

# Effective Utilization of Resources and Infrastructure for a Spaceport Network Architecture

Robert P. Mueller<sup>1</sup> and Tracy R. Gill<sup>2</sup>

*National Aeronautics & Space Administration (NASA), Kennedy Space Center, Florida, 32800, USA*

Wiley J. Larson<sup>3</sup>

*Stevens Institute of Technology, Hoboken New Jersey, 07030, USA*

and

Jeffrey S. Brink<sup>4</sup>

*National Aeronautics & Space Administration (NASA), Kennedy Space Center, Florida, 32800, USA*

Providing routine, affordable access to a variety of orbital and deep space destinations requires an intricate network of ground, orbital, and planetary surface spaceports located across the Earth (land and sea), in various Earth orbits, and on other extra-terrestrial surfaces. Advancements in technology and international collaboration are necessary to enable such a spaceport network to satisfy private and government customers' research, exploration, and commercial objectives. Technologies, interfaces, assembly techniques, and protocols must be adapted to enable critical capabilities and interoperability throughout the spaceport network. The conceptual space mission architecture must address the full range of required spaceport services, such as managing propellants for a variety of spacecraft.

In order to accomplish affordability and sustainability goals, the network architecture must consider deriving propellants from in-situ planetary resources to the maximum extent possible. Water on the Moon and Mars, Mars' atmospheric CO<sub>2</sub>, and O<sub>2</sub> extracted from Lunar regolith are examples of in-situ resources that could be used to generate propellants for various spacecraft, orbital stages and trajectories, and the commodities to support habitation and human operations at these destinations. The ability to use in-space fuel depots containing in-situ derived propellants would drastically reduce the mass required to launch long-duration or deep space missions from Earth's gravity well.

Advances in transformative technologies and common capabilities, interfaces, umbilicals, commodities, protocols, and agreements will facilitate a cost-effective, safe, reliable infrastructure for a versatile network of Earth and extraterrestrial spaceports. Defining a common infrastructure on Earth, planetary surfaces, and in space, as well as deriving propellants from in-situ planetary resources to construct in-space propellant depots to serve the spaceport network, will lower exploration costs.

## Nomenclature

C1	=	Caravan 1
E-M L1	=	Earth to Moon Lagrange Point 1
GEO	=	Geostationary Equatorial Orbit
GER	=	Global Exploration Roadmap
GTO	=	Geostationary Transfer Orbit
ISECG	=	International Space Exploration Coordination Group
ISS	=	International Space Station
ISU	=	International Space University
ISPA	=	International SpacePort Authority
ISRU	=	In-Situ Resource Utilization

<sup>1</sup> Senior Technologist, Surface Systems Office, M/S: NE-S, and AIAA Senior Member

<sup>2</sup> Engineer, Technology Integration Office, M/S NE-T

<sup>3</sup> Distinguished Service Professor, School of Systems and Enterprises

<sup>4</sup> Engineer, Vehicle Integration and Launch Support Branch, M/S LX-D1

kg	=	Kilogram
KSC	=	Kennedy Space Center
LCROSS	=	Lunar CRater Observation and Sensing Satellite
LEO	=	Low Earth Orbit
LH <sub>2</sub>	=	Liquid Hydrogen
LO <sub>2</sub>	=	Liquid Oxygen
NASA	=	National Aeronautics & Space Administration
OASIS	=	Operations And Service Infrastructure for Space
PILOT	=	Precursor ISRU Lunar Oxygen Testbed
PMF	=	Propellant Mass Fraction
PPP	=	Public Private Partnership
RFP	=	Request for Proposal
SPC	=	SpacePort Company International Consortium
t	=	Metric Tonne
US	=	United States of America
$\Delta V$	=	Delta Velocity (km/s/kg)
$\Delta V^2$	=	Energy Metric (MJ/Kg)

## I. Introduction

THE history of mankind has proven on numerous occasions that with a great goal in mind, an open network based approach developed in a step by step evolutionary process, leads to tremendous results. Ancient Romans proved this, when they proceeded to build the roads of the Roman Empire. Knowing that efficient travel and trading required reliable sea routes and pathways with safe havens for rest, supply and transfer, led the Romans to develop the greatest road system and ports of the ancient world, a precursor of all the current routes in Europe. Previously, the Chinese silk routes which linked Asia to Europe and Africa, demonstrated how a commerce and resource driven transportation network can shape the culture and history of many nations. Trade on the Silk Road and eventually along sea routes, was a significant factor in the development of the civilizations of China, India, Persia, Europe and Arabia. The advancement of technologies such as celestial navigation, better road construction, logistics, relay staging and ships that could sail up wind contributed to the development and feasibility of these transportation networks. Later generations of Europeans, fully aware of the economical and societal advantages of trade between diverse nations and lands, made an enormous effort to create new routes with safe ports on the way to enable spice trading, and other emerging markets. Famous ports on these sea routes such as the golden domed city of Venice, Italy are proof of the lucrative nature of this commercial activity. In an analogous fashion, now is the time to take advantage of the almost limitless resources in outer space by establishing routes to the stars with safe havens and logistics nodes in space, known as Spaceports, marking the most important stops on the way through the Solar System and beyond.

Providing routine, affordable access to a variety of orbital and deep space destinations requires an intricate network of ground, orbital and surface spaceports across the Earth (land and sea), in various Earth orbits, and on other extraterrestrial surfaces. Advancements in mission architecture, technology, and international collaboration are necessary to enable such a spaceport network to satisfy private and government customers' research, exploration, and commercial objectives. Technologies, interfaces, assembly techniques, and protocols must be adapted to enable critical capabilities and interoperability throughout the Spaceport network. This paper describes a conceptual space mission architecture which addresses the space transportation network and the full range of required Spaceport node services, such as managing propellant production, storage, handling, and transfer for a variety of spacecraft, as well as other cis-lunar economic activity, with the goal of reaching Mars and going beyond.

To accomplish affordability and sustainability goals, the spaceport network architecture must provide for use of in-space fuel depots containing in situ derived propellants. This drastically reduces the mass required to launch propellant for long-duration or deep space missions from Earth's gravity well. In terms of energy required to escape it, the Earth's gravity well is extremely harsh. A good way of measuring energy is  $\Delta V^2$ , which is represented in units of Mega Joules / Kg. Note that by using the  $\Delta V^2$  metric, Low Earth Orbit (LEO) is 83% of the one way trip to the Moon (Blair et al, 2002). By avoiding the transportation of propellant (which accounts for more than 90% of the mass fraction of the launch vehicle) from the Earth's surface to LEO, then the propellant can be transported from the

Moon to LEO for a small percentage of the total Earth to Moon transportation energy. Another good use of in-situ derived propellants is to fuel a re-useable on orbit, upper stage replacement for orbital transfer operations. The upper stage propellant typically accounts for a significant portion of the mass of a space vehicle being launched from Earth, while the Propellant Mass Fraction (PMF) of this stage is 84% or higher, for example the Atlas V second stage has a PMF of about 91% (Holt and Monk, 2009).

Defining a common infrastructure on Earth, planetary surfaces, and in space, as well as deriving propellants from in situ planetary resources to construct in-space propellant depots to serve the spaceport network, will lower exploration costs due to the use of these propellants and standardization through infrastructure commonality.

## II. Solar System Resources

The key to humanity's future is contained in the vast resources of the Solar System and ultimately the universe. "Our civilization's demand for energy and material resources is rapidly growing toward the limits of the planet. There is mounting evidence that we are beginning to feel those limits in some of the non-renewable energy and mineral resources (Bentley 2002; de Almeida and Silva 2009; Lin and Liu 2010; Mudd and Ward 2008), and that they cannot support our current rates of population growth or industrialization for another century. Fortunately, the processes that formed our habitable Earth also endowed the solar system with billions of times more resources than exist on one planet alone (Hartmann 1985; Lewis and Lewis 1987; Lissauer 1993; Duke et al 2006). These resources exist in the form of propellants for our space transportation infrastructure, metals and silicates for producing robotic equipment and goods, as well as energy to power all of our activities. In addition the human intellect and knowledge are required to design and operate the resultant solar system resource network. We do not have a lack of resources in the solar system: we have a lack of imagination and investment. The challenge is in finding a way to economically access those resources for the benefit of humanity." (Metzger, Mueller et al, 2012).

"Space resource utilization can provide an enabling foundation for a new space transportation architecture, and it can also plant the seed for a sustainable human presence throughout the solar system. It could form the basis of a solar system economy, where regolith derived resources are traded as commodities to enable life in space and improve life on Earth" (Mueller et al, 2010).

"During the Solar System formation, there were a variety of processes taking place that resulted in planetary body formation. Due to the varying conditions that existed in the vicinity of each planetary body, a zonal structure developed ranging from metal rich silicates near the Sun, through concentrations of organic and rocky material in the mid solar system to concentrations of various ices in the outer solar system. In addition, gravitational perturbations cause asteroids and comets to enter into the inner solar system in periodic orbits. In the early formative stage, a cloud called the solar nebula formed, and as it cooled down, the matter condensed to form various objects. Near the sun, the higher temperature only allowed metal rich minerals to condense (Mercury, Venus, Earth Mars), while further away in the inner asteroid belt between Mars and Jupiter, some chondrites formed (that were never affected by melting and collisions), while other asteroids show significant lava based rock and metal interiors. In the outer asteroid belt, carbon rich materials and other chondrites condensed, in various sizes and forms.

Further out, between the outer belt and Jupiter, the temperature and conditions are such that the presence of water ice is possible, so that in this region there are many moons with water and other ices present today. Jupiter, Saturn and Uranus all have rings that are composed of ice particles and they have many moons, some of which remain undiscovered. The known moons contain a variety of icy compounds such as water ice, carbon dioxide ice, methane and ammonia ices. In this region, near Jupiter, compositions of 50% water ice and 50% mineral rock are not uncommon, while further out, near Saturn, the composition becomes mostly water ice. Finally in the outer solar system, the temperature conditions sustain ice that is made of methane and ammonia (Finney and Jones, 1986).

