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Legal, Business and Science Case for Modular Space Access and In-orbit Services Through Geostationary Orbit

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ABSTRACT

In the next two decades, the space science and industry look set to be utilising regular space travel solutions to access select key objects in our Solar System, Moon and Mars in particular. Specifically, as first long-term deep space missions and temporary (research-led) off-Earth settlements will be established beyond low-earth orbit (LEO), a new (modular) space access infrastructure will be required to facilitate such endeavours. Hence, Gateway Earth Development Group (GEDG) has been proposing to develop a technically and economically viable architecture for interplanetary space exploration, based on a space station at the edge of Earth's gravity well, called Gateway Earth. Using inflatable modules and multi-stage access through reusable launch to LEO, this complex is proposed to be the main outpost for starting and finishing missions further afield, as well as utilising in-situ resources, in particular existing disused spacecraft.

Having completed a preliminary analysis of technological readiness in 2017, and developed a detailed understanding of the station design, assembly and launch in 2018, this paper is presenting a solid science case, business model and legal position for the Gateway Earth programme. We start by outlining an in-depth analysis of literature, including international legal requirements for facilities in or near geostationary orbit (GEO) and the international legislation likely to regulate the building, assembling and operating the Gateway Earth complex. We then examine the costings and revenue streams within the Gateway Earth economic model, noting true-cost market prices and fluctuations, and subsequent detailed analysis of different available financial solutions for the proposed development. We note challenges in the very slowly developing space tourism market, which was previously billed as the enabling opportunity for the development of Gateway Earth, and propose to instead focus on servicing, recycling and manufacturing satellites in GEO and near graveyard orbits. In addition, we outline a science case for GEO station to be the main manufacturing/repair hub and docking port for interplanetary spacecraft for exploration (human and robotic), conducting critical bio-medical research in the effects of radiation and spaceflight psychology, as well as training and acclimatising crews for deep-space missions.

KEYWORDS: Space Access Architecture; Gateway Earth; Geostationary Space Station; Legal Position: Economics Model; Science Case; GEO

INTRODUCTION

Gateway Earth is proposed as a (7 or) 8 stage space access infrastructure[1–4], centered on a geostationary space station. These include a reusable launch into low-Earth orbit (LEO), the operation of a tug to geostationary orbit (GEO), where a space station will serve as a hub for in-orbit manufacturing and as docking port for departing and returning spacecraft. In recent research, the Gateway Earth Station was proposed to be placed just above GEO (150-200km), where it is in optimal position to extract and return satellites into various GEO orbital slots[5].

The Gateway Earth Development Group (GEDG), which is steering the development of this architecture, is confident that the eventual success of the Gateway Earth proposal will depend upon a combination of bringing together the research and industry stakeholders and activities already taking place, some direction in terms of government expenditure (e.g. LEO refuelling work; additive manufacturing work, ISRO work), and some integration of future planning activities between government and commercial investors.

Continuing with this work, GEDG is on track to produce a full white paper proposal by the end of 2020. Developing industry and public awareness, we are placing ourselves in a pole position to from then on seek private and public partners to form applied research consortia and establish frim commitments to the development of central systems engineering capability to steer all enabling technologies and from common interfaces, supporting integration on architecture level.

Hence, we are now in a stage, whereby a coherent legal position, economic model and science case are required. In particular, using real-life examples, we need to establish clear answers as to what are the key pressure points form the legal, economic and science point of view and what are our unique solutions and selling points. In this paper, we review in particular which are the relevant legal frameworks and how do they constrain Gateway Earth legal position; how has the economic model for the Gateway Earth revenues and costs evolved since its initial conception; and what are the main scientific opportunities for Gateway Earth station?

GATEWAY EARTH'S LEGAL POSITION

Spaceflight is a heavily regulated area with significant international and national legislations, and their interplay must be considered in order to establish the scope and limitations of Gateway Earth space access architecture. In particular, it is necessary for a legal framework to be established proposing how a favourable legal position may be achieved. There are four legal aspects of particular relevance to the modular space access architecture via a geostationary space station:

- **Orbital slot and frequency band allocation:** Both of orbital slots and frequency bands in geostationary orbits (GEO) are considered finite resources[6]. The International Telecommunications Union (ITU) is an international body which oversees and regulates their allocation. It must be considered if or how these laws extend to orbits just beyond GEO, which is deemed a potentially suitable orbit for Gateway Earth in light of its purpose for satellite servicing[5].
- **Third party liability in space:** With a private-public partnerhip consortium being the Gateway Earth proposal, it needs to be established to what extent will the private or governmental organizations involved be held responsible? Currently in place to address this matter is the Outer Space Treaty (OST), complemented by several national legislations.
- **Potential utilization of space resources:** The Gateway Earth complex will facilitate a modular space architecture, acting as a base for other space enterprise which may involve utilization of space resources. Subject to much controversy, the utilization of space resources is governed by the OST and conflicting national legislations in the US and Luxembourg.
- **Intellectual property protection and export regulation:** It is essential for stakeholders of Gateway Earth Development Group (GEDG) to have a favourable and inclusive intellectual property protection and export regulation policies. Being a politicized field, GEDG hopes to facilitate discussions to encourage international cooperation, transcending current limiting, and in some cases, the lack of national legislations.

As Gateway Earth is proposed to be launched after 2050 the speculated future developments of the Outer Space legal field, as well as geopolitical factors, which undeniably affect the implementation of different national space laws, will form an important part of the following discussion.

Orbital slot and Frequency Allocation

Regulation in place: The International Telecommunications Union

Only a certain range of radio frequencies are currently suitable for telecommunication purposes: high frequency electromagnetic radiation is reflected by the Earth's ionosphere, whilst low frequencies are absorbed and scattered by the Earth's atmosphere. This leaves a range of 8.3 kHz – 3,000 GHz suitable for telecommunication purposes in geostationary and low earth orbit. This range is split into smaller bands and allocated carefully to prevent the interference of signals from different satellites[6]. Additionally, satellites in GEO must be a minimum of 18km apart, to avoid signal interference and minimize risk of satellite collision, resulting in a limited number of available orbital slots.

