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ESTABLISHMENT OF A SPACEPORT NETWORK ARCHITECTURE

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Since the beginning of the space age, the main actors 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 infrastructures to support these missions is still lacking. To provide easy and affordable access into orbital and deep space destinations, there is the need to create a network of spaceports via specific waypoint locations coupled with the use of natural resources, or In Situ Resource Utilization (ISRU), to provide a more economical solution.

As part of the International Space University Space Studies Program 2012, the international and intercultural team of Operations and Service Infrastructure for Space (OASIS) proposes an interdisciplinary answer to the problem of economical space access and transportation. This paper presents a summary of a detailed report [1] of the different phases of a project for developing a network of spaceports throughout the Solar System in a timeframe of 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). The approach includes engineering, scientific, financial, legal, policy, and societal aspects.

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

**I. INTRODUCTION**

An oasis is a fertile area in a desert, where there is water. Oases are typically located at waypoints vastly separated between destinations to facilitate travel and commerce. Nomads and travellers stop at these places to restock food and water, rest, repair broken parts on their equipment or, if available, obtain new parts and supplies. Like oases in the desert, the organization of spaceports presented in this paper outlines a pioneering, multi-purpose logistics network of safe havens, enabling human and robotic expansion into the hostile space environment. A spaceport is an infrastructure waypoint that provides services for space vehicles and facilitates their departure and arrival.

Operations And Service Infrastructure for Space (OASIS) aims to progressively develop a network of spaceports (oases) providing support for space exploration and commercial activities and eventually to expand humanity into space. The International Space Exploration Coordination Group (ISECG), comprised of

fourteen space agencies interested in peaceful exploration, created a Global Exploration Strategy that provides OASIS with an excellent opportunity to promote its vision under the framework of international cooperation and public-private partnership. 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 [2].

Getting to and living on these exciting destinations poses some significant challenges. Current launch systems, while very capable, are unable to provide sufficient mass to orbit at an acceptable cost. Current launch systems often place a spacecraft as well as five to ten tons of propellant into orbit. This propellant boosts the spacecraft to its desired destination but consumes much of the launch system's volume and energy. The OASIS team proposes to change this model by placing the propellant and other support items in a

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convenient location in space (a spaceport), allowing current launch systems to lift more spacecraft mass into Low Earth Orbit (LEO).

Placing the propellant in LEO for orbit transfer from Earth orbit to other orbits facilitates government space exploration and more affordable commercial use of space. The addition of life-support consumables and support services in Low Earth Orbit would constitute a full-service spaceport. A spaceport in LEO would enable more affordable tourism, space-based telecommunications, energy, and debris removal. Once spaceports prove to be effective in LEO, the OASIS team proposes the creation of a network of spaceports that include locations on the Moon, and Mars' moon Phobos to further enable space exploration.

All space-faring nations and corporate entities will be very interested in this change so OASIS anticipates significant political, legal and social debate regarding the spaceport network. After examining global success with public-private partnerships, OASIS proposes the creation of a new inter-governmental organization to support the development of the spaceport network. In addition, the OASIS team describes a new treaty and explores options to deal with specific political, legal, societal and ethical considerations.

OASIS follows a phased approach to the design, development and operation of the spaceport (which in detail is presented in [1]):

- a. Assess existing and planned capabilities of terrestrial spaceports (not part of this paper but included in the report [1]);
- b. Identify spaceport functions, capabilities and services necessary for several connections, or waypoints, of a spaceport network;
- c. Select appropriate spaceport nodes that meet government space exploration and commercial development needs; and
- d. Prescribe a possible sequence of spaceport node development based on market needs, risk profile and sound business practice.

Each spaceport node relies on the quantity and setting of local resources, which the network can leverage within the design. The near-term identifies the main products supplied to space missions by in situ resources will mainly be propellants and life support consumables; as such these areas form the focus of the discussion.

The spaceport network solution will be designed after completing the market and feasibility analyses. The requirements, functions and architecture of the spaceport network determine the basis for the roadmap of the important steps and time phasing of this spaceport network.

Legal and political aspects determine the impact of such a network on Earth. Key issues include registration, ownership and free access issues. This

work examines the issues on liability as well as the use of resources in a legally-, politically-, and culturally-acceptable manner as well as the cultural and social topics of long-term missions.

The OASIS team investigated a conceptual design of a spaceport node in LEO alongside the different services it provides, such as repair, orbit slot change, de-orbit, and salvage. This proves that there is at least one capable option and constitutes an "existence proof". Such a node can also offer services such as storage, idling, warm backup, a solution for space debris, and potentially decommissioning of space structures. Moreover, a rough order of magnitude analysis was made for Node 2 and impact on the cost of water in LEO as well as the launch cost to Moon surface.

An example mission study of tugging a satellite into Geostationary Transfer Orbit (GTO) from LEO continues the "existence proof" and was presented in [1]. This, coupled with a cost study of launching a satellite directly from the Earth to GEO, serves as a baseline for the mission justification. Comparisons are made on the source of propellant, whether it is provided from the Earth or the Moon.

One of the big challenges of the 21st century is to lower the cost of access to space and the OASIS team is accepting the challenge by describing a revolutionary vision of approaching space travel.

## II. BUSINESS CASE

OASIS introduces a transportation network intended to extend the existing infrastructure on Earth into space. Indeed, OASIS spaceport network will take advantage of existing terrestrial spaceport facilities to contract launch services to transport necessary resources and payloads from Earth's surface to space. Selection of terrestrial spaceport facilities offering the most suited inclinations with low-cost, reliable and high mass to orbit will reduce the initial development cost of the spaceport network. Table 1 shows major launch vehicles capability and launching price of it and Fig. 1 presents the major spaceports.