Fortunately, recent discoveries indicate that Earth's Moon, which is relatively close to Earth and has been visited by humans, contains abundant resources as well. The Moon is a unique resource in the inner solar system. It has a thick regolith that is rich in oxygen, titanium, iron, and other metals. It also appears to have vast deposits of water ice and other volatiles frozen into the permanently shadowed craters at the poles. The regolith also has low concentrations of solar wind implanted Helium-3, which could be an important resource for nuclear fusion energy production sometime in the future. Reduced gravity (1/6<sup>th</sup> Earth gravity) and the absence of an atmosphere makes it

relatively easy to launch resources from the surface. Furthermore, gravity on the surface is adequate to operate with relative ease (compared to the ultra-low gravity of an asteroid). These factors make the Moon the ideal location for obtaining or manufacturing oxygen, water, hydrogen, metals and ceramics. Spare parts and larger items such as spacecraft frames and regolith derived heat shields could be robotically manufactured through additive processes on the Moon, rather than lifting the mass from Earth. From the Moon, resources or manufactured parts and equipment could be moved easily to a Lagrange point, to Low Earth Orbit, or outward to Mars and beyond. Other resources on the Moon include the abundant solar energy, especially near the poles where some locations receive sunlight almost continually, and the cold temperature in the permanently shadowed craters, which is sufficient for superconducting.

Mars has two moons, Phobos and Deimos. Phobos has low mass and gravity (about 1/1000 earth's gravity), making it potato-shaped rather than spherical. Phobos orbits very close to the surface of Mars at about 9378 km on average. It has no atmosphere and is probably a captured asteroid. It appears to be composed of C-type rock, similar to blackish carbonaceous chondrite asteroids. Phobos is heavily cratered, with one 10 km long crater named Stickney. The surface is very powdery from impacts and its low density indicates a porous core, which has led to speculation of ice underneath its surface. The lower moon, Deimos, is about 9,300 km above the surface of Mars and orbits about three times per sol. It is oblong with a surface gravity that varies between 0.0002 and 0.0009 G by location. Its average diameter is about 22 km. It is covered with a layer of dust and appears to be a captured carbonaceous chondrite asteroid. Its density is too low to be solid rock, so it may be porous. It has also been proposed that the regolith of Phobos contains regolith ejected from Mars by impact processes, so sampling the regolith of Phobos is an easy way to sample Martian regolith without having to land on and launch from the surface. Working on Phobos will be difficult because the ultra-low gravity will necessitate some form of anchoring.

The individual asteroids within the main belt are categorized by their spectra, and most fall into three basic groups: carbonaceous (C-type), silicate (S-type), and metal-rich (M-type). Much more analysis and observation are needed of these asteroids, but the NASA Dawn spacecraft visited Vesta in July, 2011 and will travel onwards to Ceres by February, 2015. Asteroids reside primarily in a belt between Mars and Jupiter, but the edges of the belt are not clearly defined and so asteroids are found throughout the inner solar system and even crossing Jupiter's orbit, and of course crossing Earth's. Three dynamical populations of asteroids (Trojans, Greeks and Hildas) are associated with the Lagrange points of Jupiter. Asteroids are an abundant source of metals: nickel, iron, titanium, cobalt, platinum, etc. These may be useful for space construction or even someday imported into Earth's economy. Whereas large planets in the early stages of the inner solar system experienced differentiation, with the heavier metals sinking to form the core while silicate minerals floated up to form the crust, the smaller asteroids did not differentiate, and so this makes them unique in the solar system for easy metal harvesting. There is also some evidence of volatiles in asteroids, and so they could be mined for water and hydrogen, while oxygen could be liberated by reducing the silicate minerals and metal oxides of its surface. It is unclear how much regolith covers the asteroids. Mining the asteroids may involve rock mining, not simple regolith scooping, as on the Moon or Mars. The ultra-low gravity will necessitate anchoring.

Ceres is believed to have significantly thick regolith and vast quantities of water in its mantle. Some of the minerals in the surface include clay minerals and carbonates. The vast quantities of ice in Ceres and the low escape velocity should make it a prime location for human settlement and resource extraction for export. Located at the junction between the inner and outer solar system, Ceres could send its water, oxygen, propellants, metals and other materials in either direction, as well as manufactured parts. Ceres could also form the hub of asteroid mining operations

Most schemes for resource utilization in the solar system involve mining and extraction from the regolith and volatiles contained in it. Data indicates oceans of water beneath ice in the moons of Jupiter such as Europa but further research and exploration is needed to characterize this and it is far away and difficult to access. The trade space for regolith utilization is a function of the propulsion delta-velocity ( $\Delta V$ ) needed for transportation to and from the resource location, the resource that is being sought, the mining and extraction method, the surface gravity and the time required by a given propulsion method" (Mueller et al, 2010).

### III. Transformative Vision

A good systems engineering process starts with the end state and then works “top down” to establish the necessary campaigns, architectures, missions, elements, systems, technologies, related concepts of operations and launch manifests. The desired end state is described in a previous paper (Metzger et al, 2010) as a transformative vision and associated plan, which will allow unconstrained, free access for humans to all parts of the Solar System and eventually beyond, by harnessing the vast resources in the Solar System. In this paper, Metzger et. al. demonstrated via computer modeling, that it has potentially become economically feasible to bootstrap a self-sustaining, self-expanding lunar industry that will expand across the solar system at no further expense to the Earth’s economy through the use of space based resources and information technology based digital manufacturing and operations methods. The authors showed how, once successfully bootstrapped, the replicating robotic network can access, process, transport, and utilize the solar system’s resources form a variety of destinations for humanity’s benefit. This is a long term vision and will require some intermediate steps to be realized. This paper addresses one of the necessary first steps which will allow the Metzger et al bootstrapping vision to be fulfilled: the creation of a network of spaceports to provide affordable space transportation by using in-situ resources. Once space transportation becomes affordable by implementing a spaceport node infrastructure, costs will plummet, by using space resource utilization beyond Earth’s gravity well and later by, associated economies of scale. This will result in actualization of the first step of the solar system economy boot strapping process.

Although methods for human expansion into the solar system have been proposed previously (Gerard K. O’Neill (1989), Zubrin (1999), Various NASA studies (1963-2012), Mueller, (2006)), these plans have not been practical to develop because of the high costs and logistics associated with them. Recent advances in technology development and space resource discovery will allow new and disruptive paradigms to be implemented in the conservative business of space transportation and exploration. These advances include:

- a) Robotics (e.g. Robonaut)
- b) Advanced additive and digital manufacturing (3D printing of metallic and polymer parts)
- c) Microprocessor instruction processing speeds exponential growth ( Moore’s law)
- d) Confirmation of lunar volatiles resources as well as carbon and metals in the regolith ( NASA LCROSS)
- e) In-situ resource utilization processes and prototypes (NASA technology development, ROxygen, PILOT) (Metzger et al, 2012)

Robots do not have the biological life support and survival problems that humans have, while traveling the vast distances of the solar system, and they can set up pre-deployed transportation and habitation infrastructure enabling us to follow. Within the first several decades a vital industry could be established on the Moon and in the Asteroid Belt using technologies that are for the most part only modestly advanced beyond today’s state-of-the-art. After that, human outposts, laboratories, and observatories can spring up everywhere between the Kuiper belt and Mercury. It can grow exponentially and provide mankind the ability to do things that today are only dreams. By launching 12 to 41 metric tons of “seed” hardware to the Moon, the boot strapping process can begin (Metzger et al, 2012).

However at an assumed cost of US \$80,000 per kilogram landed mass on the Moon, this would cost between US \$960 Million to US \$3.28 Billion in transportation costs alone. In addition, the cost of design, development and test of this advanced robotic equipment and the subsequent life cycle operating costs must be included. This means that the first step in such a resource driven, robotic bootstrapping architecture is still too costly, in the order of Billions of U.S. dollars. This approach would require significant public or private investment and therefore be prohibitive to easily “igniting” the bootstrapping of the business case. Our conclusion is that there is a missing step which will bridge this financial and political “valley of death”. In this paper we show how this missing step could be implemented.

#### **IV. Spaceport Transportation Network Infrastructure**

The construction and operation of the Eisenhower US Inter-state highway system was one of the greatest economic development accomplishments in the past 100 years in the USA, with huge benefits. This infrastructure drastically reduced the cost of road transportation and allowed higher mobility for goods and people. The Dwight D. Eisenhower System of Interstate and Defense Highways must surely be the best investment that the USA has ever made. Consider this:

- It has enriched the quality of life for virtually every American
- It has saved the lives of 187,000 people
- It has prevented injuries to nearly 12 million people
- It has returned more than \$6 in economic productivity for each \$1 it cost
- It has positioned the nation for improved international competitiveness
- It has permitted the cherished freedom of personal mobility to flourish
- It has enhanced international security

It is not an exaggeration, but a simple statement of fact, that the interstate highway system is an engine that has driven over 50 years of unprecedented prosperity and positioned the United States to remain the world's pre-eminent power into the 21<sup>st</sup> Century (Cox et al, 1998).

The role of government in this venture was to finance, organize and regulate this open network, and private enterprise is free to use it in the most economically efficient manner chosen, while taxes are collected from users for its maintenance and repair. Similarly, the role of government in space should be to provide the spaceport infrastructure for public benefit, and to assume the risk involved. By doing so, the fledgling space industry will be nurtured and incubated, ultimately providing economic expansion and an increased tax base.

