Four Memorandums of Understanding (MOUs) between NASA and each of the other ISS partners as well as various implementing arrangements have also been established under the IGA in subsequent years in order to implement the design, development, operation and utilization of the ISS.

In 1998, Russia's *Zarya* module became the first ISS node launched into orbit. Major contributions from other ISS partners followed, including Russia's *Zvezda* service module in 2000, NASA's *Destiny* laboratory and Canada's *Canadarm*2 in 2001, ESA's *Columbus* laboratory and JAXA's *Kibo* laboratory in 2008, and NASA's *Tranquility* module and ESA's *Cupola* observation module in 2010. The ISS has been continuously inhabited since 2000 and has supported a full crew of six since 2009. The completion of ISS assembly is expected in 2011.

International cooperation on the ISS has allowed for more facilities, larger crews and better-equipped laboratories available to many space and non-space actors. As the ISS transitions from assembly to utilization, its continued success will depend on how well it is exploited over the coming years. Enhanced utilization will also be an

[13] http://www.nasa.gov/mission_pages/NEEMO/

[14] http://www.scar.org/

important enabler of a future global space exploration program, as ISS facilities serve as unique testbeds for exploration technologies and operational schemes, and ISS partnerships and legal frameworks could give way to those used in missions beyond LEO.

NASA currently plans to prolong ISS lifetime until at least 2020, in concert with the other partners. In February 2010, US President Obama included funding in his FY 2011 Budget Request for this extension as well as for increased utilization of the ISS as a National Laboratory. During a meeting in Tokyo in March 2010, heads of ISS partner agencies also agreed to plan for the ISS until 2028, concluding that they share "strong mutual interest in continuing operations and utilization for as long as the benefits of ISS exploitation are demonstrated" [26]. However, there are specific constraints regarding the implementation of international projects spanning many years or decades. These constraints are due to, for example, the nature of the US annual appropriations process and the European four-year renewal of Member States' commitments to ESA's budget. In the context of the current economic crisis, a robust program must address these programmatic risks by building on political support and including a timeline for definition, approval, budget cycle, confirmation, development and consolidation within the agreed budget.

2.2.1. ISS exploration science

Research on the ISS delivers increasing scientific return. Over 400 experiments have been performed in the last ten years on topics such as biology, human physiology, physical science, material science, Earth science and space science. These experiments and their accomplishments are summarized in *International Space Station Science Research Accomplishments During the Assembly Years: An Analysis of Results from* 2000 to 2008[15] and a summary of current ISS facilities can be found in *Research in Space: Facilities on the International Space Station.*[16]

The ISS serves as a unique laboratory for the international advancement of human and robotic space exploration beyond LEO. Its facilities enable scientific research on the effects of long-duration exposure to the space environment as well as development and testing of technologies and materials for future exploration systems. ESA has recently released a Call for Ideas (CFI)[17] open to a wide range of applicants (including scientific institutions, national agencies, entrepreneurs and industry) to obtain an indication of interest in using the ISS from 2011 onwards (for specific experiments, technology demonstrations, outreach activities, etc.) to prepare for human exploration beyond LEO.

The European Life and Physical Sciences and Applications in Space (ELIPS)[18] program made Europe the largest scientific user of the ISS. Since the early 2000s, the ELIPS program has pursued applied research on the ISS in six disciplines relating to life and physical sciences. ELIPS is currently in its third phase and is conducting studies on radiation biology and physiology; health care and human performance under extreme conditions; life support and thermal control systems; food production in space; fluids handling and processing in space; materials exposure and advanced materials; and contamination prevention and planetary protection.

Japan's *Kibo* Laboratory includes a Pressurized Module, Exposed Facility and a Remote Manipulator System, which collectively house experiments on a wide range of topics such as Earth science, space medicine, material science and communications. *Kibo* is currently in its first phase of utilization (2008–2010), during which it has two scientific research priorities: material science and life science. During this first phase of utilization, *Kibo* will support future human space activities by carrying out relevant technology demonstrations and medical research. *Kibo*'s second phase of utilization (2010–2012) will expand on these activities [27].

Russia's ISS efforts have focused primarily on providing transportation to and from the ISS rather than on developing and utilizing ISS facilities in preparation for human exploration beyond LEO. Russia has recognized that this could result in the country falling behind in human spaceflight along with related science and technology disciplines as other nations continue to invest in this sector [28]. Nonetheless, Russia continues to conduct exploration research using its ISS facilities such as the LADA green house and the EXPOSE-R payload, which are described in Section 2.2.2.

Within the United States, the National Research Council's Space Studies Board is currently conducting the *Decadal Survey on Biological and Physical Sciences in Space*[19] (the Interim Report[20] was released in July 2010 with the final report due in early 2011). This decadal survey will define and prioritize US objectives for life and physical science research in microgravity over the next decade in order to meet the multidisciplinary challenges of future space exploration activities. It will also identify potential research synergies between NASA and other US government agencies, commercial entities and international partners. NASA will use these recommendations to develop an implementation plan for exploration experiments and missions in LEO and beyond.

