Metztli is the Aztec goddess of the Moon. She has two faces; one face representing the protection of the harvest and promotion of growth, and the other bringing the cold, mysterious shapes found in the night.

Metztli is the product of a Team Project of the International Space University’s (ISU) 2003 Summer Session Program. Forty-six students from a diverse set of national, cultural, and disciplinary backgrounds chose to participate in the project.

Mission

To create an international approach to peaceful lunar development which encourages a permanent lunar presence and furthers space exploration.

Scope

To examine ways in which the International Space Station assets and organisation can be utilised to support a programme of lunar development and exploration.
The Moon has been a source of inspiration for nearly every civilization in human history. Although significant advances have been made in our knowledge of the Moon, there is still much yet to be discovered. In this manuscript, a framework has been outlined that promotes a deeper understanding of the Moon, from its origin to its current state. Pursuing this framework will provide substantive knowledge and enabling technologies necessary to lead to sustained human presence on the Moon.

Phase I

Earth-Based Research: Ground-based mission simulations will investigate closed-habitat operations (including Environmental Control and Life Support Systems - ECLSS), social and psychosocial human aspects, operations and control, robotic and automated processes, surface issues, and infrastructure aspects.

Cislunar Space Research: A frame of research focused on the cislunar environment is required, with emphasis on understanding the radiation effects on living organisms and electronic hardware while spacecraft travel in this region.

Orbital Exploration of the Moon: Lunar development and increased exploration will require detailed mapping of the lunar surface and sub-surface, information on the lunar environment, lunar surface processes and evolution, materials, chemistry, and physical properties. Improved remote sensing orbiters will provide a lot of this information.

Reduced-Gravity Research: Phase I calls for preliminary investigations of the effects of gravity on fundamental processes, such as granular flow, fluid dynamics, and chemical reactions, as well as reduced-gravity life sciences. Research into the latter will focus on cardiovascular deconditioning, muscle atrophy, bone loss, and neurovestibular disorders. Phase I also requires research into lunar In Situ Resource Utilisation (ISRU).
Phase II

Communication/Navigation: At first, remote sensing orbiters will double as communications / navigation relays. With increased lunar development, a dedicated satellite network will be required.

Astronomy: Lunar-based astronomical observatories are an important aspect of using the Moon for science. Phase II will begin lunar astronomy with simple radio antennas and possibly small infrared and ultraviolet telescopes on the surface.

Trials for Earth-Moon Transportation System: Phase II will include precursors of the transportation system that will carry humans and cargo between the Earth and Moon.

ISRU Precursors: Robotic precursors will test ISRU processes on the Moon. These tests will focus on extracting hydrogen and oxygen, as well as by-product metals. After the precursor missions, ISRU capabilities will be developed on a larger scale to prepare for the increased lunar development of Phase III.

Phase III

Phase III begins once the transportation system is implemented. Relying on the system’s capabilities, the minimum infrastructure to support human habitation on the Moon will be completed. These efforts will result in a human lunar outpost largely sustained by fully operational ISRU and ECLSS.

Robotic Lunar Surface Studies: Robotic rovers will investigate the lunar surface and subsurface. These studies will augment remote sensing of the geochemical and geophysical properties of the Moon, particularly in the polar regions.
In designing a lunar programme (or any programme) that will be humanity’s next step in space, it is prudent to give particular thought to the role of the International Space Station (ISS). A main motivation for using the ISS is to extend the international partnership, already established, to the next possible step in space exploration, namely towards the Moon. In this regard, aside from complementary studies, the synergetic effect of a global partnership could unite the lunar programmes of individual space-faring nations.

With one of its objectives being to provide a testbed for developing 21st Century technology, the ISS has a great potential to support the development of technology for a lunar programme. The ISS can facilitate the initial micro-lunar researches, simulation, and findings for eventual permanent human presence on the Moon. Various modules and components of the ISS are invaluable towards a successful lunar programme.

**Scientific Support**

Scientific experiments and research onboard the ISS can help resolve questions of fundamental biology, chemistry and physics, in addition to practical matters crucial for planned permanent human presence on the lunar surface.

The ISS would be a useful training ground for crew simulation and adaptation. One can analyse the various psychological, social, and physiological issues in a extended-stay microgravity environment. This would have direct applications to future extended-stay lunar environments.

The ISS’s Centrifuge Accommodation Module creates the opportunity for a simulation of lunar gravity. With lunar gravity (which is one-sixth of Earth’s gravity) simulation, further analysis can be performed on how plants grow and metabolise on the Moon. This analysis would help humanity determine the requirements for food sustainability in future lunar operations.
The ISS allows for various radiation studies. The ISS Matroshka, a simulated astronaut, could help in determining the effects of radiation in LEO and potentially in cislunar space and on the lunar surface.

Technical support

The ISS can serve as a development base for bio-regenerative life support systems. This would assist potential human lunar activities where ECLSS are essential.

The ISS can use its current low-temperature facilities, human research facilities, and robotic arms to technically support potential lunar activities.