The International Space Station (ISS) assembly sequence was completed in 2011. While the value of the more than US\$100 Billion investment is debated by the public, there is wide agreement that the ISS has been a valuable foreign policy and diplomatic initiative which helped ease the world out of the "cold war" era in the 1990's (Whiting et al, 2003). The benefit of any effort helping humanity to live in a cooperative and collaborative state, rather than in a state of tension and destructive competition, cannot be measured adequately in dollars alone. In addition the costs were defrayed by sharing them among the ISS member nations leading to more affordability for each country, even though there was some extra overhead associated with the overall international effort. Maybe most importantly for the space industry, the international agreements forged in the ISS program allowed the space station to survive numerous political cycles within governments, in various nations around the world, and therefore it must be declared a success in terms of sustainability. In June 1993, a bill to cancel the Station program failed by one vote in the US House of Representatives, showing how vulnerable US discretionary spending on the space program is. Consequently, future space programs that have solid international agreements in place and a vested interest from a collection of international partners, have a higher chance of surviving political changes and upheaval over time.

In the summer of 2012, thirty-four highly capable international participants (young professionals and university students) from nineteen countries and spread across five continents convened at the International Space University (ISU) Space Studies Program (SSP) 12 hosted by NASA Kennedy Space Center and the Florida Institute of Technology (FIT) in Melbourne, Florida, USA. Under the leadership of the authors, they have developed a conceptual network of spaceports that has a high potential to revolutionize access to space. The project team seeks to convince government and commercial members of the space sector that this network is viable and will become self-sustainable, ultimately lowering the cost of access to space. This is known as Project Operations And Service Infrastructure for Space (OASIS), (Team OASIS, Clegg et al, 2012). Some members of the space community are already convinced of the value of the space economy, and have begun commercial ventures, to mine resources from the Moon or an asteroid, or to provide tourist voyages to the Moon. Project OASIS seeks to provide a tangible, affordable and feasible plan to implement a solution which outlines international collaboration, governance, legal aspects, mission architecture, technologies, modularity and standards with economic benefits. (Larson et al, 2012)

There have been many reasons and mission architectures proposed which attempt to justify and implement human spaceflight beyond Low Earth Orbit (LEO). Sherwood (2011) argues that the reasons can be de-composed into four value propositions:

- a. Explore Mars
- b. Accelerate space passenger travel
- c. Enable space solar power for Earth
- d. Settle the Moon

By focusing on the Spaceport network as a public-private-partnership financed infrastructure, OASIS accommodates and enables all four of these value propositions. Instead of trying to accomplish a mission, OASIS seeks to provide the legal, business and technical framework which makes all of these endeavors possible since it will dramatically lower the cost of space access and commuting by the use of in-situ resources.

Similarly, Woodcock (2007) also examined projects that may have economic value and are feasible in the near term:

- a. Lunar oxygen production for propellant
- b. Extraction and return to Earth of platinum group metals (PGM)
- c. Lunar tourism
- d. Extraction and return to Earth of Helium-3 as a fusion fuel

In this analysis Woodcock found that the first three projects appear to be economically and technically feasible, but the fourth (Helium 3 Fusion) has not been technically proven yet. He also indicates that the commonality between these projects is such that it could allow for one space transportation architecture. *However aggressive cost reduction must occur or these projects will not be possible. The equipment must be developed with an commercial or industrial approach in order to be economically viable.* The OASIS infrastructure is also capable of supporting all four of these proposed projects.

In 2006, 14 space agencies began a series of discussions on global interests in space exploration. Together they took the unprecedented step of elaborating a vision for peaceful robotic and human space exploration and they formed the International Space Exploration Coordination Group (ISECG). According to the ISECG Global Exploration Roadmap (GER), the goal in human exploration of the Solar System is Mars. The majority of these studies envision two scenarios to reach this destination, by considering going to either the Moon first or to an asteroid first (ISECG, 2011). NASA policy also currently states that the ultimate destination is Mars.

A space transportation infrastructure for cis-lunar economic activity which uses Lunar resources was proposed by Spudis and Lavoie (2010). It depends on a human tended lunar outpost with a heavy lift launcher. The outpost is capable of producing 150 metric tonnes of water per year which can produce roughly 100 tonnes of propellant – the cost estimate for this architecture was established for an aggregate cost of less than \$88 billion (Real Year dollars), including peak funding of \$6.65 billion starting in Year 11.

In a study at the International Space Development Conference in Albuquerque, New Mexico, Potter et al (2001) proposed a LEO propellant depot that electrolyzed Earth launched water into cryogenic propellants and stored it in an in-line gravity gradient configuration to minimize drag and allow propellant settling. Smitherman (1998) examined potential services that could be the basis of a cis-lunar economy including on-orbit servicing and orbital transfer.

In addition, Bienhoff (2011) has proposed a reusable cis-lunar transportation architecture with propellant depot nodes (using Lunar water derived hydrogen and oxygen) at LEO and Earth-Moon Lagrange Point 1 (E-ML1). He also showed how using propellant depots can substantially increase landed payload mass on the moon by re-fueling in LEO (Bienhoff, 2008). Furthermore, Blair et al (2002) conducted a thorough economic analysis of a lunar water In-Situ Resource Utilization (ISRU) based transportation architecture, which showed the trends and sensitivities related to the business case. In this study Blair et al. estimated that the water content of regolith was 2% but the Lunar Crater Observation and Sensing Satellite (LCROSS) mission (2009), has since indicated concentrations in excess of 5%, which would substantially affect the results of the modeling, making the case for lunar water derived propellant better. The cost estimate for establishing the total architecture capability was in the order of

approximately US\$8 Billion which, when escalated to 2012 dollars (at ~3% inflation), amounts to about US\$11 Billion. This study just considers the surface equipment necessary to produce and supply water for propellant, therefore implying robotic missions without a human presence.

All of these studies indicate a strong case for emerging space transportation markets but the barriers to entry remain high since the total cost estimates range from \$11 Billion to \$88 Billion and higher without a clear business case for profitable Lunar water derived propellant sales in LEO. The higher estimates assume the necessity of human tended industrial operations, making the costs prohibitive for anything other than government financing. If lower costs are desired then the space transportation architecture must be robotic in the early stages. This means that investments in the order of \$11 Billion will be required, but this is still too high and requires significant government investment which is very difficult to achieve in the current political and socio-economic environment. In order to achieve a realistic and feasible space transportation architecture, an evolutionary and incremental bootstrapping philosophy has been studied in this paper, where successive iterations producing commercial profits can be used to invest in the next phase. In this way, small initial investments can be leveraged to defray the costs of such a venture. *However this is contingent on the cis-lunar space market developing.* If it does not, then the financing may have to be in the form of a public private partnership, including International partnerships, to spread the costs of development. When the lunar propellant supply chain to LEO has been established, then substantially lower Lunar water derived propellant costs (< US\$3,000 /kg) at LEO depots can stimulate these markets to the point where they do actually emerge, and government participation can be reduced to a regulatory role only.

Project OASIS has analyzed such a scenario and generated a very promising solar system spaceport network infrastructure model which has the potential to be feasible, politically and financially sustainable and can surmount the significant barriers to entry. This was made possible by using advanced robotic technologies, recent new developments in ISRU processing, new data about water ice on the Moon, and efficient commercial space flight hardware development methods.

## V. Project OASIS Solution

Since the beginning of the space age, the main participants in space exploration have been governmental agencies, enabling a privileged access to space, but with very restricted and rare missions. The last decade has seen the rise of space tourism, and the founding of ambitious private space mining companies, showing the beginnings of a new exploration era, that is based on a more generalized and regular access to space and which is not limited to the Earth's vicinity. However, the cost of launching sufficient mass into orbit to sustain these inspiring challenges is prohibitive, and the necessary infrastructure to support these missions is still lacking. To provide easy and affordable access to orbital and deep space destinations, there is the need to create a network of spaceports by way of specific waypoints coupled with In Situ Resource Utilization (ISRU), to provide a more economical solution.

As part of the International Space University (ISU) Space Studies Program (SSP) 2012, the international and intercultural team of *Operations and Service Infrastructure for Space (OASIS)*, proposed an interdisciplinary solution to the problem of economical space access and transportation (Clegg et al, Team OASIS, 2012). This report details the phases of a project for developing a network of spaceports throughout the Solar System within 50 years. The requirements, functions, critical technologies and mission architecture of this network of spaceports are outlined in a roadmap of the important steps and phases. The economic and financial aspects are emphasized in order to allow a sustainable development of the network in a public-private partnership via the formation of an International Spaceport Authority (ISPA). This report highlights the improvements in technology and international cooperation that are necessary to develop a spaceport network that satisfies the needs of its users. The approach includes engineering, scientific, financial, legal, policy, and societal aspects.

Team OASIS provides guidelines to facilitate development of feasible space transportation via a spaceport logistics network, and Team OASIS believes that this pioneering effort will revolutionize space exploration, science and commerce, ultimately contributing to permanently expand humanity into space.

### A. OASIS Architecture, Nodes & Elements

The DESACMI (Define, Establish, Synthesize, Analyze, Compare, Make a decision, Implement) method drives the approach for the development of the existence proof (Ryschkewitsch et al., 2009). The team derived top-level



requirements and criteria from the mission statement and input from the economical and scientific point of view. The team identified possible nodes and performed literature research on those locations. Because of the vast amount of possible combinations, only the most promising network possibilities (with regards to velocity change and mission duration) were evaluated.

The “closest” spaceport options for the first step were compared against each other with the established criteria. The same approach was used for the choice of the second and third location. After defining the network and establishing its services, missions and related elements, a network architecture was created to fulfill the requirements and services.

**Evaluation criteria**

To ensure systematic and objective decision making, evaluation criteria were chosen based on which all the trade-offs regarding the network were made.

