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Geostationary Space Station: Necessary Next Step for the Space Ecosystem

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Abstract

Over the past decade Gateway Earth Development Group (GEDG) has been conducting several strands of research into the technical, economic and scientific case for a geostationary space station. This combines a modular architecture for access to geostationary orbit, a new opportunity for on-orbit satellite re/upcycling and manufacture and analysis of the unchartered waters of using a geostationary station for deep space missions and space tourism. Above all, GEDG has been examining new, cheaper and more sustainable space engineering techniques and material, exploring the options to make this new asset more democratically accessible and financially sustainable without relying on the dominant space powers. With this objective in mind, we present a landmark White Paper summarising the key findings of more than a dozen technical papers we put forward and chart future R&D objectives, as well as funding needs, organisational development and international legal framework.

Keywords: space access, modular architecture, space station

Acronyms/Abbreviations

CERN	European Organisation for Nuclear Reserach
ESA	European Space Agency
EVA	Extra-Vehicular Activity
DARPA	Defense Advanced Research Projects Agency
GDP	Gross Domestic Product
GEDG	Gateway Earth Development Group
GEO	Geostationary Orbit
GTO	Geostationary Transfer Orbit
IADC	Inter-Agency Space Debris Coordination Committee
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
LEO	Low Earth Orbit
NASA (US)	National Areonautics and Space Administration
SRMF	Satellite Repair and Manufacture Facility
WIPO	World Intellectual Proerty Organisation

1. Introduction

In the very long term, humans will need to be able to inhabit other parts of the solar system, because of the certainty of astronomical and other catastrophes which threaten the Earth as an abode for life. Furthermore, the solar system represents a source of raw materials to augment those found on Earth, and which can become part of economic development opportunities. The premise for the proposed course of action in this White Paper is that a space-faring civilization will need a reliable means of interplanetary travel that is affordable. Clearly, we know one way of traveling outwards from the Earth – exemplified by the achievements of the Apollo missions to the Moon in the 1960's – but they cost the US taxpayer around 5% of GDP, which is not considered affordable for a sustainable human exploration program back to the Moon or to further interplanetary destinations. This has resulted in a 50-year hiatus in human spaceflight beyond low earth orbit. Any proposed solution to address the requirement must therefore include the funding issue, and the incentives to the public, as a key part of the problem to solve, and not a mere consequence or inconvenience.

The good news is that much has happened during that 50-year span, which can provide the elements of a solution. This approach however will differ significantly from the previous government-led Apollo methodology. It is the belief of the writers of this White Paper that for a successful outcome we need a combination of government and commercial activity, and importantly we need a proposition which uses commercial incentives to drive the initiative. Government will have to reconcile its plans with those of commercial space ventures and their associated timescales and revenue streams. However, the following list of commercial space elements, all developed since the Apollo era, suggests that the basis for a proposed solution already exists:

- A dynamic and thriving satellite industry, mainly providing telecommunications and broadcasting services, much of which operates in Geostationary orbit (GEO);

- The beginnings of a space tourism industry, which has provided the incentive to manufacturers to foster reusability techniques;
- The successful demonstration of reusable launch vehicles and spacecraft; and
- The development of 3-D manufacturing technologies, even including some demonstrations of the capability in the space environment, on the International Space Station (ISS).

2. Proposition

What we are proposing, and calling the Gateway Earth architecture, uses the experience gleaned from these commercial businesses and developments, together with some basic Newtonian physics, to provide a new approach to long term interplanetary human and robotic space travel, which will substantially reduce the overall costs and improve the reliability of such ventures. Furthermore, taxpayers will be relieved of the need to budget for much of the required infrastructure, since it will be provided as part of independent and self-sufficient commercial ventures. The technique will make possible affordable journeys to the Moon, Mars and other solar system objects at significantly reduced costs, while simultaneously creating a series of new commercial space business opportunities, with associated employment potential. This is a twenty-first century spacefaring architecture that will not only be sustainable but has the potential to eventually generate overall net income rather than be a drain on national budgets. The diagram in Appendix A explains the elements of the proposed architecture.