Canada contributes to ISS exploration science through various initiatives. CSA's OSTEO experiments study the bone cell behavior in microgravity for further understanding of human bone degradation in space. In 2002 and 2003, CSA conducted Extravehicular Activity Radiation Monitoring (EVARM) experiments that used dosimeters in the form of small badges placed inside spacesuits to measure the levels of radiation astronauts received during spacewalks, with the aim of optimizing spacesuit radiation shielding. Currently, CSA sponsors Bodies in the Space Environment (BISE), a series of computer-based tests conducted on ISS

[15] http://www.nasa.gov/pdf/389388main_ISS%20Science%20Report_20090030907.pdf

[16] http://nasa.gov/pdf/393789main_iss_utilization_brochure.pdf

[17] http://www.esa.int/SPECIALS/HSF_Research/SEMB4VVO1FG_0.html

[18] http://www.spaceflight.esa.int/users/index.cfm?act=default.page&level=16&page=453

[19] http://sites.nationalacademies.org/SSB/CurrentProjects/ssb_050845

[20] http://www.nap.edu/catalog.php?record_id=12944#toc

Table 3
Sampling of current ISS facilities for exploration research.

Facilities (Launched)	Owners	Subjects	Descriptions
Destiny (2001)	NASA	Various	NASA's primary pressurized research laboratory
HRF-1/2	NASA	Physiology	Researching the effects of long duration spaceflight on humans and testing countermeasures for preventing the negative effects of space travel
ALTEA	NASA	Physiology	Helmet-like device measuring the effects of cosmic radiation passing through the ISS on human brain activity and visual perception
Tranquility (2010)	NASA	Various	The newest pressurized module to the ISS
ARED	NASA	Physiology	Providing new exercise capabilities on the ISS and collecting data regarding loads, repetitions, strokes, and other parameters regarding crew exercise
COLBERT	NASA	Physiology	Treadmill for crew exercise and studying how to maintain cardiovascular health and prevent muscle and bone loss during long duration spaceflight
Columbus (2008)	ESA	Various	Pressurized laboratory harboring several research facilities
Biolab	ESA	Biology	Researching the effects of the space environment on biological organisms
FSL	ESA	Physical Material Science	Multiuser facility for conducting fluid physics experiments in microgravity to aid development of fluid delivery systems in future spacecraft
Kibo (2009)	JAXA	Various	Also known as the Japanese Experiment Module (JEM)
AQH	JAXA	Biology	Tanks accommodating small fish for experiments on the effects of the space environment on living organisms
JEM Exposed Facility	JAXA	Various	Unpressurized external platform holding up to 10 payloads for research in communications, material processing, engineering, etc.
Zvezda (2000)	ROSCOSMOS	Various	First multipurpose research laboratory of the ISS
LADA Greenhouse	ROSCOSMOS	Biology	Supporting multigenerational experiments on plant biology and space farming for a variety of plants such as sweat peas, tomatoes and lettuce
EXPOSE-R	ROSCOSMOS	Biology	An external payload facility holding variety of biology experiments that require long term exposure to the harsh space environment
EXPRESS Racks (Various)	Various	Various	Modular, multipurpose payload racks storing and supporting ISS experiments, located on the *Destiny, Columbus* and *Kibo* Modules.
SpaceDRUMS (*Tranquility*)	NASA	Material Science	Hardware for conducting containerless material processing to develop advanced materials for new spacecraft and future Moon and Mars bases
EMCS (*Columbus*)	ESA	Biology	Growth chambers for conducting multigenerational experiments on the effects of microgravity on early development, small organisms and plants

crewmembers to discern how humans orient themselves in near-weightless environments.

2.2.2. *ISS facilities for exploration research*

ISS facilities are currently being used for exploration research, as summarized in this section and sampled in Table 3. Many of these facilities are installed on specific modules, though collaboration exists between space agencies and research institutions so that they may be exploited more widely. Some smaller pieces of hardware are portable, allowing for utilization on various ISS modules.

***Destiny* (NASA)**: As NASA's primary pressurized research laboratory, *Destiny* harbors a wide range of experiments and hardware to help prepare for future missions beyond LEO. For example, its Human Research Facility (HRF) conducts experiments that further our understanding of the effects of long duration spaceflight on the human body and tests countermeasures for preventing the negative effects of space travel. The Anomalous Long Term Effects in Astronaut's Central Nervous System (ALTEA) is a helmet like device that measures the effects of cosmic radiation passing through the ISS on human brain activity and visual perception.