The following summarizes the primary criteria taken into account:

- Accessibility (travel time and velocity change required)
- Potential for tourism, science research, profitability in general, and exploration at the node or in proximity
- Environment (gravity, radiation, space debris, temperature gradients, power generation, resources availability)
- Costs (operational and maintenance, construction, development)
- Maturity of technology required and
- Contribution or value of each element for the network

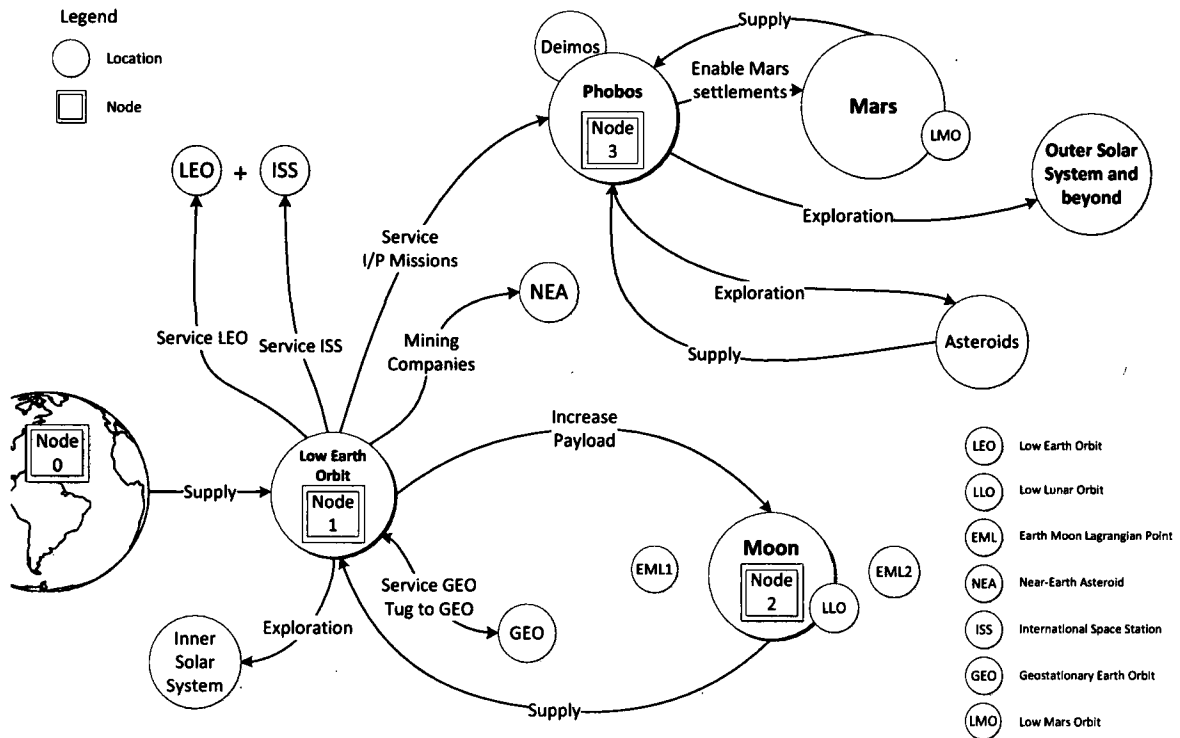


Figure 1: OASIS Spaceport Open Network Architecture

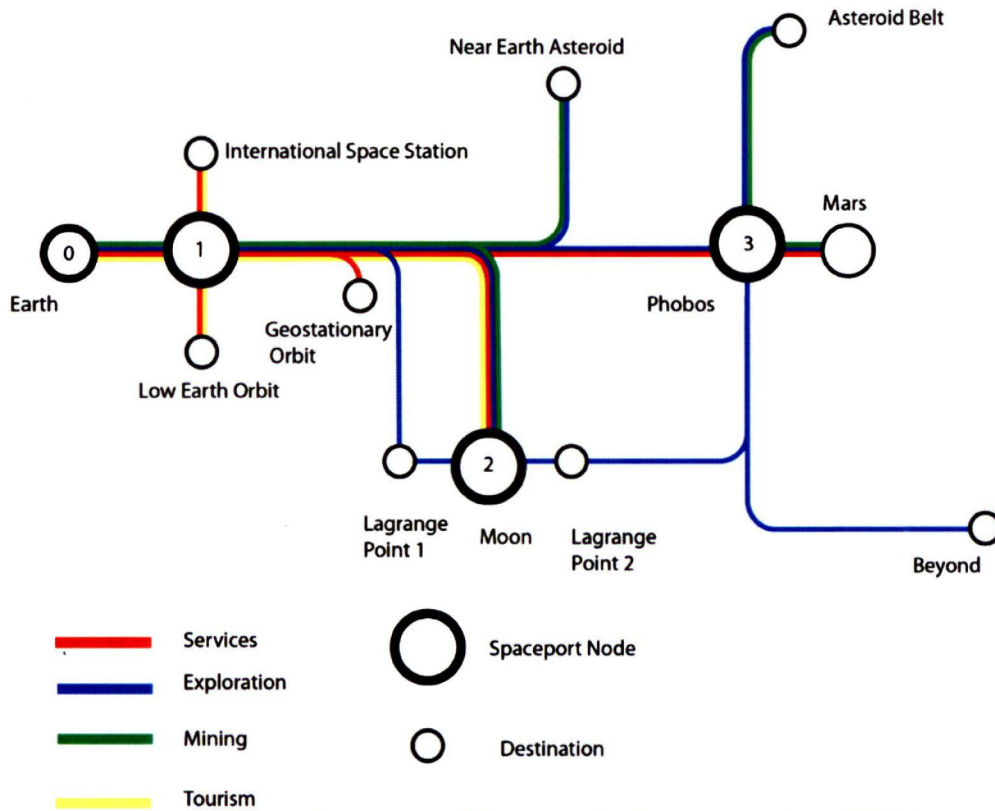


Figure 2: Metro Map Schematic of the Spaceport Nodes and Markets

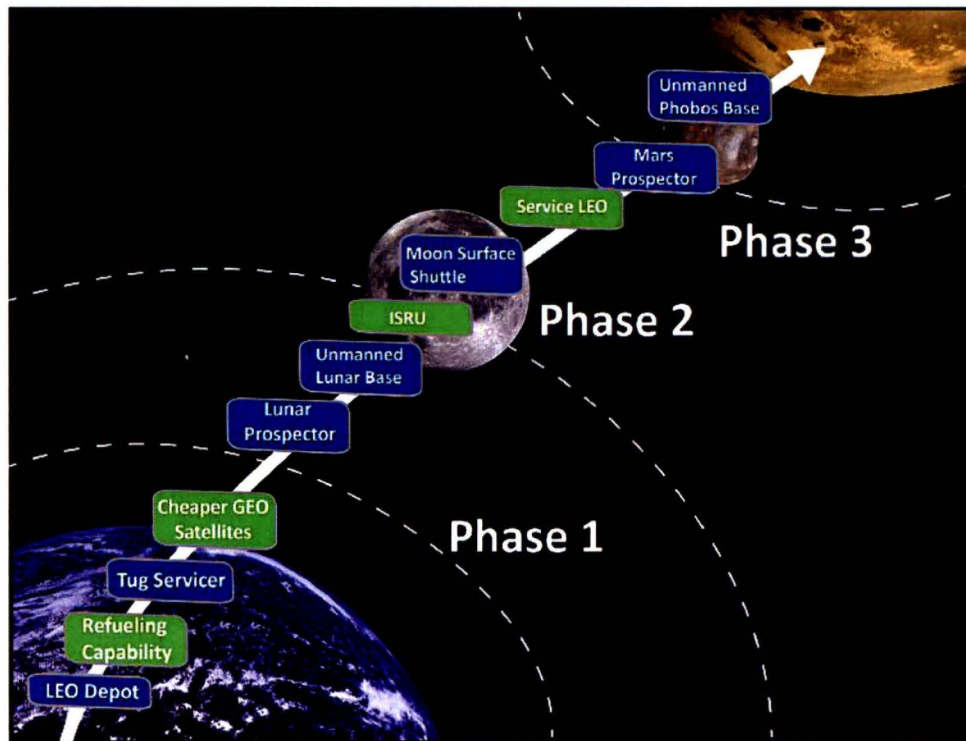


Figure 3: OASIS Phasing Plan

The network of spaceports consists of three nodes in space and one node on Earth which is Node 0 (Kennedy Space Center). Node 1 is assembled in Low Earth Orbit (LEO), Node 2 is placed on the Moon's surface and the proposed network is completed by Node 3 on Phobos.

**Node 1**

The Low Earth Orbit node would allow servicing of GEO satellites by tugging them from LEO to GEO. This would reduce the launch cost of these satellites, enabling the use of smaller launchers to put similar satellites into orbit. Reducing the launchers' mass, or increasing its payload, would also be a great advantage for missions to the Moon and Mars, where this node could be considered as the main staging point for missions up to Mars. Furthermore, the possibility of servicing LEO satellites, the ISS and next generation space stations is also a capability that makes this node the most fundamental in the proposed first phase of the network.

Depot major components	Power (kW)	Mass (kg)
Tank, thermal protection and debris shielding	0	1500
AOCS	-0.2	200
Electrolyzer, radiator and cryocooler	-200	6300
Thin film amorphous silicon photovoltaic arrays	+206	550
Communication systems and antennas	-0.3	30
Robotic arm for the solar panels	0.4	300
<b>Total</b>		<b>8580</b>

Table 1: Mass Budget and Power Balance for the Depot

At Spaceport Node 1 (Figure 4), the orbital platform provides support like power generation, station keeping, communication, navigation, and docking support to the other elements. An international docking adapter allows different spacecraft to dock. Water tanks connected to the propellant generators (via electrolysis) are directly connected to the tug servicer, which is shown in Figure 5. It should be noted that the system is modular and more elements can be added to increase the needed capability. Finally, it will provide cryogenic (LO2 and LH2) consumables to service any spacecraft. The Node 1 is expected to operate for the whole duration of phase 1 of the network (2015-2025).