We have noticed that there is a fortuitous circumstance in that the edge of Earth's gravity well is close to GEO, where the majority of commercial space business takes place. This makes possible a reliable and economic seven-step process from Earth to anywhere in the solar system. The diagram explains the required seven steps. Step 1 and Step 2 already exist, so long as the ISS continues to operate, and serve as the LEO node for the overall system. Step 3 is the assembly of a combined governmental/commercial outpost in GEO. The government part is not a repetition of the ISS, but a much smaller facility serving mostly as a factory for 3-D manufacturing of interplanetary spacecraft; the commercial part is conceived to be in part a hotel for space tourists – but may also contain the requirements for operating a GEO satellite servicing operation. Step 4 refers to the need for regular tug transfers between LEO and GEO and back again, carrying people and supplies. This is familiar territory for GEO communications satellite manufacturers and operators. Step 5 refers to the need to refuel the tugs by having a gas station in LEO (although it may be possible to avoid the need for a fuel depot by directly matching each LEO-GEO transfer with a dedicated fuel launch) . Step 6 indicates the journeys of the reusable interplanetary transfer vehicles, the vehicles having been fabricated in GEO from bulk raw materials, thus avoiding the need for heavy duty launch environmental protection, or thermal control systems for re-entry. These vehicles will never be operating in atmospheres. Step 7 refers to the final stage of planetary landing; the planetary landers will also be built by 3-D manufacturing at the Gateway Earth GEO station.

The proposition, therefore, relies upon a joint governmental/commercial endeavour, wherein the commercial ventures would be self-sufficient operating entities, and where the governmental contribution provides mostly the funds to purchase taxi rides to LEO and thence to GEO, and assists with technology development for orbital gas stations and the design and manufacturing of interplanetary craft in GEO, using a logistical supply train being operated by the independent commercial businesses. The government agencies in return will have a platform near the edge of Earth's gravity well, from which they can dispatch, and to which they can return, astronaut crews or robotic payloads on interplanetary missions which employ reusable, rather simple, and consequently low cost hardware. The governmental astronaut teams will have a new set of roles to undertake; they will function in GEO, 100 times farther out than the ISS, both to keep the Gateway Earth station safe, and to operate the manufacturing facility. They will test out the newly assembled interplanetary craft and landers, before some of them will become crews for the ensuing interplanetary missions.

The business model depends upon the pre-supposed parallel establishment of a series of self-contained and financing commercial ventures:

- GAS STATION: The operation of a LEO gas station and its regular supply chain (if needed for logistical reasons);
- TRANSPORTATION BUSINESS: The building and subsequent operation of regular tug services LEO-GEO-LEO that will transport people and supplies (including 3-D manufacturing raw materials) to and from Gateway Earth;
- GEO SATELLITE REPAIR AND MANUFACTURING SERVICES: providing significant revenue as well as addressing orbital slot and graveyard sustainability challenges;
- HOTEL BUSINESS: The assembly in GEO, and subsequent operation, of a space hotel and facilities for other GEO commercial ventures; and
- GOVERNMENT CONTRACTOR: The building and subsequent support for a governmental manufacturing facility in GEO,

and the subsequent construction/assembly of interplanetary craft with consequential cost savings compared with terrestrial assembly-based alternatives.

We are now seeking funding to continue to explore the viability of the concept, including conducting market research, costing analyses, investigation of 3-D manufacturing capabilities, and identifying entrepreneurial commercial entities interested in establishing one or more of the four identified categories of new space businesses.

3. The Physics of the Gateway

The Gateway Earth Development Group (GEDG) proposes to install a space station in a GEO much higher in Earth's gravity well compared with low earth orbit (LEO). It requires approximately 49.5 million joules of energy per kilogram (Appendix B) more to launch Moon or interplanetary missions from LEO compared with launching from GEO. It is far more astro-dynamically and economically effective to launch from GEO, and Gateway Earth can be the start and end point for interplanetary missions. Moreover, through a public-private partnership based around models currently being developed at the International Space Station (ISS), in particular the relatively harmonious collaboration between international governmental and industry partners. Gateway Earth is proposed to generate further revenue by acting as a space hotel, an additive manufacturing/construction facility and fuelling hub for interplanetary vehicles as well as a satellite farm and servicing/recycling hub. This has been well documented and justified in previous papers [1-4].