The operational viability of the spaceport network is highly dependent on whether or not the network is making a profit and therefore can build on its profits to upgrade its infrastructure and expand to other locations in Space. Sufficient revenue from services offered must be generated to cover the operational cost and recover the initial investment after some years.

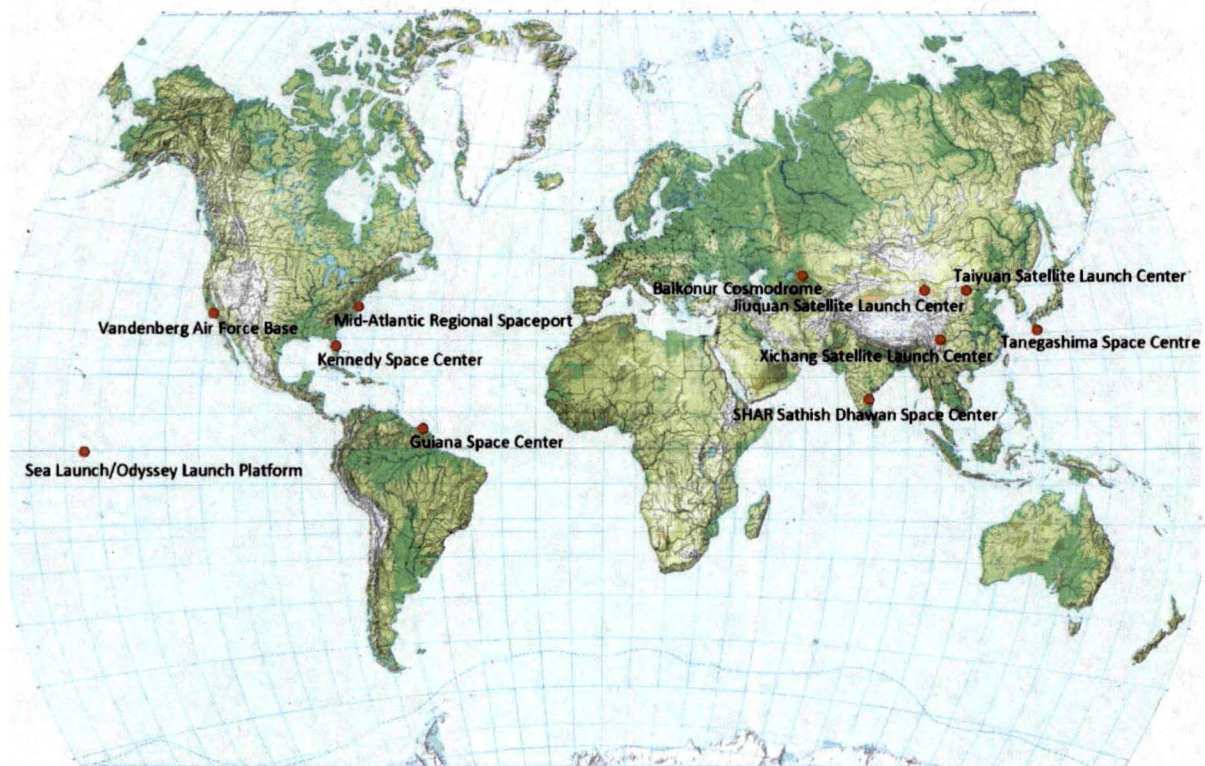


Fig. 1: Major Spaceports around the world [1]











Launch Vehicle	Delta IV Heavy	Atlas V Heavy	Falcon Heavy	LM-5	Ariane-5	Proton-M	Zenit-3SL	LM-3B	H2B	Falcon 9
										
GEO [Tons]	6.6	6.5	N/A	5.1	5.0	3.3	2.9	1.8	N/A	N/A
GTO [Tons] @ inclination	13.0 @28.5°	13.0 @28.5°	19.0 @28.5°	14.0 @19.5°	9.5 @6°	6.15 @23.2°	6.1 @0°	5.5 @28.5°	8.0 @28.5°	4.9 @28.5°
LEO [Tons] km@ inclination	22.6 407@ 28.5°	29.4 200@ 28.5°	53.0 200@ 28.5°	25.0 200@ 42.0°	21.0 200@ 51.6°	23.0 180@ 51.5°	7.3 1000 @0°	11.5 200@ 28.5°	16.5 300@ 30.4°	13.2 200@ 28.5°
Price Est. [\$M 2012]	200	200	128	150	150	100	100	80	150	54

Table 1: Major Launch Vehicle Capability and Price (Sources include launcher websites and expert interviews) [1]

The selected spaceport network architecture consists of an Earth Node 0, a Spaceport Node 1 in LEO in the short-term (2015-2025), a Spaceport Node 2 on the Moon's surface in the medium-term (2025-2045) and a Spaceport Node 3 on the surface of Phobos, one of Mars' moons, in the long-term (2045-onwards). By considering the potential services to be provided by the spaceport network during the architecture design, OASIS ensures an optimized development and operational cost for its spaceport network.

### II.1. Short term (2015–25)

The geostationary spacecraft represent a mature market that has remained stable over the past 10 years consisting of an average of about 20 spacecraft launched per year with an average mass per satellite of 4.0 tons, per spacecraft. It is expected that the number of spacecraft launched into the GEO orbit will remain between 20-23 satellites per year. However, the average mass per spacecraft is expected to increase, as "the trend is to build heavier, more capable satellites" [3]. In the future, the average mass per GEO spacecraft will reach about 4.5 tons per satellite [1]. In the short-term, Spaceport Node 1 intends to capture part of the GEO satellite market and demonstrate its ability to satisfy the needs of customers to place heavier spacecraft in GEO.

A tug servicer, introduced in the following section, will be used to transport spacecraft from LEO to GEO. 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 in LEO and then tutged to GEO.

The value propositions of this service are multiple. The first one is the possibility to launch nine tons into GEO. The second is a lower price than current launchers (cf. Fig. 2, 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.