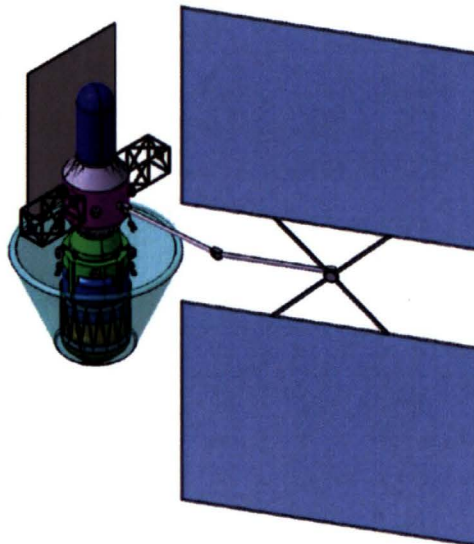


Fig. 4: Spaceport Node 1

### Tug Servicer

The first tug is expected to operate for the whole duration of phase 1 of the network (2015-2025), during this time an average of 4-5 missions per year is expected.

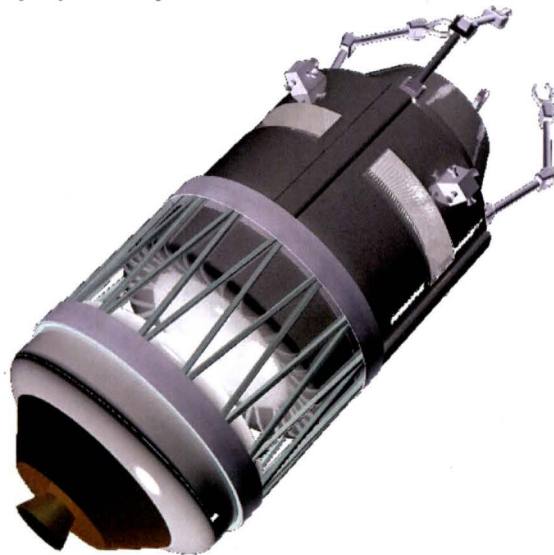


Fig. 5: Tug Servicer

Our business case determines that initially the main service for the tug is to transfer satellites from LEO to GEO for orbital inclinations of  $0^\circ$  to  $51.6^\circ$  (ISS orbit) and circularize their orbit if necessary. Higher inclination requires a large amount of propellant, so the constraint of not going further than ISS inclination was applied. The tug carries enough propellant to deliver a 9 ton satellite from LEO to GEO and then return itself back to the depot for refueling. Returning from GEO to LEO, the tug uses aerobraking to save fuel, in order to create drag during an aerobraking maneuver, a conical section deployable aerobrake is fixed to the side of the engine nozzle structure.

Due to the availability of LO<sub>2</sub> and LH<sub>2</sub> processed in orbit, fuel cells are selected as a power source since they can be replenished with the cryogenics provided by the tug. Photovoltaic arrays are avoided due to the unknown configuration of the serviced satellite as they may cause maneuvering, approach and access problems. The tug may have to provide service to a satellite that is not in a stable attitude; thus a grapple mechanism is necessary. Additionally, tele-operated robotic arms are available, carrying interchangeable tools and cameras for video feedback to the control station. The mass breakdown for the tug servicer is given in Table 2.

Tug Major Components	Mass (kg)
Engine, 110kN thrust (Pratt and Whitney Rocketdyne)	400
Structure, thermal and aerobraking drag device	600
Tanks with passive cooling	1600
Robotic arms	200
Fuel cells, 4kW	20
Communication systems and antennas	30
Attitude and orbital control	50
Total dry mass	2900

Table 2: Mass Breakdown Tug Servicer



### Concept of Operations

The concept of operations for the key service of tugging a satellite from LEO to GEO is described in the following.

A launch vehicle from the home spaceport at Kennedy Space Center, delivers the client's satellite to LEO, and the tug leaves Spaceport Node 1 to rendezvous with it. The tug docks with the satellite and makes the appropriate orbital transfer maneuvers to deploy the satellite to the requested GEO orbit. The tug is capable of performing the GTO to GEO circularization burn, so that the satellite does not carry the mass penalty of propulsion motor stage. The tug releases the satellite and returns to Spaceport Node 1 in LEO and docks for refueling.

Additional capabilities and example services of the tug servicer can be found in the OASIS report (Clegg et al, Team OASIS, 2012). The steps and missions including critical technologies to be developed to realize Spaceport Node 1 are shown in Figure 6.

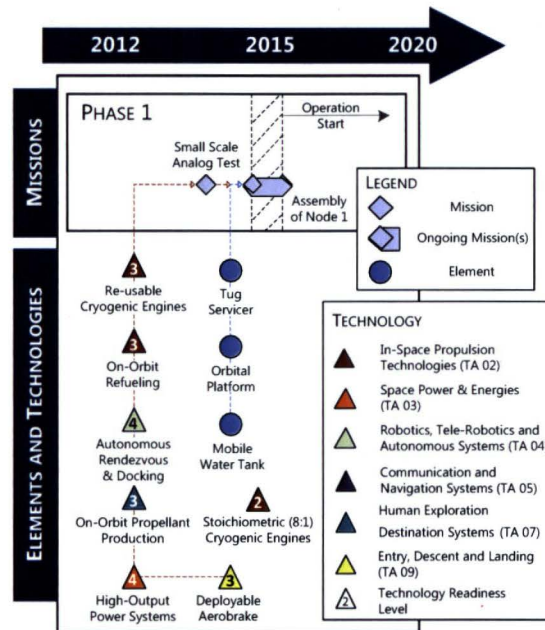


Fig. 6: Roadmap for Phase 1

### Node 2

The Moon has been considered a top exploration target for most of the space agencies in the world (ISECG, 2011). Its potential as a space tourism destination opens the door for private investment and the resources available on the surface enable the possibility of in situ production of propellants, solar panels and habitation modules. The resources could be useful to support Spaceport Node 1 in LEO and represent an important "stepping stone" towards the development of Spaceport Node 3 on Phobos by providing resources and also offering a test-bed for critical technologies.

On the Moon's surface, apart from operational support like power generation and communications, a system of elements will be set up. A regolith excavator will gather regolith for resources, and an ISRU plant will transform them into water. There will be a facility for propellant generation to generate propellant for the lander, which is used to lift the water tanks into orbit. Storage for water is provided. Another part of the Moon surface infrastructure will be a spaceport that enables spacecraft to launch and land safely avoiding dust contamination. Later on, consumables for life support systems (Oxygen, fresh water, and food) will be provided for a human presence Figure 7 shows the roadmap for the development of Node 2.

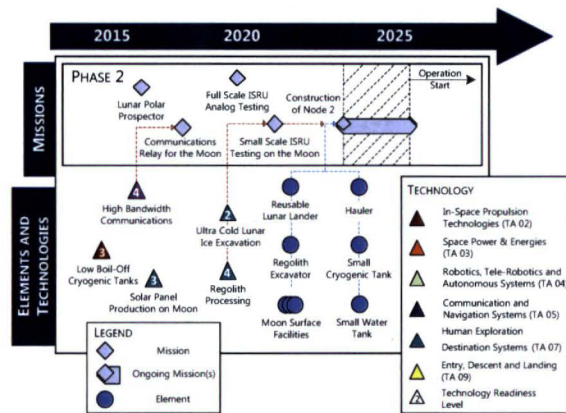


Fig. 7: Roadmap for Phase 2

**Node 3**

The third step on the development of the spaceport network would be the implementation of a node on Phobos. Mars and its orbits have been identified as important goals of space exploration for many space agencies. Phobos allows an easier access to Mars' surface and the reduced gravity field of Phobos facilitates access to its surface. This provides an advantage when compared to going directly to the Mars surface. Even though the presence of resources on Phobos is still not fully proven, regolith might be used for the construction of the node and possible water sources include near-Mars asteroids and main belt asteroids (e.g. Ceres) which would be used for propellant. A base on Phobos will be similar to a base on the Moon with operational support, possible propellant generation, propellant storage infrastructure and a port for transportation of resources from wet asteroids (e.g. Ceres) or transportation of people to Earth and other spaceports. Regarding asteroid mining, going to the asteroids and getting in situ resources is one option. The other one is to capture the asteroid and transport it to the Mars orbit to extract the resources there. Between the infrastructures, a surface transportation system does not have to be used due to the low gravity of Phobos. Instead, a "clamp-on" railway or "tethered" system might be implemented. A roadmap for the development with some missions starting during phase 2 is presented in Figure 8.

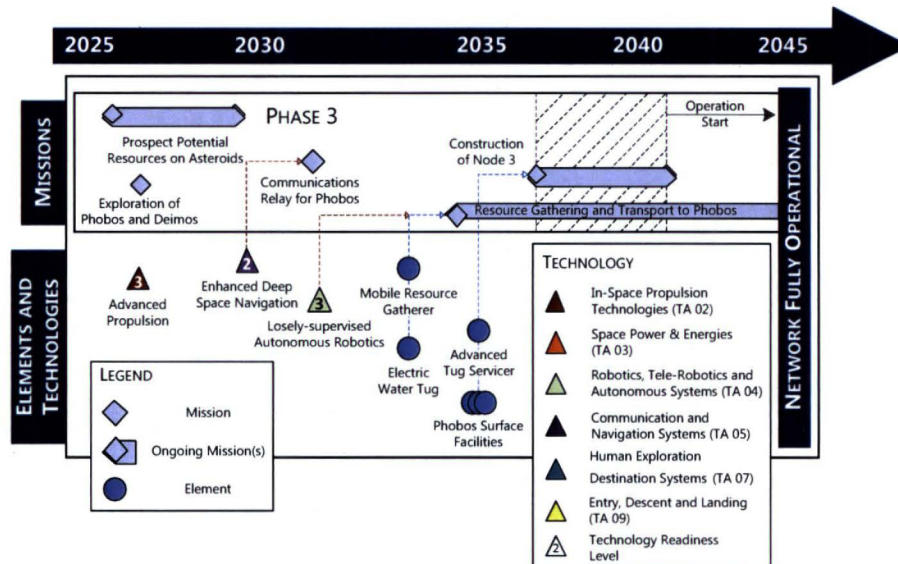


Fig. 8: Roadmap for Phase 3

## **B. OASIS Legal Structure & International Collaboration**

OASIS is a long-term project, which sets its primary goal at LEO and expands ultimately to Phobos, the Moon of Mars. For the starting point, OASIS project aims at calling out the attention of space agencies worldwide and establishing an international cooperation organization, a new governing authority, for support and the viable execution of the proposed network of spaceports.