Having the Gateway Earth space station (architecture) facility in this location makes it an ideal “launching pad” for outward going robotic and crewed interplanetary missions, to any solar system destination, and a docking port for those returning. Using Gateway Earth as a construction facility will reduce the mass of launches considerably as satellites, space vehicles and infrastructure will not have to withstand launch vibrations so less mass will be required. In addition, the nose cone and upper stage diameter will no longer be a constraint on the size of the object being launched. Made in Space has already tested building one metre length struts in a vacuum [5], used additive manufacturing in micro gravity with a 3D printer on the International Space Station [6] and in parabolic flights at the Johnson Space Centre in Houston. [7]

The GEDG has conducted detailed studies into the configuration of the Gateway Earth architecture [1], potential launch schedules, logistics and internal configuration and radiation shielding. [4] All research available on the Gateway Earth website: http://www.gatewayearth.space/, as well as detailed studies into the viability and legal constraints of each of the many individual aspects of the architecture. For instance, recent research showed that further developing revenue streams through the servicing of GEO satellites makes Gateway Earth a more appealing proposition to businesses with revenues up to $40.6 billion [4].

The Gateway Earth space station is planned to be in an orbit 100 times higher than The International Space Station (ISS) in GEO at ~36000km from the surface of Earth or 4.2164x107m from the Earth’s centre based on equation 1 and a sidereal day of 23 hours, 56 minutes and 4.09051 seconds. [8] After discussions with satellite manufactures, it was found that the suggestion of putting Gateway Earth in GEO would cause additional problems with overcrowding, take up a large amount of valuable communication space and potentially strategically important space. Further research in this area was needed and this is what is presented here.

$$rGEO = \sqrt[3]{\frac{GMeT^2}{4\pi^2}}$$

Where rGEO is the radius of GEO
G is Newton’s universal gravitational constant [9]
Me is the mass of Earth [10]
T is sidereal day length

$$rGEO = \sqrt[3]{\frac{6.6408x10^{-11} \times 5.9772x10^{24} \times 86164.09051^2}{4\pi^2}}$$

= 4.2164 x107 m to 5 S.F.

This work builds on the original GEO proposal to propose a more suitable orbit that will not interfere with the operations of the Geostationary and Geosynchronous Orbit satellites and their clearly defined spatial boundaries while accessing rich resource and revenue streams. GEO has over 1000 inactive satellites and countless more debris; over 700 active satellites are in the GEO zone and they will need servicing or removing from orbit at some point [11]. The proposal is to locate the Gateway Earth architecture further out than GEO, but not too close to the graveyard orbit at 300-400km out. Here it has the potential to visit every satellite in orbit with reusable space drones, such as, Effective Space’s Space Drones [12], collecting satellites and shifting their orbit to bring them within reach for orbital servicing/recycling/repurposing.

When considering locating a space station close to GEO then there are a number of considerations, most notably how close can a station be placed without causing a collision risk. Gravity variations due to the geoid [13] will change the orbit of any object in orbit however there are minimal changes in gravitational field strength due the geode at this distance from Earth, at GEO gravitational field strength (g) is 0.2242 ms-2 with a maximum variation of + 0.031ms-2 (based on the maximum and minimum variations in g + 0.7% [14]

$$g = \frac{GM}{r^2} \ (2)$$

$$\frac{(6.67408 * 10^{-11}) * (5.9722 * 10^{24})}{(4.2164 * 10^{7})^2} = 0.2242$$