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 service 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.

The potential markets and customers for short term are listed in Table 2.

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 fuelling in LEO	Use the water depot and electrolyzer in LEO to provide cryogenic LO <sub>2</sub> /LH <sub>2</sub> fuelling services to spacecraft or satellites going beyond LEO. Space agencies and commercial planetary missions
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
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 (e.g. GPS, TDRS, Galileo) Space agencies, insurance companies, and commercial satellites

Table 2: List of Potential Services and Customers for Short-Term (2012–25)







	Price per kg	\$ 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. 2: Price per Kilogram Charged to Customers

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.

The estimated initial investment required for Spaceport Node 1 is \$296M and can be recovered within 7 years with just 4 GEO satellite launches of 4.5 Tons per year. 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.

The total 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 8,730kg. Considering that 1.28kg of water produces 1kg of propellant, the required amount of water is 11,174kg. Considering a cost of launch from Earth to LEO of \$4,000/kg (the remaining payload of launcher is going to be water, enables us to assume lowest per kg price) for both satellites (Proton: \$4,348/kg; Falcon 9: \$4,106/kg), \$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 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 \$99M or \$10,963/kg of GEO satellites.

The initial costs, as can be seen in Table 3, consist of the development, manufacturing and testing of the tug, the electrolyzer, solar panels for the electrolyzer and the

launch of these. The LEO tank (capable of hosting 30t of water) is counted as operational cost.

Tug Servicer	\$241M
Electrolyzer	\$12M
Solar panels	\$3M
Launch of components (9.7t at \$4,106/kg)	\$40M
<b>Total initial cost</b>	<b>\$296M</b>

Table 3: Breakdown of initial costs

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.

## II.II. Medium term (2025–45)

Building on profits and an improved attitude toward orbiting spaceports made during the short-term period, the spaceport network will expand in the medium-term with a second node, Spaceport Node 2. This node consists of a spaceport on the lunar surface that will enable in situ resources extraction and utilization. Indeed, extracting water from mining operations on the Moon's surface to provide propellant to the existing Spaceport Node 1 will significantly decrease the operating cost at Spaceport Node 1 compared to the short-term solution (water from Earth) thus increasing the profit generated by Spaceport Node 1.

Establishing a spaceport on the Moon will also be the origin of new markets related to services provided to customers operating on the Moon in the long-term.

The infrastructure of Spaceport Node 1 will also enable the development of Spaceport Node 2 on the Moon at a lower cost, through on-orbit fuelling in LEO or even by using the tug from LEO to Lunar orbit.

Note that the process for selecting the Moon as Spaceport Node 2 is detailed in later sections but also makes sense from a business and financial risk point of view. Humans have already been to the Moon and understand the resources available there better than on any other celestial body. The technology for extracting water on the Moon is in development. The risk of technical failure remains low. In addition, the Moon is close to Earth and close to Spaceport Node 1. Choosing the Moon will reduce the time required to fill the LEO depot and decrease the necessary infrastructure cost (more than one additional tug) required if Spaceport Node 2 were to be on an Asteroid for example.

The Moon spaceport could either be human or robotic. A robotic spaceport will ensure a minimum cost in the medium-term. An extension of the spaceport to accommodate humans in the long-term is considered as part of the overall architecture.

The potential markets and customers for mid-term addressable by OASIS spaceport network are listed in Table 4.

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 fuelling in LEO	Same as above: Cis-Lunar Same as 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 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 Fig. 3.

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.

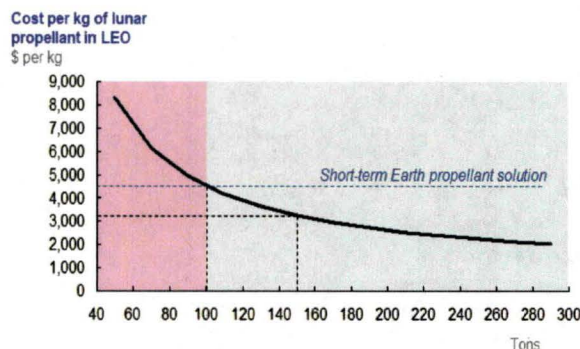


Fig. 3: Evolution of the Cost of Lunar Propellant in LEO – Payback Period: 15 years

### II.III. Long term (2045-Onwards)

The potential markets and customers for long-term addressable by OASIS spaceport network are listed in Table 5.

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, settlement on Mars
On-orbit propellant loading in LEO, in Moon orbit and on Mars orbit	Deploy depot both on LEO and on the Moon 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. Same as above
Lunar surface space solar power	Create solar power photovoltaic arrays in situ from lunar regolith, beam from Moon to Earth Same as above

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

In the long-term, Spaceport Node 2 will accommodate and support human-related activities on the Moon. Having a human spaceport will allow the network to offer services (landing, launching, telecommunication, life support, etc.), eventually including support for tourism, mining companies and space agency science missions. It is also a necessary step in the development of technologies for future Mars settlement.

In addition, the increased human activity on the surface of the Moon will generate additional revenue for the “tug” service from LEO to orbit around the Moon as well as on-orbit fuelling in LEO or fuelling on the surface of the Moon.