***Tranquility* (NASA)**: As the newest pressurized module to the ISS, NASA's *Tranquility* accommodates advanced life support and environmental control systems as well as second generation exercise equipment such as the Advanced Resistive Exercise Device (ARED) and the Combined Operational Load Bearing External Resistive Exercise Treadmill (COLBERT). ARED and COLBERT have been designed to provide more efficient and effective exercise as well as relay data back to NASA exercise physiologists to further understanding of how exercise helps maintain cardiovascular health and prevent muscle and bone loss experienced during long duration spaceflight.

***Columbus* (ESA)**: ESA's *Columbus* Module is a pressurized laboratory that houses several research facilities used as testbeds for space exploration. Among them is Biolab, a facility designed to support experiments on microorganisms, cells, tissue cultures and small plants and invertebrates that further understanding of the effects of the space environment on biological organisms. The Muscle Atrophy Research Exercise System (MARES) is an exercise instrument for researching the effects of microgravity on muscles. The Fluid Science Laboratory (FSL) investigates the physics of fluids in space for the design of fluid delivery systems in future spacecraft. The Columbus External Payload Facilities (CEPF) is a multiuser external attachment to the outside of the *Columbus* Module with fittings for four external payloads or facilities. Two attachments currently hold European payloads: the European Technology Exposure Facility (EuTEF) for experiments requiring exposure to the space environment and a platform for measuring solar spectral irradiance known as Solar. CEPF also houses experiments of other ISS partners, such as NASA's Materials International Space Station Experiment (MISSE) for testing the durability of potential spacecraft materials.

***Kibo* (JAXA)**: Also known as the Japanese Experiment Module (JEM), *Kibo* is a pressurized laboratory for experiments in space medicine, biology, Earth observation, material production, biotechnology and communications. In particular, its Saibo Experiment Rack is a multipurpose payload rack accommodating various life science experiments and consisting of a Clean Bench glovebox for isolating organisms being studied and a Cell Biology Experiment Facility that includes an incubator, centrifuge and sensors. Its Aquatic Habitat (AQH) houses small fish for investigating the effects of space environmental factors on living organisms. The Remote Manipulator System (RMS) connects the pressurized laboratory to the JEM Exposed Facility (JEM-EF), an unpressurized external platform that can hold up to ten experiment payloads for research in various fields, including those related to future space exploration.

***Zvezda* (ROSCOSMOS)**: *Zvezda* was the first ISS multipurpose research laboratory and remains a key supporter of exploration research on the ISS. Its Human Life Research program consists of various systems for studying human life in space, such as the Immune System Study Kit and Weightlessness Adoption Study Kit. *Zvezda's* LADA greenhouse has also been used to study fundamental plant biology and space farming by growing multiple generations of sweet peas, wheat, tomatoes and lettuce in microgravity. EXPOSE-R, a payload facility mounted on the outside of *Zvezda*, holds a variety of biology experiments that require long duration exposure to the space environment.

EXPRESS Racks: Expedite the Processing of Experiments to Space Station (EXPRESS) Racks are modular, multipurpose payload racks that store and support ISS experiments. EXPRESS Racks are currently located on the *Destiny*, *Columbus* and *Kibo* Modules and often house experiments contributing to exploration activities. Examples include NASA's Advanced Biological Research System (ABRS) for growing plants, microorganisms and small arthropods; ESA's European Modular Cultivation System (EMCS) for multigenerational studies on the effects of gravity on the development and growth of plants and small organisms; and NASA's Space Dynamically Responding Ultrasonic Matrix System (SpaceDRUMS), a collection of hardware for containerless material processing to develop advanced materials for future spacecraft and planetary bases. EXPRESS Racks are the most flexible modular research facility currently on the ISS, with 50 percent of the racks still available for use.

Given its newly integrated facilities and enhanced crew of six, it is crucial that the ISS be exploited by a wider variety of space and non-space actors (including emerging space powers, developing countries, academic institutions, private organizations and others) in cooperation with the ISS partners. Europe took a step in this direction in October 2010 with the announcement of a new policy that will allow European non-ISS partner countries to place experiments on the ISS during a three-year trial period through 2013.[21] The next decade will be vital for leveraging the ISS to advance exploration science research. It will also be important to integrate this research with supporting non-ISS projects such as Earth-based bed rest and isolation studies as well as microgravity experiments using parabolic flights, drop towers and sounding rockets. Mechanisms for achieving these goals are discussed in Section 3.2.

2.3. Worldwide CubeSat program in support of exploration

CubeSats represent a specific type of nanosatellite measuring $10 \times 10 \times 10\ \text{cm}^3$ and weighing slightly more than 1 kg. Their small size and mass make them relatively inexpensive and simple to build and allow them to be launched as secondary payloads at much lower cost and higher frequency than traditional monolithic satellites. The standard CubeSat size of 1U ($10 \times 10 \times 10\ \text{cm}^3$) has been scaled to other configurations such as the 2U ($20 \times 10 \times 10\ \text{cm}^3$), 3U ($30 \times 10 \times 10\ \text{cm}^3$) and 6U ($30 \times 20 \times 10\ \text{cm}^3$) CubeSat.