$$\frac{0.007}{0.2242} = 0.031$$

This equates to a maximum acceleration due to gravity variation of 31mms-2 as Gateway Earth passes over GEO allowing it to theoretically be within about 200 metres of GEO without risk of collision, normal station keeping operations are easily able to counteract this small acceleration differences. In addition, the normal station keeping operations because of the higher harmonics of Earths gravitational potential (along with Moon-Earth-Sun system variations) East-West will have higher thrust requirements for GEO satellites. Active satellites will correct be able to correct anything within 100 metres with active station keeping so placing Gateway Earth in an orbit 200 metres further out from GEO should be acceptable, however some satellites have been known to have 'non-optimal' thrusts when station keeping [15] and this could make 200 metres a potential hazard. At 200 metres it would mean that, based on calculations for the MATLAB Homan Transfer Orbit tool created for this paper (available on request), it would take thousands of days (Appendix C) for Gateway Earth to synchronise with non-coplanar satellites (half a GEO orbit). To 'reinsert' any GSO satellite back into its orbit after this length of time is clearly not satisfactory, so where should Gateway Earth be placed?

Whilst a theoretical value of 200 metres away from GEO is acceptable, a 'near miss' of 335 metres caused the whole ISS crew to prepare for rapid departure in June 2011 then a 200-metre distance between Gateway Earth and GEO is completely unreasonable. [16] Now crucially the GEO protected region designated as regions covering an area 'swept out' from the GEO as +200km and making an angle of +15º through the centre of the Earth (Appendix D). These are defined as Geosynchronous Regions and any activity in this region needs to ensure safe and sustainable use. [17] Authorisation will be required to operate in this region and very tight mitigation protocols will have to be drawn up when carrying out servicing/repurposing/recycling activities. However, if it is deemed Gateway Earth will have to be located outside of this region then the capture and re-deployment times will be increased, and it will then run into the issue of being too close to the 'graveyard' orbit. I believe working with the Inter-Agency Space Debris Coordination Committee (IADC) to create suitable mitigation protocols will allow operations inside the protected region.

It is proposed that the orbital position of Gateway Earth should be at the mid-point between GEO and the graveyard orbit beyond GEO. Gateway Earth can be positioned inside the protected zone as it will not be overtly affected by the minimal changes in gravitational field strength due the geode. After various different orbital scenarios were considered and inserted the MATLAB Homan Transfer Orbit tool placing Gateway Earth 150km away from the closest graveyard orbits and 150km from GEO seemed the best solution. It will have access to the 700+ GEO satellites and the >1000 satellites in graveyard orbits, [17] GEO satellites and Gateway Earth would synchronise ~1.9º earlier every orbit meaning that satellites could extracted for servicing and reinserted without long term forward planning (Appendix E).

Because of this higher orbit Gateway Earth will travel more slowly over a larger circumference, this means that for every one orbit of a GEO satellite it will be a certain distance behind (Appendix F). I added this calculation to the MATLAB calculation tool to calculate the minimum time it would take to extract a satellite from GSO and then reinsert it into a similar orientation. This would be after half a GEO orbit in distance and would be 94 days at 150km from GEO (Appendix F & G). The lower acceleration due to gravity and the larger circumference orbit means that Gateway Earth travels slower and further, so in one day there is a significantly larger lag at a 150km higher orbit compared to the 200 metre higher orbit drastically reducing synchronisation times. This would require medium to long term planning to execute extraction, servicing and reinsertion, these transfers would have higher delta V values and be more complex, however these transfer calculations are well known and used. For the majority of GEO satellites no major Z axis corrections will be needed, there are a significant minority of satellites that lie within the protected + 200km zone of geostationary orbits so extra fuel and time requirements will be needed. In addition, satellites in graveyard orbits exceed this + 200km zone but could still contain valuable resources or potentially be re-entered into service by servicing/upgrading. At 150km further out from GEO then Gateway Earth will be able to access these resources and start the long job of clearing debris from GEO charging the owners for this service.

Homan Transfer Orbit trajectory (Appendix H), based on two chemical propulsion thrusts have been calculated, the same transfers can be achieved with ion engines with a constant thrust but over longer time-periods. This would not affect operations as long-term logistical planning will ensure time is allocated to these transfers. At 150km the transfer time from orbit to orbit will be ~12 hours based on an average effective exhaust gas velocity (ve) of 700 ms^{-1} for chemical rocket engines.