The International Telecommunications Union (ITU) is an agency of the United Nations in charge of allocating orbital slots and frequency bands in GEO and, although it is not officially a legislative body, the ITU Convention and Radio Regulations play a similar role as international treaties[7]. Its main principles include:

- Ensuring efficient and equitable access to orbit resources, including orbital space and frequency spectrum[7].
- Orbital slots are allocated on a first come, first served basis[8].
- Once authority for a given orbital slot and frequency spectrum has been granted, the space object must be in that orbital slot within five years[8].
- There is no cost associated with accessing an orbital slot and they are available for the lifetime of the satellite[8].

Implications for Gateway Earth

Due to its unique function in space, acting as a base for a range of space enterprise which will result in a complex telecommunications network[1], the GEDG must develop close ties with the ITU and become a pivotal player in its organisation and regulation. This will involve becoming a non-state member of the different sectors of the ITU, particularly the Radiocommunication Sector (ITU-R) and the Standardisation Sector (ITU-S), which concern the following:

ITU-R	*"Plays a vital role in the global management of the radio-frequency spectrum and satellite orbit resources, and develops international standards for radiocommunication systems[9]."*
ITU-S	*"Develops international standards known as ITU-T Recommendations, which act as defining elements of the global infrastructure of information and communication technologies[9]."*

ITU membership would allow GEDG to take a seat at the Plenipotentiary Conference, held every four years in order to discuss any necessary changes to the ITU Convention and Radio Regulation[10].

Third Party Liability and Insurance in Space

Legislation in place: The Outer Space Treaty and several national legislations

Third party liability insurance protects operators and other participants in space activity from claims made by third parties for damage caused as a result of their activity during all phases, including pre-launch, launch and operation. The OST imposes liability on States, which can be unlimited, who in response have developed their own national legislations requiring operators to obtain insurance, before the launch of their space object can be authorised.

The minimum level of liability insurance required by different nations in 2016 is presented in the figure below. To whom this liability is assigned varies across nations and claims exceeding this level are covered by the State.

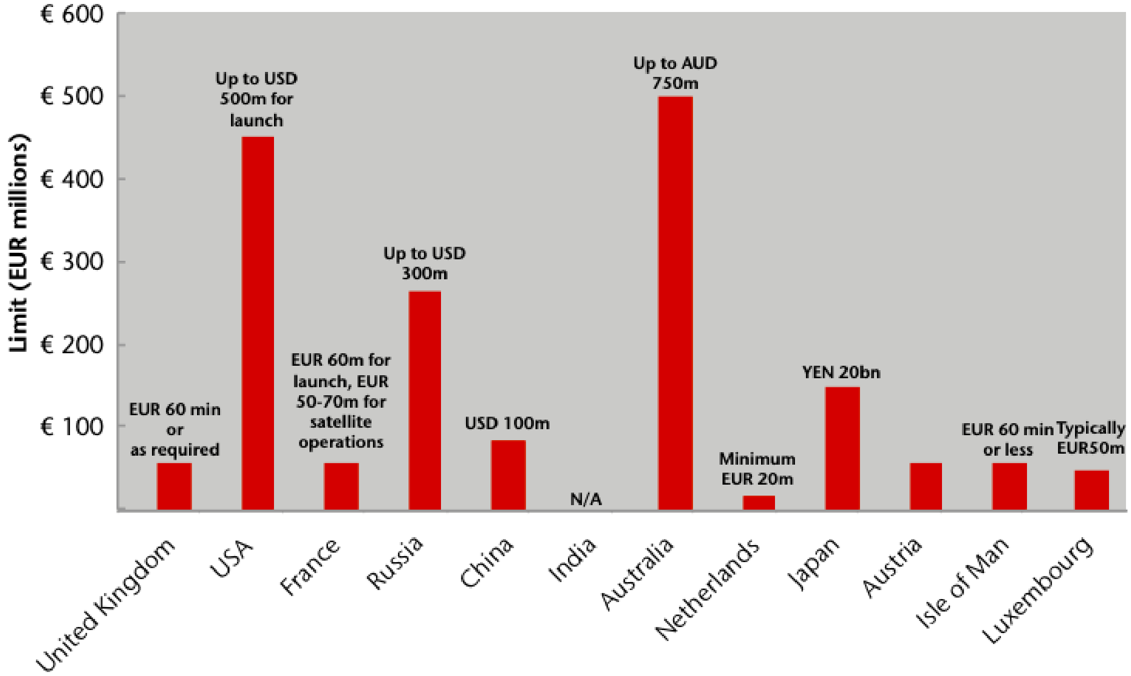

Figure 1: International minimum level of liability insurance by State[11]

In the discussion that follows, the key provisions arising from the OST, and its implementation in national legislations are explored.

GEDG is envisaged as an international intergovernmental organization, which for this reason would be considered a 'State' under the provisions of Article 1 of Section C of the OST[12]. This makes GEDG liable to for any damage caused in outer space, as outlined by *'The Convention for International Liability for Damage caused by Space Objects'* in Section C the OST[12]:

- If a space object of one State causes damage to that of another State or to the persons or property on board, the former State is only liable if the damage is due to its fault (*Article 3*).
- If this damage affects a third State, the first two states will be jointly and severally liable. The extent of this liability depends on the fault of either of the first two States or the persons for whom they are responsible. If this cannot be determined, compensation is shared equally between them (*Article 4*).
- If two States jointly launch a space object they shall be jointly and severally liable for the damage caused (*Article 5*).
- A launching State which has paid compensation for damage has the right to present a claim compensation from other participants in the joint launching (*Article 5*).

Further, GEDG must make agreements with a launching State from which the Gateway Earth Station architecture will be deployed. By Article 2 of Section C of the OST any launching state is "absolutely liable to pay compensation for damage caused by its space object". As a consequence of this, launching states have created national legislations which regulate this liability between the state, manufacturers, launchers, operators of the space object.

For this reason, it will be essential for GEDG to form close partnerships with governments and other organisations to ensure full insurance coverage for incidents occurring in outer space and during launch. To explore the potential partnerships that could be established by GEDG, the national legislations of a number of leading nations in the space sector, including the UK, Luxembourg and the US, are be discussed.