Shelter for Astronauts, Tourists and Science Missions	Settlement structures constructed in the ground using Moon regolith to protect from radiation in case of emergency. These structures will provide shelter to humans active on the Moon. Tourism companies, Mining companies, Space Agencies
Communications Surface Segment and Relay Station	The establishment of a segment for optical communications transmission to Earth orbit and other space destinations. Same as above
Landing and Launching Infrastructures	To offer launch and landing platforms to enable arrival and departure of spacecraft with cargo and humans. Same as above
Extraction of Water	To offer water for mining, tourism and science, in addition to propellant production. Same as above
Infrastructure Leasing	Structures will be built and leased to customers for operational and business activities on the Moon. Same as above
Life Support	Life support services provided to customers as an extension of the one required for water mining operations. Same as above
Space Solar Power	Clean Solar Energy produced on the Moon and transmitted back to Earth Public Utilities, Agriculture, Fresh Water Production, Power to Cities, Power to Disaster Sites; Reduce Carbon Emission

Table 6: Potential Moon Installation Related Services in the Medium-Term (2025–45)

Providing the services listed in Table 6 will allow the spaceport network to generate economies of scale on initial investments, increase its profit in the future and boost the tourism market on the Moon by providing the necessary infrastructures required for a short stay.

As part of the long-term plan, the network will also expand by establishing an additional node on Phobos, one of Mars’ moons. Potential use of in situ resources and the low gravity field will allow the spaceport network to establish “a fuelling station” on Phobos. Spaceport Node 3 will enable Mars settlement, which is expected to be an important market in the future as it is the destination that humanity is looking at as a second home.

### III. THE NETWORK OF SPACEPORTS

This section outlines the result of the systems engineering analysis of a network of spaceports. The OASIS mission statement, a customer-oriented market study, as well as an evaluation of the distribution and accessibility of extra-terrestrial resources to fulfil the customer’s needs, represented the basis for this study, which in detail can be found in [1]. Here presented is the proposed architecture which results from this analysis. The network of spaceports consists of three nodes in space and one node on Earth which is the Node 0 (Kennedy Space Center). Node 1 is assembled in Low Earth Orbit (LEO), Node 2 is placed on the Moon surface and the proposed network is completed by Node 3 on Phobos.

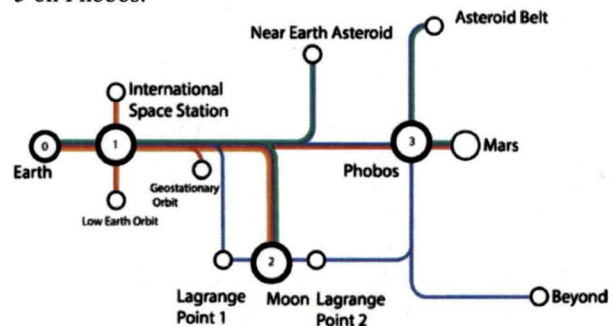


Fig. 4: Network Metro Map Analogy; Red: Services, Blue: Exploration, Green: Mining, Yellow: Tourism

In Fig. 4, the proposed network can be seen, presented in a metro map analogy. In the following each node is described as well as a roadmap for the realization of this node is offered.

#### III.1. Node 1

The Low Earth Orbit node, at 300km altitude and 28.5° inclination, 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.

Orbital Platform 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>Totals</b>	<b>+5.5</b>	<b>8580</b>

Table 7: Mass Budget and Power Balance for the Orbital Platform [1]

At Spaceport Node 1 as seen in Fig. 5, 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 (Fig. 6). 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 (LO<sub>2</sub> and LH<sub>2</sub>) consumables to service any spacecraft. The Node 1 is expected to operate for the whole duration of phase 1 of the network (2015-2025).

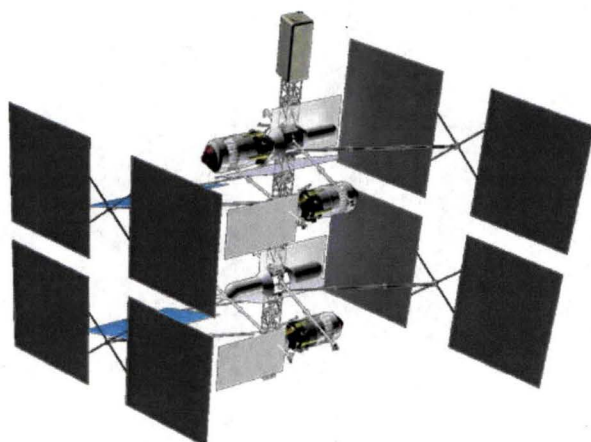


Fig. 5: Spaceport Node 1

### 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.

The business case determines that initially the main service for the tug is to transfer satellites from LEO to GEO for orbital inclinations of 0° to 51.6° (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.

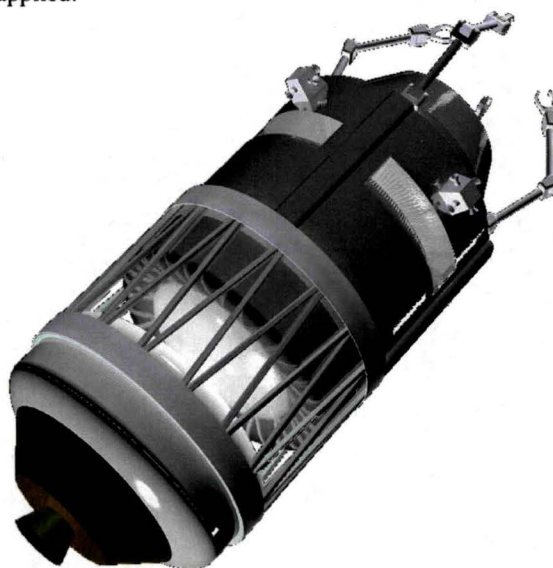


Fig. 6: Tug Servicer

The tug carries enough propellant to deliver a 9 ton satellite from LEO to GEO and then return itself back to the depot for refuelling. Returning from GEO to LEO, the tug uses aerobraking to save fuel, in order to create drag during an aerobraking manoeuvre, a conical section deployable aerobrake is fixed to the side of the engine nozzle structure.