As delta V calculations work for both increasing and decreasing orbits then the MATLAB calculation tool can be used to show that space drones could transfer 'dead' satellites from the graveyard orbit to Gateway Earth. This would be the same time and fuel requirements as the 150 km from GEO and slightly longer for 250 km further out. Some of these could be rejuvenated and put back into service, and where this is not the case then the materials and components will be repurposed or recycled as stated earlier. This resource and revenue stream [4] would be secondary to the main aim of debris removal and servicing of GEO satellites. It does exemplify again that having a space station servicing facility 150 km above GEO will have a revenue and resource stream that will be sustainable for many years and strengthens the case for a permanent facility to create a sustainable interplanetary future for Humanity.

4. Science & Function Case

Like the ISS before it, the Gateway Earth space station is envisioned as a centre of scientific research. The long-term crew of astronauts will carry out research activities in addition to station operations and maintenance. Gateway Earth will be able to exploit the unique advantages of its position in geostationary orbit, in addition to hosting similar experiments as those performed on the ISS or other potential future space stations. Below, we first outline GEO-specific research and then give a brief overview of other research work done on the ISS or proposed for NASA'S Gateway which is equally suitable for Gateway Earth.

4.1 Research in GEO

The principal rationale for a space station in GEO is to enable the *assembly and launch of spacecraft for scientific missions* outside Earth's gravity well. Gateway Earth will reduce the expense and design burden of spacecraft and their payloads, which will no longer need to withstand the thermal, vibrational, and gravitational stresses of launch from the ground. This applies to interplanetary craft such as Mars and lunar missions, but also to satellite launches into GEO and other Earth orbits and to space-based telescopes. Spacecraft built on Gateway Earth can be sent out to record observations or collect samples, returned to the station, and serviced for new missions, increasing the frequency of missions without increasing costs. The GEO space travel node will be the capstone of Gateway Earth's research agenda as well as of the modular space architecture design itself.

A key area of research on space stations is *human health and space medicine*. The IDA Science & Technology Policy Institute's 2019 report "Evaluation of a Human Mission to Mars by 2033" [41] found that environmental control and life support systems remain the most undeveloped area of technology for interplanetary human spaceflight missions. This is due to the lack of any long-term human presence in the deep space environment. Yet experience in LEO has shown that the space environment can have unpredictable effects on human health. ISS research on the effects of microgravity on human health has revealed problems of muscle atrophy, bone loss, and fluid shifts. The human presence in LEO has further taught us the risks of space-specific conditions like Spaceflight-Associated Neuro-Ocular Syndrome. Experiments on plants and animals transported to the ISS have also discovered differences in the growth and development of organisms in microgravity. Health impacts of microgravity remain a large and important area of research, and Gateway Earth will provide a new laboratory to study them.

While GEO offers the same access to a low gravity environment, unlike LEO its radiation and plasma environment is similar to that of deep space, exposed to high-energy X-rays, galactic cosmic rays and solar proton events as well as trapped radiation from the Van Allen belts (high-energy elections and low-energy protons). The ability to study the effects of both short-term and long-term exposure to this radiation environment on living cells, tissues, and DNA will be invaluable for future human spaceflight to destinations such as Mars, which will expose astronauts to the deep space radiation environment for long periods of time. Instruments such as charged particle detectors (magnetic spectrometers) to measure the changing fluxes of high-energy particles can be mounted to the outside of Gateway Earth to enable long-term and real-time study of the radiation environment and the solar cycle and provide warning to astronauts of hazardous radiation levels. Continued testing of plants, non-human animals, and microorganisms in GEO can supplement knowledge of space medicine by improving our understanding of health impacts and the ability of simpler organisms to survive in space.

Finally, the synergistic effects of microgravity and deep space radiation on human health are a related important research area and cannot be studied in any environment other than high orbits or deep space itself. Gateway Earth will make it possible to better understand the potential threat posed by deep space radiation to astronauts and develop remedies and protections well before undertaking long-term deep space missions.