UK Space Industry Act 2018

After the removal of the €60M liability cap in the UK in 2017, the 2018 UK Space Industry Act (SIA) establishes unlimited third party liability for organizations involved with the launch and operation of space objects. This makes the UK an attractive base only for small satellite launches, in which case possible damage to third parties is minimized. Facing some criticism from the industry that the removal of a liability cap can make launches "uninsurable or prohibitively expensive"[13], the UK government is currently considering a system in which liability is considered case by case[14].

Luxembourg

Figure 1 indicates Luxembourg has an exceptionally low minimum level of liability, making it an attractive center for space activity. This law does not cover liabilities related to the launch of space objects as Luxembourg does not have any such facilities, and instead objects are launched from spaceports abroad.

The US Commercial Space Launch Competitiveness Act

The US space law does not discuss third party liability and insurance other than that Space launch facilities should '*seek to take proper measures to protect themselves, to the extent of their potential liability for involvement in launch services and re-entry services, and compensate third parties for possible death, bodily injury, or property damage or loss'*[15].

The brevity of the US space law owes to the fact most space enterprise, even that of private companies such as SpaceX, are still largely state-funded, and insured by the state[16]. The level of liability of space enterprise is negotiated in the licencing process on a case by case basis. Hence despite an apparent high minimum level of liability insurance, the US still is a leading State in the space industry.

Implications for Gateway Earth

The number of different organisations or states involved with the launch and operation of a single space object results in a complex network of insurance policies. In many cases, particularly European space projects, the liability is shared between several stakeholders involved, to limit the potential costs to which participants may be subjected. In places where the space-industry is largely state-run, such as China and Russia, the government provides full insurance coverage. These conflicting third-party liability policies may hinder international cooperation. Gateway Earth will build on the ISS model to facilitate the transition to a global international cooperation in space enterprises. The implications of this are that it must have large number of private stakeholders and choose a launching state who has a considerable interest in space activity, as well as having a well-developed insurance centre, such as Luxembourg or the US.

Resource Utilisation in Space

Legislation in place: The Outer Space Treaty and several national legislations

Outer Space Treaty: Section A; Treaty on the Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies.

The OST was established in 1967, with the prime purpose of suppressing the escalation of the space race, thereby ensuring the peaceful use of outer space, and the prevention of appropriation of space resources[12]. However, over the past decades the rapid development of technologies and increased levels of investment in the space sector have allowed nations to envision a space economy exploiting space in ways unimaginable at the time the OST was drafted[17]. Asteroid mining is notionally providing a potential solution to the depletion of natural resources on Earth, providing a source of rare metals and minerals used in the microelectronics and robotic industries. The mining of such space resources clashes starkly with the legislation established by the OST and its legal position must be resolved. Several nations have in the past years found loopholes in this treaty, which would allow for the mining of space resources. The US and Luxembourg are leading this legal field.

Article 2 of OST states:

'Outer space, including the moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.'[12]

Whilst at first glance this treaty appears to suggest space resources *cannot* be mined, the development of national legislation has revealed some loopholes, raising questions such as

- Is an asteroid a celestial body?
- What is the meaning of the word 'use'?
- Can resources which are first extracted from a celestial body be appropriated?

The ambiguity of this clause has given room for nations to exploit the *Lotus principle*, which states that what is not strictly prohibited is allowed.

<u>Luxembourg</u>

Luxembourg has been at the forefront of commercializing space resources. Article 1 of Luxembourg's 2017 space law states:

'*Space resources are capable of being appropriated'*

(Note that this is followed by Article 2 which states that this does not apply to satellite communications, orbital positions, or frequency bands)[18].

<u>United States of America</u>

The US Space Launch Competitiveness Act states:

'[One] shall be entitled to any asteroid resource or space resource obtained, including to possess, own, transport, use and sell the asteroid resource or space resource.' [15]

Implications for Gateway Earth

The loopholes exploited by the US and Luxembourg are temporary fixes to the outdated position of the OST. GEDG fully expects amendments to be made to the OST or a mature international legislation to emerge and is looking forward to facilitating such a development. However it is unlikely such amendments will be made before a larger number of national legislations following similar principles as the US and Luxembourg will emerge, which may hinder international collaboration in this field.

Intellectual Property Protection and Export Regulation

Legislation in place: National legislations

The US employs a strict export regulation, which significantly affects the space sector, in particular through the International Traffic in Arms Regulation (ITAR). It is based on a precautionary approach to national security restricting the export of technology and information that might be used against the US. The prohibited exports, published in the United States Munitions List (USML), include rockets, satellites, launch vehicles, microelectronics and all related technical data[19]. In order to export an item that does appear on the USML, an ITAR export licence must be granted by the State Department. The disadvantage to this policy is that it reduces international collaboration in technical fields. Additionally, ITAR makes it difficult for non-US workers to contribute to American space projects and further significantly increases the cost of research and innovation due to having to probe ITAR compliance[19]. This is an extensive approval process, especially detrimental to smaller companies.

China, on the other extreme, has in recent years been accused of IP theft of technology and information on multiple occasions. This has led to mistrust of China by European nations and the US, with the result that European countries are reluctant to share or sell any technology to China[20]. Although China is moving towards stricter IP regulation, enforcement is likely to remain an issue.

Article 3 of the ESA Convention (Information and Data) explicitly obliges its member states to ‘facilitate the exchange of scientific and technical information pertaining to the fields of space research and technology and their space applications’[21]. They are however *not* required to communicate any information with non-members if they feel it is a breach of national security or inconsistent with third party agreements. Therefore, this the policy employed by ESA allows for unrestricted transfer of information without requiring significant time and cost, and without undermining national security.

Russia, similar to China, has very limited IP regulation as the space industry is within government control, whilst in the past IP has been stolen as part of industrial espionage. Currently, the Skolkovo Innovation Centre, which has been referred to as the Russian Silicon Valley, is being built near Moscow[22]. In order to support and drive entrepreneurship there, Russia will be forced to introduce stricter IP regulation.

Implications for Gateway Earth

GEDG considers that under the current extensive international collaboration, restrictive regimes such as ITAR have a detrimental effect on the development of cutting-edge solutions, such as the one we propose. Hence, GEDG looks forward to facilitating robust discussions about how the future of international cooperation can be developed in a less restrictive environment.