Due to the usage of LO<sub>2</sub> and LH<sub>2</sub> processed in orbit, fuel cells are selected as a power source as they can be replenished with the cryogenics the tug carries. Photovoltaic arrays are avoided due to the unknown configuration of the serviced satellite as they may cause manoeuvring, approach and access problems. The tug may have to provide service to a satellite that is not in a stable attitude; thus a grappling 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 8.



Tug Servicer 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
<b>Total dry mass</b>	<b>2900</b>

Table 8: Mass Breakdown Tug Servicer [1]

**Example Mission: LEO - GTO (Earth water)**

The concept of operations for the key service tugging a satellite from LEO to GTO is described in the following. The tug is basically replacing the upper stage of the launcher. With this service, we can reduce the amount of propellant needed during the launch phases or, equivalently, increase the mass of the satellite to be delivered.

The “bat chart” in Fig. 7 presents the mission concept of operations. A bat chart is a graphical depiction of elements of a mission deploying over time from a point of origin at the bottom, to staging points vertically on the graph, and then to a final destination at the top of the graph, with the elements hanging from the top like bats on a ceiling. The elements may return to the point of origin depending on the mission.

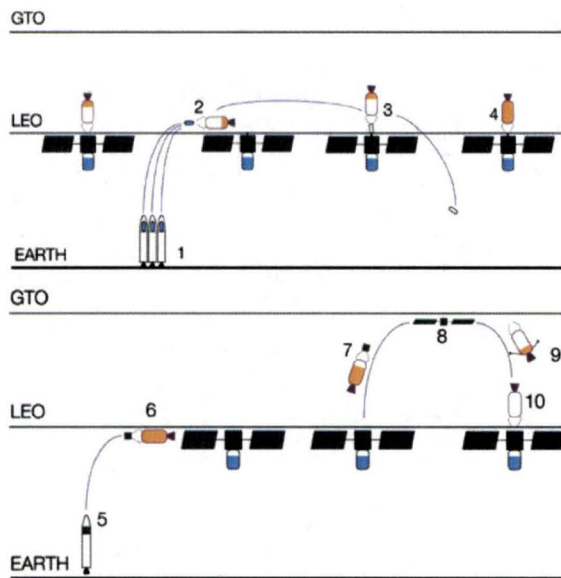


Fig. 7: Bat Chart of Mission with Supply from Earth

Legend: 1 - Launch of water to LEO; 2 - Tug docks with water tank and takes it to depot; 3 - Water is transferred to main water tank and small water tank is de-orbited; 4 - Water is converted to cryogenic

propellant and transferred to the tug; 5 -Launch of satellite from Earth’s surface to LEO; 6 - Tug rendezvous and docks with satellite; 7 - Tug takes satellite to GTO; 8 - Satellite is placed in GTO; 9 - Tug returns to LEO; 10 - Tug docks with depot and another mission is ready to start.

Additional capabilities and example services of the tug servicer can be found in [1]. A roadmap to realize Spaceport Node 1 is shown in Fig. 8.

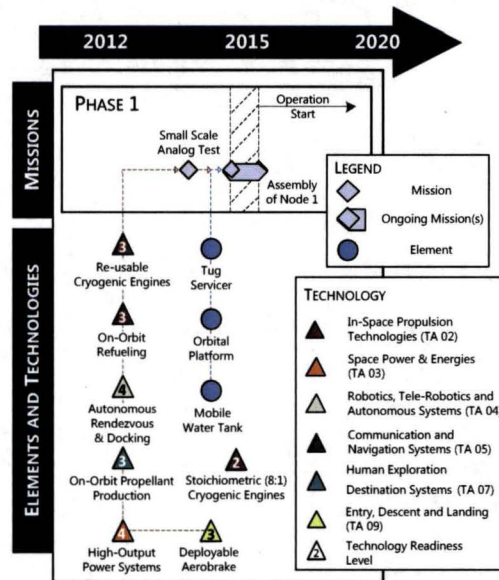


Fig. 8: Roadmap for Phase 1

**III.II. Node 2**

The Moon has been considered a top exploration target for most of the space agencies in the world [2]. 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 surface, apart from operational support such as power generation and communications, a system of elements will be set up. An excavator will gather resources, and an ISRU plant will transform it 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.

Fig. 9 shows the roadmap for the development of Node 2.

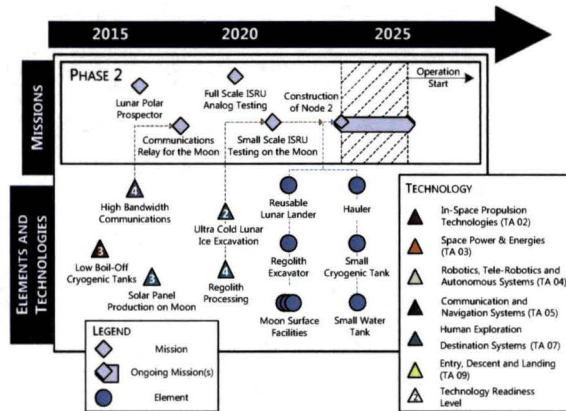


Fig. 9: Roadmap for Phase 2

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 results of this analysis are given in Table 9 and Table 10.

The following elements (Table 9) on the Lunar surface were identified to provide water in low-lunar orbit. The first assumption is that a total amount of 150 tons per year of water in LEO has to be delivered over the course of 5 missions. The presented architecture provides, in addition to the water for the delivery to Spaceport Node 1, the propellant for the Tug Servicer (outbound) and the Reusable Moon Shuttle and therefore does not require any propellant supply from Spaceport Node 1 or the Earth.