In promoting lunar exploration for humankind, it is important to raise public interest about going to the Moon. The ISS – with its international nature, long-term human presence, and its visibility in the sky – can be a great vehicle for reaching out to the public worldwide. By taking advantage of the international nature of the ISS, we can gain public appeal toward worldwide unity for lunar exploration. Space agencies should make a greater use of the ISS as an outreach tool to get the public interested about moving from the space station to the Moon.
Going to the Moon requires a transportation system. This report addresses the potential for using the ISS, at the end of its current mission, as one means of transportation to the Moon. It intends to capitalise on the programme’s significant political and industrial backing, and the resources already expended on it. If the technology to go to Moon via the ISS could be established, then it could become the model upon which future lunar relay bases are composed.

This phased case approach is not intended to be a linear series of events, but a general framework to look at options and progressions through changing the orbit of the ISS or parts of the ISS within the cislunar environment.

**Case One: Cislunar Operations and Technology Demonstration**

This case is the lower-cost option designed to study some of the problems associated with having humans living and working in the cislunar environment for an extended duration. Although some of this research could be done using microsats, having humans to finally learn to live in and operate a larger testbed that forces development of orbit configuration, maintenance and experiment change out is an interesting solution. The authors designed an Earth Moon Cycling Orbit, or EMCO, which has an orbital period of 13.6 days and passes close to the Moon every other orbit. It is nodal aligned with the Moon so that at its apogee the Moon is in between it and the Earth. They also defined a Low Lunar Orbit, (LLO) which is slightly eccentric with a perilune lunar altitude of 200 km and requires a total ΔV of about 3.7 km/s. The authors postulated the use of the extra Russian FGB (Functional Cargo Block), which is 70% complete and still on the Earth. This scenario would allow them to test technology, learn more about the environment, and explore operating issues in the cislunar and lunar environments without altering the current configuration of the ISS. The FGB weighs approximately 20 tonnes and could be pushed into either one of these orbits by a Centaur class upper stage after rendezvous and reconfiguration at the ISS.

**Case Two: Earth-Moon Cycler**

This case uses ISS parts and derived technology to create an Earth-Moon Cycler. The design is meant to be flexible and allow a change of mission into a lunar orbiter or remain an end in itself. The ISS-4 (four crewmembers) is a reconfiguration of 6 modules on the current ISS that could be built around the new FGB, whether it was flown in the previous case or brought up specifically for this case. It would require a new power module and propulsion unit for orbital transfer, and would weigh around 150 tonnes.
Case Three: Lunar Orbiter

This case addresses using ISS parts and derived technology to create a lunar orbiting station. Lunar orbit has the advantage that the station is very close to the Moon’s surface enabling a much easier study of the Moon. However, resupply or return to Earth would be a more difficult problem and only be likely if some new lunar transport system or new super heavy launch vehicle were built.

The authors investigated several approaches to entering low lunar orbit (LLO) and concluded that transferring from EMCO to LLO, from a technical point of view, would not be the most advantageous transfer. A more reasonable method using a burn at perigee could transfer from EMCO to LLO for significantly less ΔV. However, issues were identified with either approach, such as the reliability problem for high thrust engines, the huge tanks, and the cryogenic propellant administration system.
ISS Reconfiguration

To ensure the success of the mission, preliminary preparation needs to be done to the ISS before the orbit-change can be fulfilled. For every ISS-configuration, the number of Proton launches to transport necessary modules, the number of Shuttle launches to deliver smaller components, the duration of EVAs necessary for assembling, and finally the number of heavy lift launches needed for the transfer of the propulsion stage have been analyzed and minimum requirements identified.

Resupply Requirements

The resupply mass for each of the three scenarios is based on current data from the full ISS in LEO.

For the technical demonstrator (FGB) a total resupply mass of 12.9 tonnes/year for EMCO and 3.8 tonnes/a for LO are required.
For the ISS-4 scenario the supply masses are around 72 tonnes/year for EMCO and 31.3 for LO. The produced waste is around 6.8 tonnes/year.
For the ISS-7 in total 204.4 tonnes/year for EMCO and 84.4 tonnes/year for LO of supply mass are required, including propellant, payload experiments and unpressurized cargo, and 20 tonnes/year of waste have to transported away from the station.

Resupply Capabilities

Deliverable payload masses for EMCO given current launch vehicles of USA, Russia, Japan and Europe have been calculated based on the GTO payload masses. In general we can assume 80% of the GTO payload capabilities for EMCO, with reentry, and 61% for a low lunar orbit with no return to Earth. At the moment we could use the existing Atlas V heavy lift vehicles to transport a mass of 14 tonnes per launch to EMCO. For supply missions to LO with a back flight to Earth no current launch vessel can deliver the performance; therefore it is necessary to develop either new launchers and/or transfer vehicles, or increase the current rockets performance rapidly.