If GEDG were to be an intergovernmental establishment based in Europe, yet independent of ESA, it will have to conform to several countries’ individual IP protection and export regulation policies, which are likely to be conflicting. GEDG hopes to encourage a dialogue with emerging partners to establish a more comprehensive and consistent international IP protection regimes, by developing bespoke agreements between participating states.

Future developments

The importance of the space sector and its contribution to national economies, including private investment, technological advancements and attraction of skilled workers, has been realised by several other nations.

For instance, and as related to liability insurance, the UAE and Germany are currently in the process of drafting comprehensive space laws. Germany has expressed its ambition to tailor its space law to Private-public Partnerships (PPP’s)[23], whilst the UAE has signed an agreement with Virgin Galactic to work towards enabling space tourism[24], indicating both are looking to put themselves at the forefront of the international space sector.

Within ITU regimes, technological advances, such as the development of beam shaping, may improve telecommunications and allow for more orbital slots in GEO and a larger number of available frequency bands[6].

Regarding resource utilisation, the Hague International Space Resources Governance Working Group was established in 2015 in order to formulate the building blocks for a legal framework regarding the utilisation of space resources. In 2017 it published a draft addressing the legal framework which would enable the utilisation of space resources in such a way that conforms with Article 2 of the Outer Space Treaty, as well as discussing the nature of the property rights associated with resources in space and the landscape for international cooperation[25]. Their work proves promising for the development of a space mining industry, recognising that the legal framework for such enterprise is not necessarily restricted by the OST, which has the effect of encouraging nations to develop comprehensive space laws.

THE ECONOMIC MODEL FOR A GEO SPACE STATION

An Update on the Space Tourism Market

Previous publications by Gateway Earth have suggested space tourism could provide a significant revenue stream, with an optimal ticket price of $30M generating a $4B annual revenue[1]. The market for space tourism has shown remarkably slower growth than anticipated since this estimate was made, which was based on the survey ‘*Space Tourism Market Study’,* conducted in 2002.

Hence, in this study, we re-evaluated the space tourism market by discussing its past and future developments, and using this to assess the validity of the Futron/Zogby survey on which previous estimates were based. This analysis relies in part on an updated multiplier factor, which is calculated from recent rocket launch data, used to estimate the additional cost of spaceflight to GEO compared to LEO.

The current market for space tourism

Russia was the first nation to accommodate private spaceflight to the ISS in the Soyuz vehicle, as NASA had banned commercial use of the station for profitable research[26]. Between 2001 and 2009, seven space tourists visited the ISS for one to three week periods[27], paying ticket prices between $20-$40M.

In June of 2019 NASA launched its Commercial Crew Programme, promising it will enable two private astronauts to travel to the ISS each year, with the first flight taking off as soon as SpaceX's Dragon capsule and Boeing's Starliner are ready for launch, currently set to be in 2020[28]. NASA's pricing policy suggests it will cost around $35,000 per day to stay on the ISS[29], and SpaceX and Boeing are expected to charge NASA a fare of approximately $60M for the trip[26]. Earlier in 2019 the Russian space agency, Roscosmos, announced it has signed another contract with Space Adventures for two space tourists to travel to the ISS in 2021[30], for an undisclosed price.

Having achieved human spaceflight to LEO, progress is now being made on sending people to the Moon and even to Mars. SpaceX is currently developing the Big Falcon Rocket (BFR), which will first take a number of private astronauts on a cislunar flight. The first tourist has been confirmed to be the Japanese entrepreneur Yusaku Maezawa[31], reported to have a net worth of $2B[32]. It is unknown how much he has paid for the ticket, however he has made substantial contributions to the development of the BFR, costing around $5 billion, which allows him to take six to eight other tourists with him for free[33].

The future of the space tourism market

The space sector is subject to constant changes due to a volatile political landscape, rapid technological developments and a dynamic institutional framework in which it operates. In order to make a realistic prediction of the market for commercial spaceflight at the time Gateway Earth is fully operational, the changes in the space sector, most importantly the reusability of launch vehicles and the move towards a more commercial space sector[34], must be anticipated.

The first steps towards reusable launch systems have already been made, with the advent of the Space Shuttle in 1981 and, more recently, SpaceX's Falcon 9[35]. SpaceX, although its success has relied on extensive state-funding and insurance programmes, has provided convincing evidence of the benefits commercialisation of the space industry would have. A NASA cost model predicted that it would have cost NASA 68% more to manufacture and launch Falcon 9 than SpaceX[34]. The reasons for the greater efficiency by SpaceX can be explained distilled to a number of factors:

1. Smaller workforce
2. Use of in-house development
3. Fewer management layers and less infrastructure
4. Commercial development culture[34]

However, this has not led to immediate reductions in the cost of space flight. The cost savings from reusable launch vehicles are marginal, due to high impacts experienced by the spacecraft upon entering and leaving space, resulting in the need for a large number of repairs and replacements parts, as well as extensive inspections[34]. Further, it is speculated that the large reduction in payload of reusable rockets, due to the need for sparing some "landing" fuel, may make human spaceflight exempt from any cost savings[34]. Nonetheless, the increased capacity and a wider competition might create favourable conditions for new markets to emerge, in particular in-orbit services, space tourism, resources extraction.

A review of the Space Tourism Market Study

The *Space Tourism Market Study* analysed results from a survey conducted in 2002 by Futron Inc and Zogby, to predict the space tourism market for the 20 years to follow. Approaching the end of those 20 years, this is an appropriate time for reflection of the results presented.

The survey predicted that by 2021, there would be 15,712 suborbital spaceflight passengers annually at a ticket price of $50,000 and 60 orbital spaceflight passengers annually at a price of $5M[36]. These figures are far from being representative of the current space tourism market, which can be explained by the fact the survey significantly underestimated the cost of space travel at the time, as well as relying on a further future price decreases of rocket launch. The price for orbital spaceflight at the time of analysis was set at $20M, based on the approximate price paid by Dennis Tito to visit the ISS in 2001. In fact, this proved to be one of the 'cheaper' tickets, with subsequent space tourists paying up to $40M for their ticket[37]. The cost for suborbital space flight was stated to be $100,000 at the time the survey was conducted. This price quote was based on a claim by Space Adventures that they had 100 reservations for suborbital flight at $98,000, despite not having a vehicle capable of such a flight. This claim turns out to have been highly misleading, as currently Virgin Galactic is offering sub-orbital space flight tickets at $250,000 and Blue Origin between $200,000-$300,000[38].