Unlike the ISS management, OASIS requires the creation of a legal entity to provide commercial services. Taking into consideration of the variety of services provided, and the need for long-term support, the legal entity of OASIS has to combine state reliability and private management flexibility on an international level. OASIS suggests an innovative model of a public-private partnership that involves the creation of a new governmental authority, the *International Spaceports Authority (ISPA)* to assemble and operate the spaceports. Further, OASIS proposes the creation of a private transnational company - *Spaceport Company (SPC)* with ISPA member states as shareholders. The proposed model allows a public entity to plan, facilitate, and regulate the initial construction and spaceport extension at a time when the operators cannot provide large capital demand. The operator, a private entity, operates, develops, and provides services to customers. The model combines creation of vital connections between public and private parties and generates considerable profits, high booster for employment, and tax income for member parties. Within the model, ISPA is an intergovernmental and coordinate organization that is comprised of 14 ISECG members as establishing parties together with any other States interested in joining the project, for those joining later after the establishment of ISPA, an agreement of the Charter of ISPA shall be reached. All ISPA members will participate in an equitable manner, regarding their financial contribution. The distribution of power in ISPA and the decision-making power correlates to the members' financial contribution, as well as the possession of capacities and positional strength.

The OASIS partnership model proposes to ISPA a partnership with the private sector, a transnational corporation: a spaceport company. This partnership will take place through a Request for Proposal (RFP) by ISPA to get private industry involved and submit proposals related to the management and operation of the spaceport network. Benefits from this arrangement are obvious, developing local private sector capabilities through subcontracting opportunities for local/national firms, as well as exposing state owned enterprises while also supplementing limited public sector capacities and getting it prepared for future demand.

The link between ISPA and SPC is a critical point where member states agree within ISPA and control the SPC as a capital shareholder. This legal structure has been successful in many cases as in Europe, where national space agencies are members of an intergovernmental organization, European Space Agency (ESA) and at the same time shareholders in the commercial window, e.g. Arianespace among private partners. Given the financial and legal scope of the Spaceport Company, a full private investment is not a realistic option. This means that the ISPA must operate as a full public investment, but considering the reduction of capacity of public investment in lean economic times, there may be a private component to supplement government funding. Given profitability of the project as outlined in the business case, private entities will have an access to OASIS spaceport capital as a way to leverage financial capabilities, resulting in public private shareholders. Under this regime, all activities of the SPC shall be monitored by its state of registration and/or any launching states contributing to the assembly of the spaceport. The ISPA shall deliver customer authorizations to approach facilities under a licensing regime of technical regulations compatible with export controls regulations, control insurance, and indemnification warranties, following the example of the Federal Aviation Administration (FAA). Figure 9 presents a graphical overview of the structure.



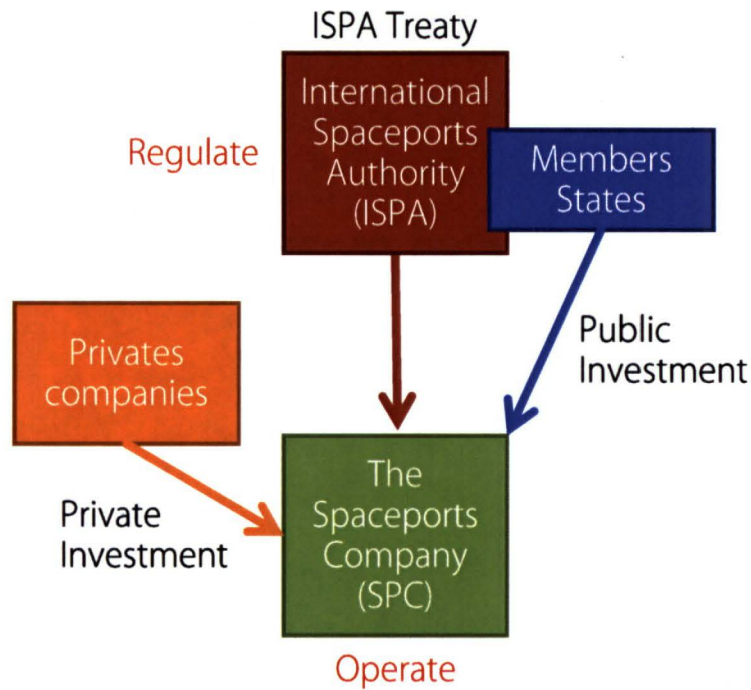


Fig. 9: Overview of the organizational structure

**C. OASIS Services & Business Case**

The potential markets and customers from short to long-term addressable by the OASIS spaceport network are listed in Table 3, Table 4 and Table 5.

Potential Services	Description Potential Customer
Tug from LEO to GEO	Use a tug unit to transport a GEO satellite from LEO to GEO. Produce propellants at Spaceport Node 1 by electrolyzing water provided from Earth. Load propellant in tug, rendezvous and connect with the spacecraft and transport to GEO. Commercial GEO satellite operators (for example, Intelsat)
On-orbit fueling in LEO	Use the water depot and electrolyzer in LEO to provide cryogenic LO <sub>2</sub> /LH <sub>2</sub> fueling services to spacecraft or satellites going beyond LEO. Space agencies and commercial planetary missions, Asteroid Miners
Space debris mitigation (optional)	Use the tug and the propellant available at the depot to provide de-orbiting services of space debris from LEO to Earth's atmosphere.



	Space agencies and governments
Space structure decommission (optional)	Use the tug and a new propellant depot to safely decommission a large on-orbit structure at the “end of life”.
	ISS, Bigelow Aerospace, Orbital Technology, Tiangong
On-orbit servicing (optional)	Use a specific spacecraft to provide inspection, relocation, restoration, repair, augmentation and assembly services for existing GEO and LEO satellites.
	Satellite operators, Space Agencies
Warm back-up (optional)	Provide back-up satellites for GEO satellites operator in case of emergency/failure of one of the satellites and depending on the criticality of the service provided.
	Space agencies, insurance companies, and commercial satellites

Table 3: List of Potential Services and Customers for Short-Term (2012–25)

A tug servicer, previously described, will be used to transport spacecraft from LEO to GEO. In Phase 1, a water tank filled with water launched from Earth to LEO using a low-cost launch will be used to provide the tug with the necessary cryogenic propellants using electrolysis performed at Spaceport Node 1. Afterwards, the GEO satellite will be launched to LEO and then tugged to GEO.

The value propositions of this service are multiple. The first one is the possibility to launch a nine metric tonne satellite into GEO. The second is a lower price than current launchers (cf. Figure 10, considering for each launcher, the price per kg calculated by the ratio of the launch price to the maximum mass usable). The third is the possibility for small size launch vehicles (e.g. Soyuz) to enter the GEO market and for large size vehicle (e.g. SLS, Falcon 9 Heavy) to provide a higher mass to Moon, Mars destinations and beyond.








		Price per kg		Cost reduction for the customer
		LEO	GTO	
Proton-M		4,348	16,260	48%
Ariane		7,143	15,789	44%
Falcon 9 Heavy		2,415	10,667	-3%
Delta IV Heavy		8,850	15,385	40%
Atlas V Heavy		6,803	15,385	40%
Falcon 9		4,106	11,134	2%
<b>OASIS solution</b>			<b>10,963</b>	

Fig. 10: Price per Kilogram Charged to Customers by Existing Launchers

Potential Services	Description
	Potential Customers
Tug from LEO to GEO and Moon orbit and back (optional)	Same service as the one provided for GEO satellites but extended to Moon orbit and back for satellites and spacecraft. Supply the LEO depot with propellants using water extracted and processed from the Moon.
	Space agencies and Space tourism (Space Adventures Ltd., Excalibur Almaz) and mining companies (Planetary Resources, Moon Express, Shackleton Energy)
On-orbit fueling in LEO	Same as Table 2 above: Cis-Lunar Same as Table 2 above: Exploration
Space solar power	Lunar propellants tug to deploy satellites for clean solar energy beamed from GEO to Earth Public utilities, agriculture, fresh water production, power to cities, power to disaster sites; reduce carbon emissions

Table 4: List of Potential Services and customers for Medium-Term (2025–45)

In addition, existing GEO spacecraft launchers charge the full price of the launcher to the GEO spacecraft operator regardless of the actual mass launched. Considering a Falcon 9 launcher from Earth to GTO, the price of the launch services is \$54m for a maximum mass to GTO of 4.85t. If the GEO satellite is 4.85t, the price paid of the satellite is \$11,134 per kilogram. On the other hand, if the GEO spacecraft is 4t, the price per kilogram becomes \$13,500, an increase of 21%. To offer a competitive price per kilogram for its customers, Ariane maximizes the mass used per launch by offering a dual launch to GTO with a maximum mass of 9.5t. Unfortunately, the number of GEO spacecraft launched per year is limited to 20 satellites. As a result, finding two GEO spacecraft with similar mass, fitting within the Ariane fairing, remains a challenge for Arianespace.