Node 2 Major Components	Component Mass [kg]	Total Cost [\$M] 2012
Regolith Excavator	280	48.94
Transportation System	364	57.34
Regolith Water Generator	1,869	116.69
Propellant Generator	5,136	314.99
Cryogenic Storage	10,040	468.11
Water Storage	1,801	171.03
Power System	660	96.24
Launch Pad	300	61.65
Reusable Moon Shuttle	3,489	1,623.63
Intermediate Totals	23,939	2,876.40
Support Equipment (10%)	2,394	
Maintenance (10%)		295.86
System Integration (10%)		295.86
<b>Totals</b>	<b>~26,350</b>	<b>~3,255</b>

Table 9: Mass and Cost Breakdown of Node 2

The mass of the components was estimated according to previous moon architecture proposals (detailed in [1]) 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.

	Direct [\$M]	Node 1 Staging [\$M]
Launch	2,107	1,706
Total Cost	5,657	5,256

Table 10: Launch and Investment Cost Overview of Spaceport Node 2

In conclusion, the cost of water from the Moon to Spaceport Node 1 in LEO would in the best case reduce the cost as it is presented in Section II. 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.

Example Mission: LEO - GTO (Moon water)

Another scenario for supplying Spaceport Node 1 with water is to have it coming directly from the Moon to further reduce costs. This occurs in the second phase of the roadmap. The difference between the Earth-supplied and Moon-supplied scenarios is in the first three steps of the Fig. 10. In this case, instead of launching water from the Earth to LEO, the tug brings water from the Moon. The bar chart below describes this first phase.

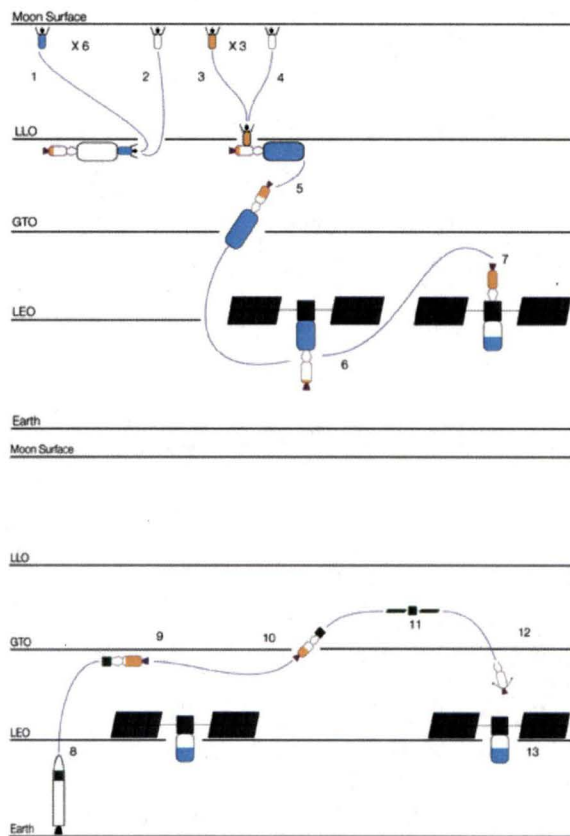


Fig. 10: Bat Chart of a Mission with Water Supply from the Moon

Legend: 1 - Moon shuttle takes off from Moon surface and docks in LLO with standing-by tug to deliver water; 2 - Moon shuttle returns to Moon surface after unloading its water tank (this step is repeated until the water tank transported by the tug is full) ; 3 - Moon shuttle takes off from the Moon surface and docks in LLO with standing-by tug to deliver propellant; 4 - Moon shuttle returns to Moon surface after unloading the propellant tank (this step is repeated until the tug's propellant tank is full) ; 5 - Tug transports full water tank to LEO; 6 - Tug rendezvous and docks water tank with depot in LEO; 7 - Tug rendezvous and docks with depot; 8 - Water is converted to cryogenic propellant and transferred to the tug; 9 - Launch of satellite from Earth's surface to LEO; 10 - Tug rendezvous and docks with satellite; 11 - Tug takes satellite to GTO; 12 - Satellite is placed in GTO; 13 - Tug returns to LEO; 14 - Tug docks with depot and stands by for another mission.

An important advantage of sourcing water from the Moon instead of the Earth is that, even though the Moon is further away from LEO, the velocity change is significantly lower with the use of aerobraking when returning to Earth. Furthermore, by using this option, the mission does not require the use of expendable

launchers to bring water from Earth's surface. Instead, the team proposes the use of reusable shuttles between the Moon surface and LLO.

### III.III. 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 the Mars surface and the low 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) whose water 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 missions already starting during phase 2 is presented in Fig. 11.

### Example Mission to Mars

An example mission to Mars using the complete network is described briefly in the following and in more detail in the report [1].

A spacecraft is launched into LEO and a tug servicer #1 from the Node 1 accelerates the spacecraft into the Mars Transfer Orbit (MTO) and returns to Node 1. A fully fuelled tug servicer #2 from Node 2 accelerates to MTO in advance with electric propulsion (an advanced version of the originally proposed tug servicer) and rendezvous with the spacecraft on their way to Mars. The second tug servicer gives the spacecraft an additional boost to decrease the travel time and brings the spacecraft to a coincident orbit with Phobos. Arriving at Node 3, the tug servicer #2 is refuelled and transports the spacecraft to Mars Low Orbit and provides additional deceleration before the spacecraft re-enters separately.

This example illustrates how the whole network can be used to enable Mars missions with a shorter mission duration as well as larger payload mass.

### III.IV.Standards

To enable easier operations between different nodes and to reduce the number of parts and procedures that need to be developed, the team proposes to standardize several elements of the spaceport network.

To facilitate international cooperation and avoid miscommunication, the metric system of units should be used throughout the design, construction and operation of the network.

A major part of the operation of the network is rendezvous and docking. All docking ports with the same functions across different spacecraft, tanks, ascent/descent modules and surface structures could use the International Docking Standard System or similar.

Finally, Fig. 12 shows the top-level roadmap towards the establishment of the OASIS network.