Crew Transport / Evacuation

Transport and evacuation of the crew to and from the station on the envisioned orbits (EMCO, LO) could be provided by a modified Soyuz TM (TM-X) and a Medical Module Return Vehicle (MMRV) based on ESA’s Crew Transfer Vehicle (CTV). Evacuation capability will be required in instances of station failure and crew medical emergency. While whole crew return is required during station failures, only injured crewmembers and the appropriate medical personnel will be returned during medical emergencies. Combinations of the two return vehicles, are needed to address the situation of the ISS-7.
Mission Operations

Changes in the ISS mission require a review of how that mission will be conducted. Some of the issues associated with new mission operations are addressed, dealing with both pre-flight planning and real-time operations. For the crewed options, substantive content is focused on how medical operations may be altered, and potential scenarios for crew rescue are considered.

Radiation Concerns and Mitigation

Spacecraft in EMCO are mostly unprotected by the Earth’s magnetosphere, increasing the probability of impact of a radiation event (e.g. solar particle event) much greater than in LEO. Depending on its characteristics, the radiation that affects a spacecraft can have a great impact on both the machinery and humans on board. Overall the radiation environment in cislunar space needs to be mapped. This can be accomplished by radiation monitoring devices on the FGB in Case One.

Medical Operations

While the distances from Earth have increased, spacecraft limitations have remained relatively constant. These constraints mean that future lunar missions must be more self-sufficient to ensure crew health. The existing ISS Crew Health Care System programme provides a foundation for providing medical care. However, the development of onboard surgical capability and a reassessment of how resources are distributed and used will be essential for human safety during lunar missions.

Crew Psychological Health

Issues that may contribute to an increased level of anxiety among crewmembers: Small crew size (ISS-4) Increased sunlight Increased return to Earth time

These stressors can be minimized by ensuring favourable crew compositions, habitable living environments, and good crew activity schedules.
The scientific programme and engineering solutions explained above require a management context in order to be seriously considered. The costs of the programme and potential sources of revenue are vital to identify, as are the potential risks in the programme.

**Costs**

The FGB technology demonstration mission is estimated to cost $3.2 billion over its two year operational life. The ISS-4 configuration, by contrast, is estimated to cost approximately $29 billion for either cycling or lunar orbiting missions over a 5 year period, and the full ISS-7 configuration would cost approximately $39 billion for the same orbits and life span. Operations costs are 50% of the total cost, due to the increase in difficulty (and therefore cost) required to service the station in the more challenging orbits.

**Funding**

Funding for such a large and international project will be difficult to obtain and most likely involve multiple sources. Participation by all of the current ISS partners and other space faring countries, especially China and India, should be a primary goal. Because of the growth of the commercial space industry the opportunity to involve private entities, such as advertising, sponsorship, and tourism, should be much greater than that for the initial ISS.

**Plan**

The ISS projected end of life is assumed to be early 2016 and is the key milestone around which the other activities are planned. An extension of life of 5 years is assumed to be feasible. The key drivers to the plan are the assumptions of the ISS end-of-life date and the duration of the life extension. Time is available in the near term for forming public policy, developing legal agreements, developing funding sources and further defining the programme architecture.

**Risks**

A large number of significant risks have been identified, assessed, and specific mitigation strategies developed. A number of these can be mitigated by programme architecture choices.

**Lunar Legal Framework**

Legal constraints exist with regards to this programme. Specifically, the legal constraints that exist with regards to lunar resource exploration, use and development; human settlement on the Moon; and other legal requirements such as registration and constraints relevant to the project are discussed in this report.

It is imperative that the legal environment moves at the same pace as technological plans for lunar development. Consequently, this report recommends that the Moon Agreement be amended, in a similar manner to the Part XI Amendment to the United Nations Convention on the Law of the Sea, so as to encourage greater international acceptance and ratification. This amendment should allow for a workable treaty that clarifies the definition of the controversial “Common Heritage of Mankind” provision.

**International Lunar Organisation**

It is recommended that an International Lunar Organisation be created under Article 11 of the Moon Agreement so as to regulate the exploration, use and development of lunar resources and future lunar activities including human settlement on the Moon.

**Objectives**

To coordinate all the potential uses of the ISS toward lunar exploration

To inform the global community about the ISS as a stepping stone towards the Moon.

To host an International Research Programme on the ISS for the Moon.

To establish a forum and mechanism for the coordination of lunar related activities.
RECOMMENDATIONS

A broad-based framework of lunar exploration and development should be established.

International organisations should be established for lunar activities scientifically, technologically, and legally.

Humanity should capitalise on the assets, the infrastructure, and the organisational structure of the International Space Station for lunar-related activities.

The ISS should be considered as a lunar transportation system between the Earth and the Moon.

A technology demonstrator should be implemented to verify the concept of the ISS lunar cycler.

Once technical and operational issues are addressed, the ISS-4 human transportation vehicle should be seriously considered.

An International agreement on a lunar regulatory framework should be established.
This Executive Summary and associated report were written by students in the 2003 Summer Session Program at the International Space University. Published: September, 2003.

The 2003 Summer Session Program of the International Space University took place in Strasbourg, France. It was hosted by the Pôle Universitaire Européen de Strasbourg on behalf of its six members: the three universities of the city, the Urban Community of Strasbourg, the Bas-Rhin Department and the Alsace Region.

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