CubeSats began as an affordable educational tool for university students in science and engineering fields to gain hands-on experience in aerospace development programs. In more recent years, the wider utility of CubeSats has been increasingly recognized; countries now see them as cost-effective platforms for performing science research, technology demonstrations, and education and outreach activities (see Table 4). Indeed, fast and inexpensive development from concept to launch is important not only for educational programs, but also for emerging space powers and developing countries with limited space budgets and technical expertise. Moreover, CubeSats have demonstrated their potential as testbeds for advanced technologies as well as platforms for research in astrobiology, astronomy, Earth observation, atmospheric science and other fields [9].

There are several major organizations currently promoting CubeSats and other small-class satellites. ESA's Education Office sponsors the Student Space Exploration and Technology Initiative (SSETI),[22] which among other

[21] http://www.spacenews.com/civil/101021-europe-broaden-access-iss.html

[22] http://www.esa.int/esaMI/sseti_express/SEM19Z708BE_0.html

Table 4
Sampling of completed and planned CubeSat science and technology missions[a]

Subjects	Missions	Lead entities	Launches	Descriptions
Astrobiology	*O/OREOS*	NASA Ames Research Center	11/2010	Studying the effects of the space environment on organic compounds
Astronomy	*BRITE, CanX*-3, *TUGSAT*-1	CSA, FFG, University of Vienna	2011	Constellation of nanosatellitesforstudying asteroseismology
Atmospheric science	*FIREFLY*	NSF, NASA	06/2010–12/2011	Studying links between lightning and terrestrial gamma ray flashes
Biology	*GeneSat*-1	NASA	2006	Studying microorganisms at the gene and protein level when exposed to the space environment
Biology	*PharmaSat* (*GeneSat*-1 successor)	NASA	2009	Studying how microgravity effects the response of yeast to antifungal treatment
Education and outreach	European CubeSat Workshop	ESA	2008	Annual student workshop on CubeSat development
Earth observation	*CanX*-2	UTIAS SFL	2008	Usingan Argus IR spectrometer to analyze atmospheric gases over Ontario, Canada
Electronics	*Robusta*	CNES/ESA/Montpellier University	In progress	Validating test standards for space radiation effects on electronics
Material processing	*HawkSat*-1	Hawk Institute for Space Sciences	2009	Researching commercial material processing (could not establish communication)
Space weather	*RAX*	University of Michigan, SRI International, NSF	11/2010	Investigating plasma instabilities that lead to magnetic field-aligned irregularities of electron density in the lower polar thermosphere
Technology demonstration	*LightSail*-1	Planetary Society	2011	Demonstrating solar sail propulsion technology in LEO

[a] Adapted from Woellert et al. [9].

things promotes and conducts student nanosatellite projects. ESA also organizes the European CubeSat Workshop, an annual event where students learn about small satellite development and discuss CubeSat related topics with experts as well as each other. Within the United States, its National Science Foundation has established a CubeSat program to support development, construction, launch, operation and data analysis of CubeSats missions for research on space weather and atmospheric science. NASA's Astrobiology Small Payloads Program is currently conducting a scientific CubeSat mission, O/OREOS, described in more detail in Section 2.3.1.

2.3.1. CubeSats for emerging space nations and developing countries

While analyzing the historical paths of eight developing countries[23] as they pursued national space capabilities, Wood and Weigel [10] established a framework called the Space Technology Ladder. The Ladder is an idealized path that a country could follow as it develops national space capabilities of increasing technological difficulty. Using the Ladder, common decision areas for countries pursuing national space capabilities were identified as well as different approaches taken when dealing with these shared issues. Wood and Weigel noted that all eight of the analyzed countries chose to depend on a foreign government or company to execute at least one of the Ladder's milestones. They expressed concern that countries of lower technological sophistication are often at a disadvantage in these partnerships, and that it would therefore be beneficial for a country to first build up some independent capability in order to partner later when more technologically equal. This raises the question, however, of how a country can independently build up space capabilities without the help of foreign entities.

CubeSats could be one solution. Compared to traditional monolithic satellites, CubeSats provide a relatively simple, low-risk and expeditious method of independently gaining foundational experience in space technologies. One successful example of this approach is the *Libertad*-1 CubeSat, Columbia's first satellite, launched in 2007. An eight-member team from the Universidad Sergio Arboleda with no prior satellite development experience produced *Libertad*-1 at a total cost of only $250,000. Indeed, CubeSats are demonstrating their ability to provide cost-effective, space-based science and technology platforms for emerging space powers and developing nations [9].