Overall the survey presented spaceflight to be more accessible than it is in reality, with the survey group having a minimum net worth of $1M or annual income of $250,000. It was concluded that tourists must have a net worth of at least $7M to be potential customers for orbital space flight, which is inconsistent with data suggesting previous space tourists have a net worth in excess of $500M.

Significantly, the survey results show that the demand for orbital spaceflight in the price range $15-$25M is inelastic, with only 3% more respondents willing to pay a price of $15M over $25M. This suggests that any price decreases which *are* realistic in the next decades may not significantly increase demand.

The cost of private spaceflight to GEO: An updated multiplier factor

So far, all spaceflight discussed has concerned LEO. To make a cost estimate of getting to GEO, the most recent data concerning prices of rocket launches to LEO will be gathered and a new 'multiplier' factor established (previously, this multiplier factor has been estimated at approximately 3[1]). This multiplier factor will be based on the ratio of payload masses rockets can carry to LEO and GTO. Payload masses to GEO are not published, however the difference compared to GTO can be assumed to be insignificant.

All data is obtained from the *Annual Compendium of Commercial Space Transportation 2018*, published by the Federal Aviation Administration[39].

Vehicle	Mass to LEO (kg)	Mass to GTO (kg)	Estimated price per launch (mill $)	Multiplier
	Average	Average	Average	GTO
Atlas 5	13469	10801.5	170	1.2
Falcon 9	13150	4850	61.2	2.7
Falcon Heavy	63800	26700	90	2.4
New Glenn	45000	13000	undisclosed	3.5
Vulcan	13940	6825	172.5	2.0

Long March 3B	11500	5100	70	2.3
Soyuz 2.1b	8200	3250	80	2.5
Delta IV	20130	9330	165	2.2
Long March 3B/E	11500	5500	70	2.1
Ariane 5 G	16000	6950	192.5	2.3
GSLV Mk II	5000	2700	47	1.9
Proton M	23000	6610	65	3.5
sPSLV XL	3800	1200	26	3.2
			Average	2.4

Analysis of 13 rocket payload mass data points produces an average multiplier of 2.4. This is in line with data from Falcon 9 and Falcon Heavy, which are currently the two rockets most likely to be used for space tourism to LEO and beyond. Using this multiplier and the current average private spaceflight ticket to LEO of $30M, tourists could be charged $72M to go to GEO. This multiplier is 0.15 lower than that predicted by Webber in 2015 using the same method, likely due to the inclusion of more commercial rockets in the data set. It is found using the same data that the payload mass is positively correlated with the cost of launch, suggesting that applying this multiplier factor to cost of launch to LEO is an valid method of estimating the cost of launch to GTO.

Other options?

The expected efficiencies of launch to LEO, which formed the basis of predictions at the start of the century that the space tourism market would be well established by 2021, with thousands of tourists going to suborbital and orbital space flight each year, have not materialised. Whilst the development of reusable rockets may in the long run drive down prices of rocket launch, stimulating a market for space tourism, the difficulties obtaining funding and insurance in the commercial space sector, a notable exception being SpaceX, may slow its impact. Further inelasticity of the space tourism market established by the Futron/Zogby survey, indicates even if the price of private spaceflight decreases, there will be insufficient demand to generate a sustainable market. It is possible a space tourism market will develop alongside Gateway Earth, though this is likely to consist of infrequent visits by wealthy tourists, which will not provide a stable significant revenue, rather it will benefit the Gateway Earth primarely through consequent publicity.

However, as presented elsewhere[40], our detailed analysis of the satellite servicing market, both in-house as well as including various commercially available studies, predicted at $8.75-$17.5 billion total annual GEO satellite manufacturing/re-feeling market (using current market size of a conservative average 25 GEO satellites per year). This market is predicted to expand to $20.3-$40.6 billion in 2040 (using a bespoke scaling model and externally validated multipliers), at which point financing to manufacture and deploy the Gateway Earth architecture will be needed.

Architectural and Operational Costs

Architectural Cost

In 2017 an external configuration of the Gateway Earth station (GES) was developed[40]. It has since been established that space tourism is unlikely to provide a significant revenue stream for Gateway Earth, hence relevant adjustments have been made to the architectural model of the GES to reflect this. Accounting for the fact astronauts must have a minimum living space, the size of the station has not reduced, rather the types of modules and their functions have been altered.

Where possible, architectural components have been compared to ISS modules. GES will utilise commercially developed expandable modules, which will significantly reduce transport cost of modules as they are significantly lighter than their rigid counterpart.

The architectural components of the Gateway Earth complex, their cost and how this cost is justified are summarised in the table below. All costs are rounded to the nearest $100M.

	Component	**Cost ($M)**	**Justification**
Space station	Expandable modules	1,300	Currently, insufficient pricing details are available for Bigelow expandable modules, hence their cost is derived from comparison the ISS modules. This is a reasonable assumption as most significant cost difference between expandable modules and their rigid counterparts is not the manufacturing cost, rather the cost of their transportation. The ISS Zvezda module, which accommodates 2 crew members (habitable volume of 50m^3), cost $320M to build[41]. To house 7 crew members, 4 of these modules are required.
	Connecting module	400	ISS connecting module Tranquillity and observing dome Copula are speculated to have cost $409M together[42]. Assume cost of Copula is negligible compared to Tranquillity.
	Spacecraft	0	The spacecraft that will be docked for short amounts of time is the Dragon capsule. Its cost is covered by operational cost.
	Experimental module	900	ISS Columbus experimental module cost $880M[43].
	Satellite servicing facility	500	Orbital Express was a mission managed by the DARPA to autonomously service satellites in orbit. The project, which was launched into LEO and completed a successful demonstration, was speculated to cost between $100-300M[44]. Additional development costs will be incurred to make it suitable for servicing of larger satellites and increase its lifetime.
	Thermal and electrical power system	1,500	One quarter of the solar array on the ISS costs $300M[45] [46], hence the full array is costed at $1,200M. Additional costs for thermal cooling system are anticipated.
External	Reusable tugs	4,500	An electrical tug will carry a Dragon capsule launched to LEO by a Falcon 9 rocket to GEO. The electrical tug is modelled through the Cannae Space Freighter, which claims can take ten 10,000kg satellites per year from LEO to GEO and has a lifetime of 15 years[47]. Transporting each satellite using an electrical tug rather than launching it straight to GEO saves $30M, taking the cost

			difference between launch of Falcon 9 and Falcon Heavy (and assuming adding a Dragon capsule will increase the cost of each by the same amount). Therefore, annually the return on a Cannae freighter is $300M. Assuming a quoted lifetime of 15 years, the tug can be costed at $4.5B. A freighter can complete 10 return journeys to and from LEO every year, therefore one freighters is required for five return cargo tug journeys to the GES.
Total		9,100	