Potential Services	Description
	Potential Customers
Tug service between LEO to GEO, Moon orbit, Mars orbit	Same service as the one provided in the medium-term, but extended to Mars orbit and back for satellites and spacecraft. Mining and tourism companies, space agencies, science missions on the Moon and Mars, human settlement on Mars
On-orbit propellant loading in LEO, in Moon orbit and on Mars orbit	Deploy depot both in LEO and in Lunar orbit to facilitate further missions beyond the Moon and Mars. Same as above
Provide Lunar installation-related services	Leverage the material used to build the spaceport infrastructure on the Moon to provide services to other Moon settlers and

	visitors such as optical telecommunication, lease of infrastructure and tools, life support, and shelter.
	Mining and tourism companies, Space agencies science missions on the Moon
Lunar surface	Create solar power photovoltaic arrays in situ from lunar regolith
space solar power	Beam from Moon to Earth, same as above

Table 5: List of Potential Services and customers for Long-Term (2045– onwards)

The Spaceport Node 1 tug service provides a solution to this limitation. The tug service enables launches of single or dual GEO spacecraft into LEO and allows the remaining volume/mass in the launcher to be filled with either another LEO spacecraft or water to refill the Spaceport Node 1. This ensures a minimum launch cost per kilogram from Earth to LEO for any selected launcher. As a result, the spaceport network will be able to offer lower launch cost to GEO satellite operators and even to LEO spacecraft operators that also cannot always use the maximum mass offered by the selected launcher.

If the estimated initial investment required for Spaceport Node 1 is estimated to be approximately US \$300m and can be recovered within 7 years with just 4 GEO satellite launches of 4.5 Tons per year. Although this cost estimate may be considered low by some, it is proposed that ISPA will issue the SPC RFP with a requirement to use lean development, commercial methods to reduce costs. The details of the initial investment cost and the process to determine the price per kg charged by the spaceport network are detailed in the following description.

The total payload mass of the dual launch is 9t in GTO, the dry mass of the tug is 2.9t. The required amount of propellant to transport the tug and both satellites from LEO to GTO is 8,730 kg. Considering that 1.28kg of water produces 1kg of propellant, the required amount of water is 11,174 kg. Considering a cost of launch from Earth to LEO of \$4,000/kg (Proton: \$4,348/kg; Falcon 9: \$4,106/kg) for both satellites, \$3,200/kg for the water, and neglecting the cost of purchase and logistics of the water on Earth, the total cost to bring both satellites from Earth to GTO is \$71.8m without other charges. Considering 10% charges (tug operations and monitoring), the total cost for the OASIS Earth to GTO service is \$78.9m or \$8,770/kg of GEO satellites. Considering a 20% profit margin, the price charged for both satellites is \$98.7m or \$10,963/kg of GEO satellites.

Eventually, for the medium- and long-term periods, the Spaceport Node 2 on the Moon surface will provide the Spaceport Node 1 with water at a cheaper cost than the water launched from Earth. In the medium-term, the spaceport network will continue to provide “tug” services from LEO to GEO for the GEO satellite market. An expansion of the “tug” service is also considered for destinations like Lunar orbit, if a reasonable profit can be generated.

The total initial investment cost for the construction of a robotic spaceport on the Moon with mining operations to provide 150t of water to Spaceport Node 1 per year is estimated at \$5.3b. The payback period for the initial investment is set to 15 years. *As a result, the cost of a kilogram of propellant extracted from the Moon and made available at the Spaceport Node 1 is \$3,261.* This corresponds to a reduction of 38 % compared to the short-term Earth propellant solution.

This cost depends on the payback period chosen and the amount of lunar water provided at the Spaceport Node 1 per year. Indeed, increasing this amount will lead to economies of scale and reduce the cost per kilogram of lunar propellant in LEO as displayed in Figure 11. For a payback period of 15 years, more than 100t of lunar water should be extracted per year and provided to the LEO depot to offer a lower cost of propellant than the short term solution. The capture of future medium-term planetary or exploratory missions, tourism and mining companies’ missions will guarantee the viability of the Spaceport Node 2. In addition, if GEO Space Solar Power transmitted to Earth becomes viable due to the reduced cost of access to GEO and other technology developments, then the market

will become very large and the modular OASIS system can be scaled up to accommodate it. This will lead to further economies of scale and a corresponding reduction in price of LEO to GEO transportation.

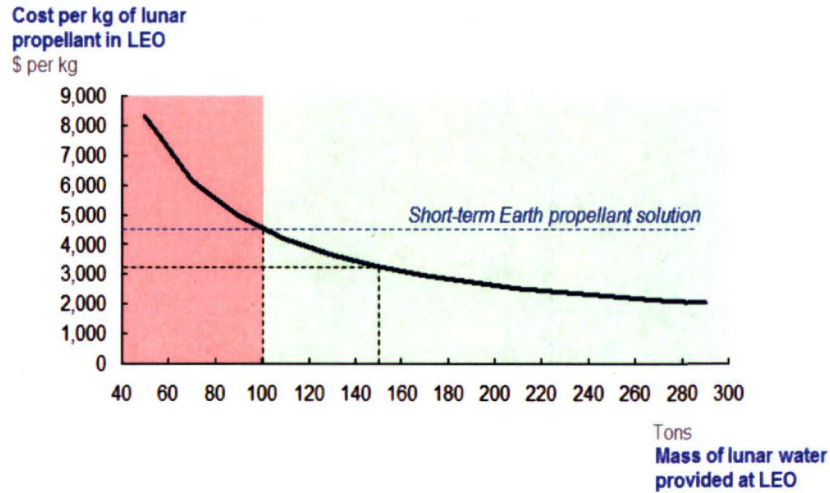


Figure 11: Evolution of the Cost of Lunar Propellant in LEO – Payback Period: 15 years

To produce a rough order of magnitude estimation of the cost of water from the Moon, the team used existing studies on Moon in situ resource utilization. *To produce a more accurate estimation more extensive studies have to be conducted.* This approximation is supposed to be a feasibility check rather than a design and to see if water (propellant) from the Moon is an interesting option.

The mass of the robotic Lunar mining operation components was estimated according to previous moon architecture proposals and recent technology developments in miniaturized robotics. The cost was estimated based on the NASA Spacecraft/Vehicle Level Cost Model, which is based on the NAFCOM (NASA/Air Force Cost Model) database and relates mass directly to cost. The model was based on 2008 US Dollars and was therefore corrected with an inflation rate of 3% to 2012 US Dollars. Every element was considered a “Scientific Instrument” except the Reusable Moon Shuttle (“Unmanned Planetary”) in the cost model and development cost as well as production cost was considered.

Additionally, system integration and maintenance costs as well as support equipment mass were accounted for with 10% each on the total cost and mass respectively. The launch cost was first approximated with \$80,000 per kilogram of payload on Moon surface. This cost could be reduced (by using the proposed tug service) to \$65,000/kg with the use of the OASIS Node 1 resulting in a total launch cost reduction of over \$400m.

In conclusion, the cost of water in Phase 2 from the Moon to Spaceport Node 1 in LEO would in the best case reduce the cost from Phase 1 where it is brought from Earth. Despite this uncertainty, in all cases, it enables increased payload capability to targets beyond the Moon and in general shows the advantage of using lunar resources. Also the cost to deliver payload mass to the Moon’s surface is reduced roughly by \$15,000/kg with the use of Spaceport Node 1.

#### **D. OASIS Missions to Mars and Beyond**

Using the OASIS network, including both LEO and Lunar resupply, a feasibility mission to Mars designated Caravan 1 (C1) was analyzed. The 10 tons (Mars landed mass payload) robotic mission docks to a Tug Servicer #1 provided at Node 1 in Low Earth Orbit (LEO) and transfers into the Mars Transfer Orbit (MTO). This maneuver requires all the propellant aboard the tug to provide the necessary  $\Delta V$ . The Tug Servicer #1 is then separated and is returned to LEO using its electric ion engines for reuse.

Well in advance of launching C1, the electric ion engines aboard the advanced version of the Tug Servicer #2 provide the velocity required to match C1 MTO velocity from LLO (Low Lunar Orbit), and a rendezvous with C1 not far from the Moon. These propellants are generated and supplied using the Spaceport Node 2 Lunar facilities and accompanying Moon Shuttle.

The technical feasibility of these deep space docking maneuvers has been demonstrated with increased frequency in actual missions. (Wertz and Bell, 2003) state that intercept missions with resolutions of under 10km is now a flight proven technology. Accordingly, the paper by (Haerberle, Spencer and Ely, 2004) provides confidence that the tug servicer attains required position measurements en route to Mars. The paper (You, Tung-Hang et al., 2007) provides several experimental numbers illustrating positioning accuracy for missions to Mars using the USA existing Deep Space Network (DSN) communications infrastructure.

Once mated with C1, the Tug Servicer #2 initiates a boost maneuver, reducing the time of flight to Mars from 258 days (standard Hohmann transfer) to 162 days via a staged Trans-Mars Injection (TMI). On-orbit staging could reduce the inbound flight duration through multiple pre-positioned stages even to 120 days as shown by Folta (Folta et al, 2012). Improved flight time helps decrease radiation exposure, required consumables and energy storage requirements for human missions significantly. Robotic missions would rather benefit from the increased payload mass, which could enable e.g. a Mars sample return mission.

Using Martian atmospheric braking and the remaining propellant aboard the Tug Servicer #2, C1 circularizes about Mars and enters a coincident orbit with Phobos via a minor Hohmann transfer.

Using the propellant provided at Spaceport Node 3 at Phobos, the Tug Servicer #2 is refueled with cryogenic propellants. The source of the water for propellant production at Phobos is considered to be a wet asteroid (e.g. Ceres) after proper phasing as well as water content have been identified. A descent to the Martian surface from Mars Polar Orbit (MPO) can be initiated, with the help of aerobraking and several retro burn maneuvers. With the availability of propellant at Phobos, the payload mass to Mars surface could be increased.