The UN has formally recognized the value of small satellites to emerging space nations and developing countries. Small satellite projects build expertise in basic space technologies and contribute to the planning and implementation of certain UN programs and projects for developing countries. In order to promote its cause, the UN hosts regular small satellite conferences such as the

[23] Algeria, Egypt, Nigeria, India, Malaysia, South Korea, Argentina, and Brazil.

UN/Austria/ESA Symposia and the UN/IAA Workshops on Small Satellites.

2.3.2. CubeSats contributing to exploration science

CubeSats can play a supportive role in exploration activities. Several pioneering CubeSat missions (sampled in Table 4 and summarized in this section) have recently demonstrated the ability to conduct scientific experiments in the fields of biology and Earth observation; planned missions in 2010 will validate their utility in other fields related to space exploration such as planetary science and space weather. CubeSats are also being used to demonstrate technologies for future space exploration, in particular solar sail propulsion. Moreover, it is envisaged that CubeSats will "piggyback" on primary orbiters traveling to the Moon and Mars to support planetary science missions.

***GeneSat*-1 and *PharmaSat* (NASA):** *GeneSat*-1,[24] under the auspices of NASA, was a successful biological science mission demonstrating the ability of free-flying CubeSats to conduct fundamental biology experiments at low-cost. *GeneSat*-1 studied the biological changes in *E. coli* microorganisms at the gene and protein level when exposed to the space environment, which furthered understanding of the impact of spaceflight on biological organisms as well as how to develop effective countermeasures. Using the same 3U configuration, *PharmaSat*[25] built upon the flight heritage of *GeneSat*-1 to study how microgravity affects the response of yeast to antifungal treatment, which furthered understanding of the efficacy of drugs in space.

***LightSail*-1 (The Planetary Society)**: The LightSail[26] program will investigate the viability of using solar sail propulsion in space exploration missions. *LighSail*-1 is the first spacecraft of the program and it will use three CubeSats to demonstrate solar sail propulsion in LEO (*LightSail*-2 and *LightSail*-3 will be larger spacecraft with more ambitious missions going beyond Earth orbit). Final designs for *LightSail*-1 are currently underway and the Planetary Society is working with NASA Ames Research Center to secure a secondary payload launch for 2011 [29].

RAX: The Radio Aurora Explorer (RAX)[27] is a mission that will study space weather. It is a joint effort between the University of Michigan and SRI International, funded by the US National Science Foundation. RAX will investigate plasma instabilities that lead to magnetic field-aligned irregularities (FAI) of electron density in the lower polar thermosphere (80–300 km). Plasma turbulence degrades communication and navigation signals and the results obtained by RAX can improve current communication and navigation technologies. The satellite is a 3 kg CubeSat and was launched successfully in November 2010 as secondary payload on a Minotaur IV rocket from Kodiak.

O/OREOS (NASA): As part of NASA's Astrobiology Small Payload Program, the Organism/Organic Exposure to Orbital Stresses (O/OREOS) CubeSat will study the effects of the space environment on organic compounds and demonstrate technologies to investigate the viability of small, low-cost space missions for conducting astrobiology experiments. O/OREOS will be NASA's first mission with the ability to support two independent science payloads on a single free-flying CubeSat. O/OREOS was successfully launched in November 2010.

CubeBots: As an extension of the concept of CubeSats in orbit, CubeBots are exceptionally small sized (1–100 kg) mobile surface systems that could provide more affordable opportunities and thus broader participation in future space exploration missions. Over the past decade, exceptionally small robotics systems have increasingly become a practical means of enabling space exploration including scientific investigation [6]. CubeBots could take advantage of recent advances in technology miniaturization to facilitate low-cost secondary payload opportunities accompanying primary surface missions to extraterrestrial bodies. These systems have several limitations, in particular those regarding communications, precise transportation and landing, and power and thermal management. However, these challenges could be overcome by sending CubeBots in groups and then linking the individual CubeBots to each other as well as to primary surface systems in order to extend CubeBot lifetime and increase data return [6].

CubeSats are becoming an affordable means of conducting scientific research and technology development. They are also being recognized as valuable tools for developing countries, as they serve as entry-level missions for gaining basic space technology and operational expertise. Current CubeSat activities in developing countries are focused on providing human benefits through Earth observations, disaster management and communication. However, the revolution in the development of valuable science payloads supporting space exploration goals for this category of small satellites provides an attractive opportunity for developing countries to embark in science and technology support for exploration. A worldwide CubeSat program that supports exploration and integrates emerging space nations and developing countries in a meaningful way will prepare for broader participation in a future global space exploration program. Mechanisms for achieving this are discussed in Section 3.3.