Operational Costs

The operational costing model is based on the schedule published by Doublet in 2017 which included a five-year deployment schedule and a regular operations schedule that would follow[40]. A number of adjustments have been made to this schedule, assuming space tourism operations will be infrequent and irregular.

Deployment of the Gateway Earth architecture

The table below lays out the number of launches required by different launch vehicles over the course of the five year deployment of the Gateway Earth architecture. The cost of launch of New Glenn is undisclosed, hence payloads proposed by Doublet to be transported through nine New Glenn launches, are instead costed by modelling it through five Falcon Heavy launches, which has approximately twice the payload mass to GEO as New Glenn. All costs are rounded to the nearest $100M. Adding up the cost of all launches, the deployment the architecture is estimated to cost $6.3B.

Launch vehicle	**Cost per launch ($M)**	**Number of launches**	**Cost ($M)**
Ariane 6	90[48]	4	400
Falcon 9 + Dragon	140[34]	27	3800
Falcon Heavy	90[49]	10	900
Atlas	170[39]	7	1200
		Total	6,300

Frequency adjustments to the operational schedule

Without space tourism activity at the GES, the frequency of the launch of manned crew to Gateway Earth only depends on the assumption that at any one time there will be seven crew members on the station, who will be on the station for two months before they are replaced. This results in a total of six launches of manned crew to and from GES per year. Further, the frequency of the launch of disposable supplies has been reduced by 25% to account for only half the number of astronauts being at the station at one time as was assumed in Doublet's model (half of disposable supplies consist of commercial supplies, which is unaltered). The number of fuel launches to LEO was set at 26 per year, to provide for a total of 63 tug journeys between LEO and GEO. The updated number of tug journeys is 21 to account for the fact the fact frequent and regular transport of space tourists is not required. This will require only one third of the previously proposed launches of the Falcon Heavy.

An updated schedule of operations and their cost is published in the table below. All costs per year are rounded to the nearest $100M.

	Activity	Cost ($M)	Frequency	Cost / year ($M)	Justification
Earth - LEO	Launch of manned crew Earth - LEO	140	6 / year	900	The cost of Dragon Capsule, and Falcon 9, which can transport seven astronauts to LEO, is $140M[34].
	Return of manned crew LEO - Earth	Included in price above	6 / year		
	Launch of cargo Earth - LEO	140	1 / 12 weeks	700	Previous work suggests the frequency that has been adjusted was calculated utilising the maximum payload mass of a Dragon capsule[40]. Launch of Dragon with Falcon 9 is $140M[34]. Additional costs may be incurred as a result of having two Dragon capsules in full time operation, as this is not taken into account into its launch cost.
	Return of cargo LEO - Earth	Included in price above	1 / 12 weeks		
	Launch of fuel for manned missions to LEO	90	6 / year	800	This frequency is based on the use of the Falcon Heavy rocket, which costs $90M per launch[49].
LEO - GEO	Cargo tug LEO - GEO	0	1 / 12 weeks	0	Once the electrical tug is acquired, there are no further running costs as no fuel is required.
	Cargo tug GEO – LEO	0	1 / 12 weeks		
	Manned tug LEO - GEO	200	6 / year	1,200	Manned crew will be transported through chemical propulsion tugs, which are modelled by a Dragon capsule. Falcon 9 can transport a Dragon capsule with payload mass 8,000kg to LEO at a cost of $140M. Using a scaling factor of 2.4, it would cost $340M to launch this to GEO, hence the journey between LEO and GEO can be costed at $200M. Previous work suggests this frequency is suitable assuming
	Manned tug GEO - LEO	Included in price above	6 / year		

					utilising full payload capacity of Dragon capsule.
Other	Replacement cargo tug	4,500	1 / 15 years	300	The lifetime of a Cannae Freighter is quoted to be only 15 years[47]. Hence, unlike other architectural elements (which may also need replacements or upgrades eventually), its replacement cost must be accounted for in the operations costs.
		Total annual operational cost		3,900	

Conclusions

The Gateway Earth infrastructure uses technologies which have not yet been developed, such as electrical and chemical space tugs and refuelling stations meaning some costings lack accuracy. However, a more significant consequence of this is the uncertainty whether these technologies will be ready by the time Gateway Earth is projected to be launched around 2050.

The lack of data available for the costings model owes to the fact that national space agencies lack transparency, and consequently a large majority of the cost estimates are based on the commercial space industry, particularly SpaceX. Further, certain components of the architecture have so far only been manufactured by national space agencies, particularly space station modules. This is important to note as there is a considerable cost difference between architecture manufactured and operations executed by the commercial space industry compared with national space agencies. It has been shown that SpaceX can manufacture systems at 32% of the cost that NASA does[34]. Overall, this results in the model not being fully reflective of the potential cost variation that would depend on the nature Gateway Earth as an intergovernmental organisation.

Nonetheless, this costing model still gives significant insights. The annual operational cost is estimated at approximately $3.9B. This figure fall short of the bracket predicted in earlier work ($6-$12B), calculated by means of a scaling factor of 1.93-3 from the average difference between LEO and GEO operational costs[1]. This may be explained by the fact commercial and state-led missions were not differentiated when calculating this scaling factor, even though most of the up to date operational costings are based only on data from commercial activity. Significant insight into the implications of the costings model is deduced from comparison of costs for Gateway Earth with the ISS:

	Deployment, architecture and operational cost assuming 20 years of operation
Gateway Earth Station	$95B
International Space Station	$100B[50] [51]

This demonstrates that using true component costings for Gateway Earth Station there is no significant difference in costs of a GEO station than it is today with the ISS. This could be justified by the fact that a significant amount of the R&D required for the operation of Gateway Earth, has already taken place for the development and running of the ISS, rendering the multiplier obsolete.