The C1 mission analysis illustrates the phase 3 enabled OASIS networks' ability to directly meet the needs of the ISECG Global Exploration Roadmap, as well as offer enhanced value to any space mission leaving the near-Earth environment. Using the same network, a return mission can be facilitated using propellants from the same nodes in the OASIS network. Additional propellant tanks can be added to any mission to further reduce flight durations. The standardized tank design and flexibility of the network offers unparalleled freedom and access to space.



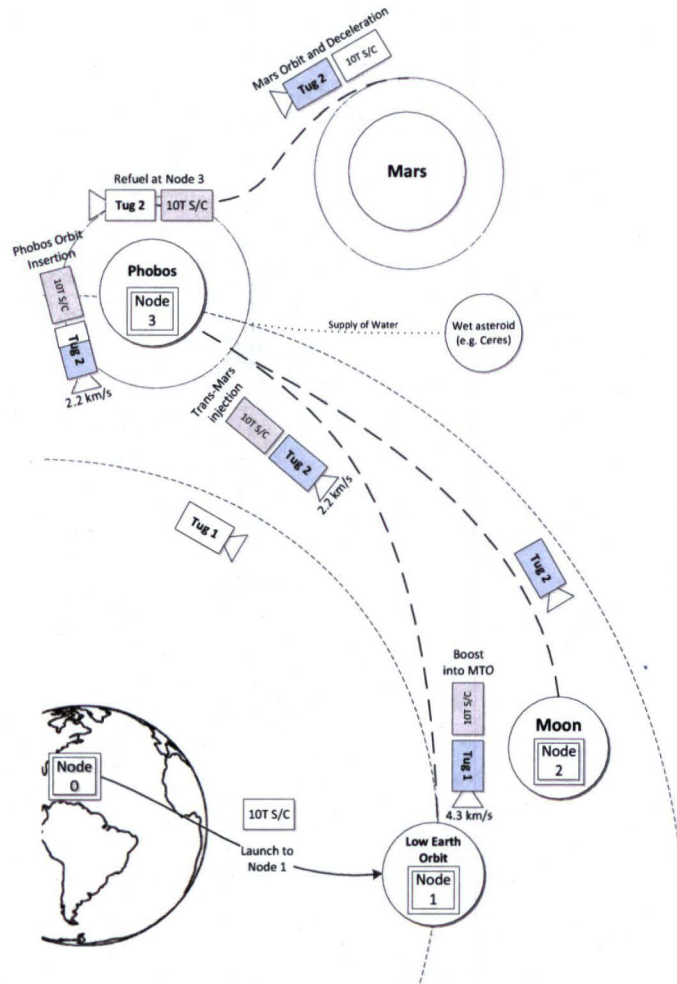


Figure 12: Schematic of Example Mars Mission

## VI. Using OASIS: A Spaceport Network Driven Economic Expansion

The cost of Project OASIS is divided up into phases that can be supported by the proposed PPP business model. When international participation is added, then the costs can be divided by multiple government and other private shareholders – so that the required funds are realistically available. If the OASIS plan were to cost about \$300 Million - \$1 Billion in Phase 1 and 10 partner nations were equally invested, then the investment per country would only be US \$30 Million to \$100 Million each over 5 years development and 5 Years operational periods – so that amounts to US \$6 Million – US \$20 Million per year during the 5 Year development phase for each member nation. It is assumed that operational costs will be covered by the SPC commercial entity in the second 5 year period. Phase 2 will likely cost between US\$5-10 Billion in order to establish a Lunar propellant to LEO production and logistics train. In this case the investment would be \$500 Million - \$1 Billion per country over a 10 year development period, which is (in the worst case) \$100 Million per year for each partner country. This means that if 10 countries commit (in the worst case) to an investment of US\$20 Million each, per year for 5 years (Phase 1), followed by \$100 Million per year for the next 10 years (Phase 2), *then bootstrapping is possible, if the equipment development and deployment costs are kept low and the countries are willing to accept a longer than usual payback period.* Operating costs are borne by the SPC private entity operating consortium, and over a 15 year minimum time period (after Phase 2 is realized, with earnings) each country's investment will be paid back as a return on investment via shareholder profits from the services provided by the Spaceport Company. This means that within 15 years the OASIS plan could successfully bootstrap its way to an independent operating status so the government can sell its

shares; effectively privatizing the OASIS spaceport network. At this point ISPA will remain as a regulatory and dispute resolution government entity similar to the way that a port authority or the USA Federal Aviation Administration (FAA) operates on Earth. The investments outlined above are well within the capacities of many nations with existing space programs. Support for OASIS will stimulate the space sector in each member nation, since they will have chances to bid on technology development, spaceport fabrication & assembly, water payload launches, and they will benefit from lower space transportation costs.

The ultimate importance is that by establishing a spaceport network, then propellant prices in LEO can be reduced to initially US \$3,200/Kg at 150 metric tonnes of propellant supplied to LEO (from the Moon) and then eventually US \$2,000/Kg at 300 tonnes supplied to LEO, due to economies of scale. In 2005 the then NASA Administrator, Michael Griffin said that NASA could be willing to buy propellant in LEO for US \$10,000 per kg (Bienhoff, 2007), thereby establishing a benchmark market price. Project OASIS will enable the reduction of propellant costs in LEO. This means that now the cost of bootstrapping the solar system economy by sending replicating manufacturing and resource utilization robots to the moon, as described in the transformative vision above, has been reduced from US \$80,000 per kg to less than \$65,000 per kg so that the total cost is then only US\$780 M (12 t) to US \$2.6 Billion (41t) at a 19% reduction from the current estimated cost of transportation to the Moon. *However, the price points are debatable since there have been no commercial landings on the Moon yet, so further economic analysis and actual commercial missions are required to gain confidence.* Since the same ISPA structure could be used for a solar system industry expansion (Metzger et al, 2012) after the spaceport network is in place, then it is reasonable to assume that the costs per country per year (10 nations over 10 years ) would amount to US \$7.8 Million to US \$26 Million per year each, allowing further bootstrapping to commence. This is extremely affordable for most nations, and the resulting benefit could be significant, and possibly in excess of the 6:1 ratio displayed by the US Eisenhower interstate highway system. One could argue that the replicating robot solar system economy should be implemented right away without setting up a spaceport network, but the required technology does not exist yet, and the solar system economy will need the infrastructure of the spaceport transportation network as a prerequisite for the exchange of resources and manufactured components between each destination node. This is analogous to components that are shipped across the oceans from seaport to seaport here on Earth. Once this capability is in place, the replicating robots will use space resources to manufacture goods and energy, without any further investment from Earth, by using the OASIS spaceport network. Net energy and goods exports from space back to Earth can then create tremendous wealth and independence from resource limitations on Earth.

Further work is required to formulate a financing plan with an associated business plan to show that by adopting this financial structure, the bootstrapping of a solar system economy is indeed possible while being politically and financially sustainable, but initial results from Project OASIS indicate that it could be possible if it is carefully implemented.

## VII. Conclusion

The International Space Exploration Coordination Group (ISECG) outlines Mars in its Global Exploration Roadmap (GER) as the ultimate near-future goal in human exploration of the Solar System. While a strong case exists for the exploration of the Solar System, in particular the Moon and Mars, few organizations have adequate financial resources to take advantage of the economic possibilities. The high cost of space exploration means that only government supported organizations have conducted most of the missions to date. The primary contributing factor to the high cost of space exploration is launch vehicle costs and subsequent space transportation costs and logistics; this poses a substantial barrier to any enterprise. However, the continually decreasing cost of technology, new mission architecture solutions, and the economic potential held in the natural resources of the Solar System enables the pursuit of space transportation and exploration as a new core business to benefit humanity.

The proposed solution is OASIS, a network of spaceports extending existing transportation and logistics infrastructure on Earth into space. This network has the objective of reducing the overall cost of space exploration and creating a vibrant commercial space market. The primary nodes of the network consist of LEO, the Moon, and the Mars moon, Phobos, corresponding to the short- (2015-2025), medium- (2025-2045), and long- (2045-onwards) term capabilities of the network, respectively.

In the short-term, the first node of the spaceport network is to be established in LEO, addressing a mature current LEO – GEO space market. As a result, the primary services provided in LEO consist of on orbit-refueling and a

'tug' service from LEO to GEO. The 'tug' service is the initial source of business in order to make the overall network economically viable in the long run. The lunar surface is the second spaceport node in the network; it will supply the LEO node with resources extracted from lunar regolith and/or water ice. Using resources from the Moon could drastically reduce the costs of propellant in LEO and ensure a strong and enabling business case for the network. It is also an important stepping stone to traveling throughout the Solar System and the development of Spaceport Node 3 on Phobos. The Martian surface has been identified as an important goal for space exploration by many international space agencies. Compared to the direct route to Mars, the low gravitational field of Phobos facilitates easy access to the Martian surface and further celestial objects via staging with the use of ISRU water derived propellants. The necessary water could be found on wet asteroids.

To facilitate the feasibility of OASIS, international cooperation is kept as a major driver of the project. For this reason, an international governing authority is established for the network of spaceports, named the "*International Spaceport Authority*" (ISPA). The members of this organization could be comprised of the 14 ISECG member states and other willing nations. To carry out the development of OASIS, ISPA will contract a private, transnational company designated as "*the Spaceport Company*", (SPC) to manage and operate the network. The legal, political, and societal framework for the SPC's operations has been identified and outlined and can be found in more detail in the ISU OASIS report (Team OASIS, Clegg, 2012).

In conclusion, OASIS provides a compelling and viable plan for extending a human presence throughout the Solar System with benefits for all of humanity. *It is the hope of the authors and the ISU Team OASIS that the vision and implementation strategy outlined in the paper will form the kernel for a revitalized space exploration effort in the near future.*

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