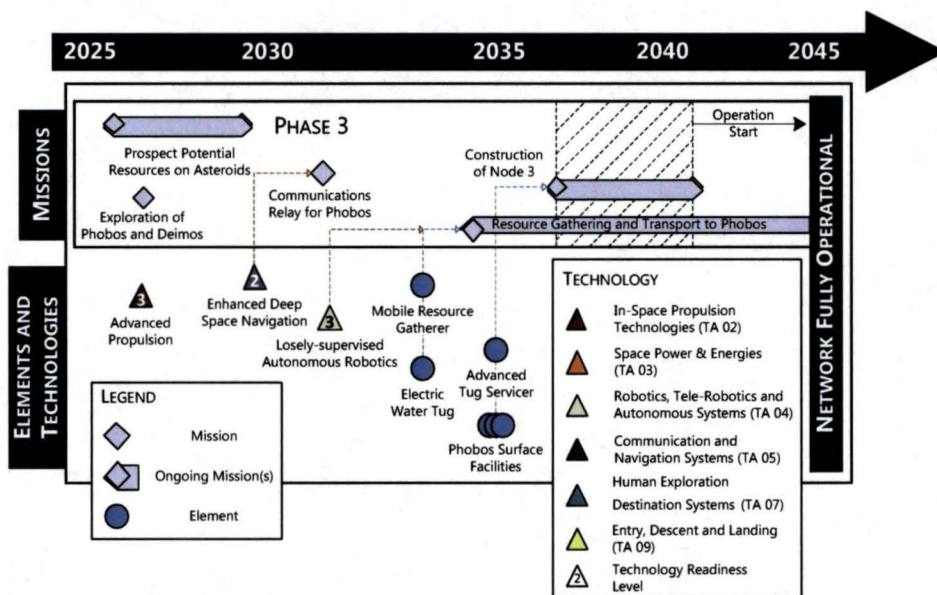


Fig. 11: Roadmap for Phase 3

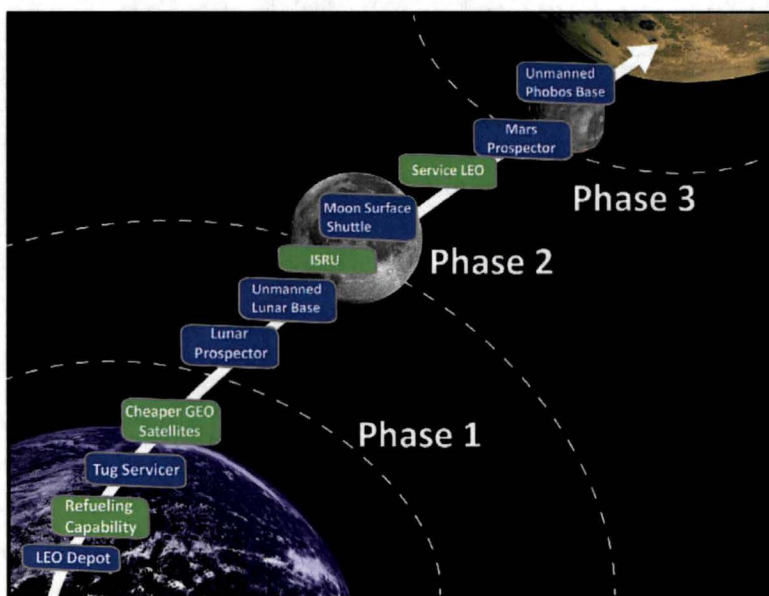


Fig. 12: Top-level roadmap for OASIS Network

### IV. ORGANIZATIONAL STRUCTURE

This section proposes an organizational structure for the operation of OASIS and potential legal framework

that might have an impact on OASIS in the expansion of its network and how to avoid any negative influences from a legal perspective.

#### IV.I. OASIS Organizational Structure Model

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, the 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 personality to provide an availability of commercial services. Taking into consideration the variety of services provided and the need of long-term support, the legal entity of OASIS project has to combine state reliability and private management flexibility on an international level. OASIS suggests an innovative model of public-private partnership that involves the creation of a new governmental authority, the International Spaceports Authority (ISPA) to assemble and operate the spaceports, and 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 when the operators cannot satisfy a large amount of 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.

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 by ISPA to get private industry involved and submit proposals related to the management and operation of spaceport network. Benefits from this model 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 that has been successful in many cases like in Europe where national space agencies are members of an intergovernmental organization, ESA and at the same time shareholders in the commercial window, Arianespace among private partners. Given the scope of the Spaceport Company, a full private investment is not as realistic an option as full public investment considering the reduction of capacity of public investment. 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 licensing regime of technical regulations compatible with export controls regulations, control insurance, and indemnification warranties, following the example of the Federal Aviation Administration (FAA). Fig. 13 presents a graphical overview of the structure.

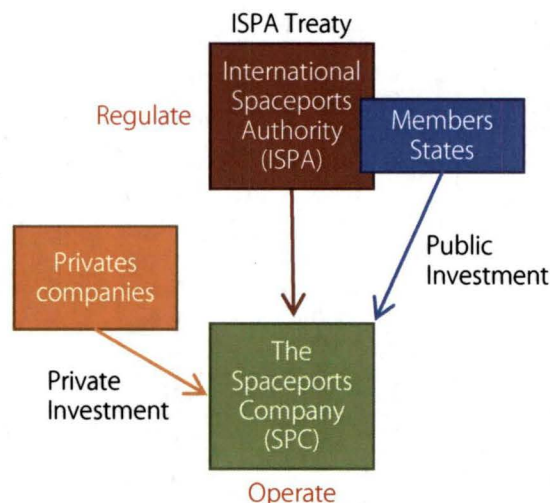


Fig. 13: Overview of the organizational structure

#### IV.II. Legal Issues Regarding OASIS Case

By carrying out activities in outer space, ISPA and Spaceport Company shall reconcile with current legal regime in outer space, including Outer Space Treaty (hereinafter as OST), Rescue Agreement, Liability Convention, Registration Convention and Moon Agreement. Within each node, different legal challenges might rise accordingly and several of them are elucidated as follows.