Hence, even if the Gateway Earth is to capture only 50% of the most conservative estimate of the GEO satellite market (at $8.75 billion[40]), this could amount to a potential annual income sufficient to run the station. A more generous estimate, assuming a modest increase in satellite market by 2040 (to $20.3B), could see the station even return a profit. This crude calculation also excludes governmental research contributions, private transfers for access to cis-lunar space or income from the antenna farm or resources return missions (with asteroid mining markets estimated at $5TN).

SCIENCE CASE

Gateway Earth has potential to act as an essential research centre and training base to accommodate future deep space missions. The complex radiation environment that exists beyond the Earth's magnetosphere must be investigated to aid the development and engineering of a safe environment for humans. Following this, GE would provide an optimal location for a training base for deep space mission astronauts, exposing them to the psychological hardships of isolation and confinement. In the following section current research into psycho-physiological factors relevant in outer space missions, and GE's potential to act as a staging post for the next stage of such investigations is discussed.

Physical effects of outer space radiation and microgravity

Beyond the Earth's atmosphere and magnetosphere, astronauts are subject to different types of damaging radiation, the main sources being solar particle events (SPE) and galactic cosmic rays (GCR)[52]. Exposure to such ionising radiation may have adverse health effects, with acute reactions potentially affecting the success of missions, and concerns over delayed effects including an increased risk in cardiovascular disease and cancer. It is essential to understand the radiation environment that astronauts will be exposed to, and their reactions to it, so that effective measures such can be taken to ensure their safety.

The space radiation environment consists primarily of penetrating ions and nuclei[52]. Particles constituting GCR have energies ranging from >1MeV to more than 10^{15} MeV[52]. This large range is due to solar wind fluxes, through which particles must penetrate. SPE's originate from magnetic disturbances in the Sun, releasing mostly protons and helium ions as well as a trace of heavier ions and electrons. Whilst often not lasting more than a few hours, they can be unpredictable and develop rapidly[52]. Reaching outer space requires travelling through the Earth's van Allen belts, which is a toroidally shaped region in the Earth's magnetosphere in which large fluxes of high energy radiation is trapped. Travelling through these belt takes only a matter of seconds[53], hence has an insignificant contribution to the total dosage astronauts receive.

The typical average dosage of radiation received by people on Earth is 3.6mSv. NASA has set a limit for radiation exposure of astronauts to 500mSv[54]. The estimated dosage of radiation received by astronauts on various space missions are compared in the table below:

Mission Type	Radiation Dose
Space Shuttle Mission 41-C (8-day mission orbiting the Earth at 460 km)	5.59 mSv
Apollo 14 (9-day mission to the Moon)	11.4 mSv
Skylab 4 (87-day mission orbiting the Earth at 473 km)	178 mSv
ISS Mission (up to 6 months orbiting Earth at 353 km)	160 mSv
Estimated Mars mission (3 years)	1,200 mSv

Investigating radiation-induced health hazards is difficult on Earth, let alone the risk from the complex radiation environment that exists in outer space. One study published in 2016, compared the mortality rates due to cardiovascular disease (CVD) and cancer, among others, in astronauts who (1) have never been in orbital spaceflight, (2) have been in LEO and (3) Apollo astronauts[55]. The ISS in LEO lies within the Earth's magnetosphere, and therefore does not represent a deep space environment that would be experienced on the Moon or Mars. This study aimed to correct similar earlier studies by comparing mortality rates of Apollo astronauts (to this date the only astronauts who have been to outer space) to non-flight astronauts rather than the general public, as astronauts are likely to be physically fitter and have had access to better healthcare than an average member of the general public. This study found the mortality rate of Apollo astronauts due to CVD is five times greater than for non-flight astronauts and four times greater than for LEO astronauts, and no significant difference in mortality rates between LEO and non-flight astronauts. No significant differences in mortality rates due to cancer was found between subgroups[55].

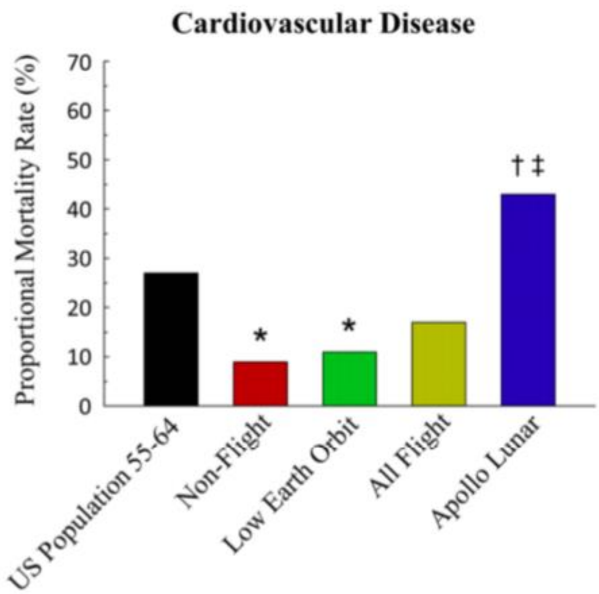

Figure 2: The proportional mortality rate due to cardiovascular disease in the United States among different sub-groups.

*Significantly different from the US population 55-64 years of age at the time of death, † Significantly different from the non-flight astronaut group, P≤0.05. †‡ Significantly different from low Earth orbit astronaut group, P≤0.1 .

In the first study, the sample group of Apollo astronauts was only seven, making it difficult to establish concrete results. Other psychophysiological factors, including weightlessness, experienced by astronauts may inhibit immune response[52], further complicating the investigation of radiation-induced health effects. This study nonetheless highlights the necessity for extensive research to be conducted into how we can ensure the safety of humans in outer space.