3. Coordination mechanisms to prepare for global space exploration

New coordination mechanisms that embrace a wider range of space actors and emphasize long-term cooperation will be required to make the anticipated era of global space exploration sustainable [11]. While new models of cooperation should be built upon legacy partnerships, they also should be targeted to include emerging space nations and developing countries. By focusing on the three stepping stones presented in this paper – (1) an international Earth-based field research program preparing for planetary exploration, (2) enhanced exploitation of the ISS enabling exploration and (3) a worldwide CubeSat program supporting exploration – the evolving space community will be able to take a logical approach toward building a sustainable global space exploration program while

[24] http://genesat.arc.nasa.gov/
[25] http://tia.arc.nasa.gov/pharmasat/
[26] http://www.planetary.org/programs/projects/solar_sailing/
[27] http://rax.engin.umich.edu/

also including emerging space nations and developing countries in a meaningful way. This section discusses potential coordination mechanisms for successfully implementing these stepping stones.

3.1. Establishing an international Earth-based field research program

3.1.1. Advantages

Although there are a number of Earth-based field sites currently being used to prepare for planetary exploration, no integrated program exists to bring together these shared efforts (see Section 2.1.2). Consequently, there is no common focus, roadmap or database within the community. In order to promote sustainability for global space exploration, there is a need for a coherent program established in consensus with partners worldwide and supported by space agencies, National Science Foundations and other relevant entities. An international Earth-based field research program is therefore an important stepping stone toward a future global space exploration program because it brings together space actors with different capabilities, thereby enhancing individual potentials and fostering collaboration. It also provides an international testbed for operational schemes and managerial frameworks, which can be fine-tuned on Earth and then applied in future activities on planetary bodies. Moreover, it increases public awareness and engagement for planetary exploration at various locations around the globe.

Most notably, lessons learned from working together on Earth in the near-term will provide important insights into how to successfully implement specific exploration missions to the Moon and Mars in the future. Transnational cooperation will stimulate the sharing of expertise and possibly resources as well as encourage the establishment of common standards, methodologies and frameworks [11]. International teams working together in the field will allow logistical, cross-cultural, proprietary and legal obstacles to be identified *before* embarking on ambitious activities beyond Earth, where solutions are more difficult to formulate and implement successfully [30]. In addition, an international Earth-based field research program will help to address the current gaps in analog studies that were identified in a recent report by the International Space University [31], in particular the need for "a long-duration analog mission design that includes robotic assistance as an integral part of the mission." The report also proposed to establish a metric to enhance cooperation, ease standardization, and sufficiently exploit datasets of analog studies worldwide. An international analog program will help to address the current gaps in analog studies as well as facilitate the establishment of such a metric by bringing together various contributors at an early stage through a coherent program.

Emerging space nations could make meaningful contributions to this program through, for example, the provision of small hardware elements. This would in turn allow them to gain valuable practical experience to support later more complex space activities. Developing countries would most likely be unable to offer direct contributions to the program in terms of hardware, but could host field campaigns (if suitable terrain exists within their country) and would benefit from observing these activities and using them as a means of educating and inspiring students. The recent proposal to use the Sainte-Rose Moon–Mars analog volcanic site at La Reunion for future robotic and human exploration provides a good example for such activities in developing countries [32].

3.1.2. Recommendations for implementation

A common roadmap for utilizing Earth-based field research sites should be established in consensus with many international partners with a long-term perspective to enhance sustainability. Campaigns should evolve from simple field trips characterizing the geological environment to complex endeavors testing large infrastructures. Evaluation of data and results should involve all participants in order to embark on important issues such as standardization, computer methods and archiving. Engaging the public and media in such initiatives is already a common practice and will be required to raise awareness in a future global space exploration program [33].

To further promote sustainability in such a program, the synergies of space exploration and Earth science should be exploited on technical, managerial and political levels [14]. This can be done through the study of life in extreme environments, which is important for understanding the limits and adaptability of life on Earth as well as on other planets. A successful model upon which to establish such an initiative is CAREX, a program recently founded within the European Commission's "Framework 7". CAREX is a multinational initiative (its network includes 58 European and non-European partners) that takes an interdisciplinary approach to research on life in extreme environments by covering subjects from microbes to animals and environments from oceans to outer space. Using workshops, summer school sessions and Knowledge Transfer grants, CAREX facilitates networking and knowledge exchange amongst European scientists and aims to establish a strategic European research agenda. Adopting a CAREX-like model and expanding it globally to support an international Earth-based field research program will encourage cooperation between the Earth science and planetary science communities as well as facilitate information exchange, efficiency and sustainability. National Science Foundations and other research institutions should be involved in addition to space agencies in order to engage experts from both communities.