#### Liability issue

Damages caused by space debris or other space objects to facilities of OASIS in space and damage caused by spacecraft of OASIS on the Earth fall into the legal regime of Liability Convention, the former case arouses an identification of a launching state to be claimed as the subject of indemnification, which will accord OASIS more difficulty to identify the launching state(s) of space debris than other space objects. In this circumstance, an agreement between ISPA and SPC is recommended to include one clause to compensate the damage from ISPA considering the rationale of ISPA is to foster and boost a success and private participation space industry. For the solution of the latter case, launching state(s), including a state launches, and/or procures the launching; from whose territory and/or facility that a space object is launched, each of the four elements comprised the potential launching state(s) that shall be jointly liable for the damage caused to OASIS and OASIS is entitled to claim a compensation for the damage from either one of them.

#### Space debris mitigation

Spaceport Node 1 is located in Low Earth Orbit where the majority of space debris accumulate, therefore a joint-effort shall be made together with the Inter-Agency Space Debris Cooperation Committee (IADC) and UNCOPUOS, mainly to mitigate space debris for the benefit of facilities and infrastructures in orbit and for potential profit generated from the mitigation services provided by OASIS network. Regarding the liability issue caused by space debris, explanation can be found in the paragraph above.

#### Non-appropriation principle and use and exploitation of resources out of celestial bodies

Node 2 and 3 of OASIS involves the development of a spaceport facility and the servicing on the Moon and Phobos surface. In order to secure a free and non-discriminative access of outer space to all countries, one of the principle extracted from Outer Space Treaty article II is that outer space shall not be subject to any means of occupied or claimed of sovereignty. Additionally, in the Moon Agreement, one salient concept is that the Moon and other celestial bodies including its resources are common heritage of all mankind. Therefore, how to balance the demands from the existing space law scheme and the needs of an expansion of a spaceport network might be an elusive issue for OASIS to resolve in the near future. Though the Moon Agreement is barely recognized by space faring nations, and is not binding to the majority of them, developing countries and undeveloped countries might claim their rights. Moreover, the principle of common heritage of mankind might be highlighted considering that OASIS project is a commercial

exploration network proposal. A future suggestion for the resolution of the issue is to establish another international authority, International Space Resources Exploration Authority, like the International Sea-bed Authority governing the "area" of high sea. For OASIS, the solution might be an agreement with this authority to exclude a perplexing situation.

Other legal issues might arise and the above mentioned are not a complete list of all the legal challenges that might be confronted by OASIS. Further detailed and in-depth legal framework will be generated concomitant with the development of the OASIS network establishment.

#### IV.III. Societal Impacts

##### International Cooperation

It is necessary for government to explain the rationale of moving to international cooperation. With the international cooperation in place it is more likely for countries to plan for a long time horizon in their space programs and less likely for countries to get involved in big conflicts between each other. This allows citizens to gain confidence in both their governments and their international partners. International cooperation allows prejudices to fade out. As an example, United States and Russian collaboration on the International Space Station (ISS) translated to positive feelings about future interactions between the countries after the Cold War. It also makes citizens more global, which is necessary for when mankind will fully expand into space.

##### Awareness

By increasing space awareness, space agencies can increase mankind's conscientiousness of the "Spaceship Earth" and gain support for their projects contributing to the mankind's expansion outside the pale blue dot [3].

Arts including literature, pop culture and media always have a big influence on society. Science fiction literature largely contributed to space exploration activities at the beginning of the last century. Dreams of extraordinary minds, written in a fascinating and compelling manner, inspire people to reach for the stars. Influential authors, if given sufficient information directly from OASIS, can largely promote its activities, increase public understanding, and gain support. In a globalized world, the entertainment industry contributed to the creation of a space pop culture based on space literature.

As the ultimate involvement for citizens, OASIS provides opportunities for private spaceflight participants in order to further enhance the space experience. Inviting the public to become a part of the spaceport network creation and helping them to understand options, might increase tax-payers support by making them more enthusiastic about space.

### Ethics and Religion

Space exploration, especially bases on the Moon or Mars' moons, can raise a lot of ethical issues. Planetary protection will continue to be a concern for missions to other celestial bodies. As soon as commercial exploitation of moons or planets becomes a reality, space environmental organizations will emerge. The two main concerns within planetary protection discussions are related to forward and backward contamination of in-situ resource utilization. It is important to acknowledge these viewpoints and respond to them publicly so society is advised on another view on this matter.

### V. CONCLUSION

The International Space Exploration Coordination Group outlines Mars in its Global Exploration Roadmap 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 market. As a result, the primary services provided in LEO consist of on orbit-refuelling 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 travelling throughout the Solar System and the development of Spaceport Node 3 on Phobos. Landing humans on the Martian surface has been identified as an important goal of space exploration for many space agencies. Compared to the direct route to Mars, the low gravitational field of Phobos (or Deimos) 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". 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" 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 [1].

In conclusion, OASIS provides a compelling and viable plan for extending a human presence throughout the Solar System with benefits for all of humanity.

### VI. ACKNOWLEDGEMENTS

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### VII. REFERENCES

- [1] Team OASIS, 2012. *OASIS - Operations and Service Infrastructure for Space*, Project Report, Space Studies Program 2012, International Space University
- [2] International Space Exploration Coordination Group, 2011. *The Global Exploration Roadmap*.
- [3] FAA Commercial Space Transportation, 2012. "2012 Commercial Space Transportation Forecasts"
- [4] Sagan C., 1994. *Pale Blue Dot: A Vision of the Human Future in Space*, Ballantine Books.