One of the studies which has contributed to this growing body of knowledge is NASA's Human Research Programme 'Twins study', which examined the effect of one year in space by monitoring the identical twins Scott Kelly, aboard the ISS, and Mark Kelly, back on Earth. Identical twins have an identical genetic makeup, allowing an investigation into how space affects the human body, that is largely independent of physical variations between individuals. It was found that most bodily functions which had changed during space flight, returned to normal within a few months of being back on Earth. Scott Kelly's one-year stay in space resulted in mostly temporary changes in gene expression, though 8.7% of DNA did not revert back to normal once returned to Earth, most likely due to the effects of radiation exposure[56]. The narrowing of artery walls, a potential cause of CVD, was observed in Scott Kelly and it is yet to be determined whether the effect will be reversible in the long term[56]. The results of the Twins Study are reassuring, through indicating the adaptability of the body in space.

The interplay of such a large number of factors which may contribute to the health risks of outer space are the root of the large uncertainties in risk estimates. To ensure the safety of astronauts during long duration deep-space missions, it is therefore essential to set up a research facility outside the Earth's magnetosphere, where experiments following current bio-physiological protocol can be conducted. Gateway Earth could provide both a suitable location and architecture for this, providing a highly precautionary yet accessible environment. Such experiments could initially include radiation monitoring until a suitable environment for humans can be established, which could be followed by animal research, which on the ISS has, according to NASA, "contributed significantly to our understanding of the effects of microgravity on biological processes that are directly relevant to humans in spaceflight"[57].

Physiological factors which influence human performance in space missions

In outer space, astronauts experience extreme confinement and isolation, both in terms of physical and social landscape, as well other stressors and stresses such as sleep disturbances[58]. Psychological responses to these challenges may affect human performance during missions, and must be considered on both individual and at group level[59].

A *stressor* can be defined as a "stimulus or feature of the environment that affects someone, usually in a negative manner"[60]. *Stress* on the other hand relates to the reaction induced in someone as a result of *stressors*. The table below summarises potential stress and stressors astronauts may be experience during spaceflight.

Stressors[60]:

Physical	Habitability	Psychological	Interpersonal
Acceleration	Vibration	Isolation	Gender issues
Microgravity	Ambient noise	Confinement	Cultural effects
Ionizing radiation	Temperature	Danger	Personality conflicts
Meteoroid impacts	Lighting	Monotony	Crew size
Light/dark cycles	Air quality	Workload	Leadership issues

Stress:

Physiological	Performance	Interpersonal	Psychiatric
Space sickness	Disorientation	Tension	Adjustment disorders
Vestibular problems	Visual illusions	Withdrawal/territorial behavior	Somatoform disorders
Sleep disturbances	Attention deficits	Lack of privacy	Depression
Bodily fluid shifts	Error proneness	Scapegoating	Suicidal thoughts
Bone loss and hypercalcemia	Psychomotor problems	Affect displacement	Asthenia

Analysis of previous missions to the Moon and ISS is not adequately reflective of long-duration deep space flight to the Moon and Mars, which may take several years[58]. Simulations of long-term isolation and confinement have been conducted on Earth, most notably the Mars 500 experiment.

The Mars500 experiment, conducted by Roscosmos in partnership with ESA and China aimed to simulate a Martian mission and investigate “the interaction between humans and the environment and to collect experimental data on the health status and fitness for work of humans isolated in a tightly confined space of limited volume”[61]. Thus far, it is the longest deep-space mission simulation conducted on Earth, lasting 520 days. The conditions that would be experienced by astronauts were mimicked by limiting the resources available to the crew, stopping the provision of supplies entirely on the 36th day, introducing a communications delay between Earth and Mars of up to 12 minutes and a brief one-week complete loss of communication[61]. Further, the crew performed extensive research and, for the first time, the simulation included a landing on the Martian surface, lasting 28 days[61].

Notable results included a confirmation of Kanas and Manzey’s “psychological separation phenomenon”[61], which manifests itself in three prominent ways:

1. an increase in physical autonomy and a decline in motivation towards work tasks,
2. groupthink (cosmonauts become less responsive to recommendations of the mission control centre, more often making independent decisions, whilst overestimating their own ability),
3. increased homesickness and feeling of isolation[61].

Such simulations on Earth have been essential in establishing the psychological reactions and demands of crew in space missions and has given insight into how effective communication between Earth and astronauts in deep space can be achieved to ensure the success and safety. A space station in a geostationary orbit would provide an essential staging post for the next stage of such psychological investigations to be conducted. It is more representative than any simulations and experiments on Earth and at the ISS, and whilst it is in outer space, it is still fully serviceable. For this reason, in the long run, GE also has potential to function as a training base for astronauts embarking deep-space missions. Exposing astronauts to operating in a more hazardous radiation environment than is present in the ISS and to acclimatising to an extremely isolated and confined environment is essential before embarking deeper into space.

CONCLUSIONS

Overall, this paper set out a beginning of a legal position, an update on the economic model and the new science case for the Gateway Earth modular space access architecture, through a space station just above geostationary orbit.

In particular, it proposed that the four critical elements of the legal framework should include the orbital regulation regimes, liability, resources appropriation and intellectual property protection. The proposed position for Gateway Earth is two-fold

- to incorporate as an intergovernmental organisation and seek recognition within the decision making and representative bodies, so that the concerns of the consortia of Gateway Earth developers are accounted for and,
- to place the organisation’s HQ within a jurisdiction with an advanced and well defined space legislation, such as UK or Luxembourg.

Secondly, though we note that the space tourism market is developing a lot more slowly than previously predicted, there is a significant economic opportunity from on-orbit satellite servicing and manufacture. In addition, the first true-cost basis calculation of the architectural and operational costs for Gateway Earth put it en par with ISS, with a total life-time costs of under $100 billion.

Lastly, it is clear that with the current interest in bio-medical research on ISS and the need for its critical expansion in preparation for long-duration deep space missions, Gateway Earth station would be an ideal location for physiological and psychological research as well as astronaut acclimatisation and training. In fact, at the time when competing (cis-lunar) “gateway” is being proposed (by NASA), that case has already been accepted globally, it is only that such base’s location has not yet been settled. Here, Gateway Earth has a significant strategic advantage, since it is able to satisfy all deep-space environment requirements, while being relatively (safely) close for emergency return to Earth.

In all, this paper is marking the beginning of the close of the proposal development stage for Gateway Earth Development Group, as well move to consolidate all work from over the past 5 years into a single white paper by the end of 2020.

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