Given the similarities between Antarctica and extraterrestrial bodies (see Section 2.1.3), successful operation and in-situ exploration models could be derived from SCAR activities that use regular meetings to exchange information about scientific research and expeditions; discuss compliance with environmental provisions; and confer on matters of common interest. A comparable model adopted for an international Earth-based field research program would allow for a constant dialogue between partners worldwide that would facilitate the exchange of information on scientific and technological advancements; discussions on environmental protection regulations and compliance; and the potential sharing of resources in the pursuit of common interests.

3.2. Enhanced scientific exploitation of the ISS enabling exploration

3.2.1. Advantages

Expanding international cooperation in the use of ISS facilities through a long-term, science research and technology demonstration program is essential for the future of global space exploration. The ISS is a unique laboratory for the international advancement of human and robotic exploration, as it enables scientific investigations regarding the effects of long-duration exposure to the space environment as well as the development of technologies and materials for future exploration systems. By building upon its international governance model and maximizing the use of its recently integrated facilities, the role of the ISS over the coming years will be to "provide important technical, operational, and management experience in the conduct of long duration, multinational space missions" [34].

It has been discussed on several occasions that including materializing space powers like China and India as space station partners is desirable. In addition, UN bodies have initiated discussions on how scientists from emerging space nations and developing countries could be integrated with ISS agencies to produce meaningful results. By restricting such cooperation to research, (e.g. sharing research facilities, data downlink opportunities and data dissemination capabilities within the framework of an international program), potential legal and technical issues arising from the involvement of non-ISS partners may be limited. Although prohibitive regulations such as ITAR still exist, new export control reforms have recently been supported by the White House and are now under consideration by the US Congress. The restructuring of the control lists, in addition to the harmonization of licensing policies and development of a single information technology system, will streamline the process of involving non-ISS partners in scientific research onboard the ISS.

Proper commitments will be required for the successful expansion of ISS participation. This need was highlighted by the NASA-Brazil partnership, established by an Implementing Arrangement signed in October 1997. Under the agreement, Brazil was to provide six pieces of hardware as part of NASA's ISS quota, while NASA was to provide Brazil with certain ISS utilization rights. However, Brazil was unable to deliver any of the elements due to a lack of funding and political priority within the country [35]. The shortcomings of this partnership illustrate the need for new mechanisms that ensure expanded ISS participation remains a high political priority within participating countries in order to ensure funding and produce meaningful results.

3.2.2. Recommendations for implementation

Upon completion of the ISS in 2010, only 48 percent of NASA's EXPRESS racks and 33 percent of NASA's external research sites will be utilized with the remainder available for other use. This availability was intentional so that the ISS would not only support NASA research, but also the research of the broader scientific community [36]. Although these available payload racks are intended for National Laboratory users (i.e. US public and private entities) to perform studies that further their own objectives, some racks should be reserved for developing countries and emerging space nations to conduct experiments in exchange for data sharing or other research related items.

Scientific utilization of modular payload racks (e.g. EXPRESS racks) would be a logical first step toward expanding ISS participation, as developing countries and emerging space nations do not have the expertise or budget to contribute station segments or provide transportation. Moreover, data sharing as a means of repayment would be consistent with NASA's "no exchange of funds" policy. Scientific cooperation could also be used to build up trust between existing and potential ISS partners in anticipation of more frequent and higher risk activities, such as hosting non-partner astronauts on the ISS or jointly developing in-situ resource utilization systems for missions beyond LEO.

In order to coordinate these activities and ensure the proper commitment of funding from these new participants, the United Nations Committee on the Peaceful Uses of Outer Space (UN-COPUOS) could identify one scientific entity from each developing country or emerging space nation wishing to participate in the ISS (in an area in which the country has developed expertise) and then match it with a scientific activity of an ISS partner. In the event that it is difficult to identify the scientific entity, announcements of opportunity or requests for letters of intent could be used. Support should also be provided by organizations that fund capacity building such as the Committee on Space Research (COSPAR). The involvement of the UN and other capacity building organizations will help to ensure the political and programmatic commitment needed to sustain funding and continuity.

3.3. Worldwide CubeSat program in support of exploration

3.3.1. Advantages

CubeSats are an ideal platform for a worldwide program that engages a wide range of space actors because their standard specifications and use of mostly commercial off-the-shelf components minimizes the potential transfer of sensitive technologies. Moreover, the lower costs associated with CubeSat development, deployment and operation in comparison to traditional monolithic spacecraft lower the barrier of entry for countries with more restricted budgets and limited expertise. Thus, developing countries in particular have a lot to gain from a worldwide CubeSat program enabling exploration, as it would allow them to secure basic capabilities in satellite development and operation at low cost and in a relatively short timeframe. The fast development cycle of science payloads addressing space biology, space weather, atmospheric science, material processing, astronomy and others [9], all relevant to space exploration goals, provides opportunities for aspiring space nations to advance technology and to participate in the larger framework of a global space exploration program. As mentioned before, basic space science and space applications (such as remote sensing) are both pillars of the UN program to promote the benefits of space-based solutions for sustainable economic and social development [8]. Although emerging space nations have already surpassed the level of technical autonomy and complexity required to independently develop a CubeSat, they can still use the program for training in space project development and management. Moreover, both developing countries and emerging space nations can benefit from using CubeSats as low-cost platforms for science research and technology demonstrations.

The UN has formally recognized the value of small satellites to developing countries. In 1999, the UN Office for Outer Space Affairs (OOSA) and the IAA began jointly holding annual workshops with the theme of Small Satellites at the Service of Developing Countries. Over the years, workshop participants have acknowledged that for developing countries small satellite technologies are an effective means of developing more complex indigenous space capabilities; advancing an associated science and technology industrial capacity and knowledge base; motivating and training students in related fields; and promoting international cooperation and interoperability [8]. A recent development of these workshops is a new initiative within the framework of the UN Program on Space Applications known as the UN Basic Space Technology Initiative (discussed in more detail in Section 3.3.2).

3.3.2. *Recommendations for implementation*

A successful worldwide CubeSat program in support of space exploration must find a way to maximize the involvement of potential stakeholders as well as the production of meaningful contributions to exploration. The involvement of UNBSTI could facilitate the process, as it intends to be an information broker and interface between stakeholders in the small satellite community, especially between those that have already demonstrated space capabilities and those seeking to establish them [8]. The UNBSTI would serve as a promoter of standardization and coordination by engaging many international stakeholders and promoting mutual benefits and meaningful scientific and social return. This approach would engage participants beyond national space agencies, thereby avoiding any formal political commitment to large-scale initiatives, and allow for different entities to follow their own rationales for engaging in such missions—all important characteristics for sustainable international cooperation in space [34].

One area of cooperation that would greatly benefit the global CubeSat community is the establishment of a worldwide ground station network. Due to a combination of low orbits and limited ground station availability, a significant challenge when operating CubeSats is the narrow window of opportunity to downlink data within a reasonable time period after its collection. A worldwide ground station network would alleviate this problem by providing near continuous periods of communication with CubeSats. The ease of establishing ground station networks has increased over recent years due to the maturation of the Internet, low-cost standard communication hardware and open-source software [9]. Providing a ground station node as part of a worldwide network is therefore an ideal way for smaller space actors to make valuable yet affordable contributions to the global CubeSat community; establish collaborative relationships with various space faring entities around the globe; gain returns in the form of technical and operational experience; and build up science and technology infrastructure within their countries. One successful satellite ground station project in development since 2006 is the Global Educational Network for Satellite Operations (GENSO).[28] Connected by the Internet and interacting via standard software, GENSO is an international network that aims to provide near-global communications coverage for every educational satellite launched, greatly increasing the educational return from these space missions.

A model of cooperation that has not yet been demonstrated is scientific data sharing in exchange for ridesharing. CubeSats developed by emerging space nations could be transported to the Moon or Mars through "piggyback rides" on more complex spacecraft developed by experienced space powers. Once at their deep space destinations, CubeSats would detach from their parent satellites to collect data on scientific research questions, identify human exploration risks or investigate planetary protection concerns. These data would then be shared in exchange for the piggyback rides.

4. Conclusion

A sustainable global space exploration program capable of conducting complex sample return and human exploration missions beyond LEO can only be made possible through international agreements and the involvement of established and emerging space nations along with developing countries. In this paper, we proposed three major stepping stones toward achieving this goal: (1) an international Earth-based field research program preparing for planetary exploration, (2) enhanced exploitation of the ISS enabling exploration and (3) a worldwide CubeSat program supporting exploration. Implementing these stepping stones will unite key stakeholders in the early stages as well as improve and ease technology transfer and cross-cultural management while also ensuring the development of interfaces that form the major prerequisites and building blocks for a future global space exploration program.

An international Earth-based field research program will serve as a truly global exploration testbed to help better prepare for future planetary exploration as well as provide opportunities for emerging space nations to foster partnerships and expand their individual capabilities. Enhanced exploitation of the ISS during its prolonged lifetime will be critical to advancing exploration beyond LEO and will also provide ample opportunities to involve new space actors in meaningful research and technology demonstrations. A worldwide CubeSat program will be particularly useful for building up basic space capabilities and science knowledge in developing countries thus enabling them to integrate in a global space exploration effort.

This stepping stone approach that includes the broad participation of many stakeholders worldwide will provide

[28] http://www.genso.org/

a bottom-up support structure to bridge the transition phase from the present state of space exploration to future large-scale endeavors and space infrastructures. Space agencies, National Science Foundations, UN bodies, COSPAR, IAA and other capacity building organizations should support such a stepping stone approach in order to reach a new level of cooperation in space exploration necessary to create effective and efficient partnerships for the future as well as foster sustainability.

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