Another important area of research will be *technology development in space*. The deep space radiation environment also affects inorganic materials, from the metals and plastics used in electronics to the food and pharmaceuticals consumed by astronauts. The effect of radiation on satellites in GEO has been studied (e.g. [42] and [43]) to determine whether it compromises satellite functioning and longevity. Gateway Earth will offer the ability to observe the long-term performance of a broader range of technology, including technology needed to support human habitation, in the GEO radiation and plasma environment. The shelf life of food and pharmaceuticals and the service life of, for example, medical equipment may be different in deep space than LEO. Gateway Earth will be a venue to explore these fundamental questions about long-term human presence in deep space, as well as to build on our knowledge of materials science as it relates to spacecraft and instrumentation.

As we expect a substantial number of tasks on Gateway Earth to be done using robotic arms, the durability and effectiveness of telerobotics in the GEO environment will naturally also be a subject of research. The Gateway Earth station will stimulate new developments in telerobotics with a wide range of potential applications, from satellite servicing to spacecraft assembly to sample collection. We likewise expect that Gateway Earth will both house and promote developments in materials science as its operations will create demand for new materials and equipment suitable to the GEO space environment. Gateway Earth will be both laboratory for and driver of a broad range of technologies.

4.2 Research in space

Below, we briefly review areas of research for which a geostationary space station is not strictly necessary but which will benefit greatly from the availability of Gateway Earth as a laboratory. Architectures for these areas are already existing and the integration of the Gateway Earth node would enhance their usefulness and scope.

Fundamental physics

The ISS has hosted experiments such as the Flame Extinguishing Experiment and the creation of Bose-Einstein condensate in the Cold Atom Lab. The 2018 Deep Space Gateway Concept Science Workshop generated proposals for fundamental physics research including an advanced space optical clock system which can be used for direct detection of ultra-light dark matter fields [44], the Dark energy and gravity Experiment Explorer and Pathfinder for direct detection of dark energy scalar fields using atomic interferometers [45], and the Deep Space Quantum Link to investigate the effects of gravity on quantum systems [46]. Gateway Earth and GEO are equally suitable for fundamental physics research of this kind.

Space weather

Space stations are ideal for studying space weather, as they allow long-term observations without atmospheric interference. Even in LEO, the ISS is host to the Atmospheric Waves Experiment, planned to launch in 2022 and study the interaction between the solar wind and waves in the lower atmosphere. Higher orbits offer the prospect of better vantage points for space weather research and prediction. Space weather architectures [47] are of interest because improved space weather prediction can avoid or mitigate damage caused by the solar wind, Earth's radiation belts, and geomagnetic storms. These issues become more urgent as the human presence in space grows. Gateway Earth is in an ideal location for space weather research due to its high orbit away from the damping effects of the atmosphere and its position in the GEO radiation and particle environment.

Earth observation

Earth observation is a well-developed area with measurements carried out by many existing satellites. Advanced geostationary satellites such as the Japanese Himawari series and the USA's GOES series generate high-resolution imagery in the visible and infrared bands and are invaluable in weather prediction, climate monitoring, and natural disaster response. A ring of similar instruments in GEO is required to provide global coverage. Gateway Earth would become part of this growing Earth observation architecture in GEO.

The scientific value of a Gateway Earth research laboratory is clear. As a private-public partnership, Gateway Earth will be able to house both basic scientific research typically supported by government funding and targeted research and development needed by the commercial space industry to carry out its objectives.

This mixed user base will distribute the funding burden among diverse stakeholders, provide returns on investment, and still meet key scientific goals of interest to all of humanity.

5. Technology Landscape

Gateway Earth's modular space access architecture pivots around a crewed space station just above Geostationary Orbit (GEO). From there critical new missions can be launched into deep space, in particular (back) to the Moon and further to Mars, as well as hosting space travellers and tourists.

However, critical for the (economic) viability of such an outpost is the potential for in-orbit satellite maintenance (life extension) and manufacturing, with potential markets in the billions of US dollars.

Unlike other key functions of the Gateway Earth station, the satellite repair and development require new technologies and operational protocols to be established. Here, work by the GEDG has been underway to specify the required configuration of on-board equipment and patent landscape analysis as to its current state of development and future potential.

The technical fields and technologies contributing to the establishment of GEO satellite repair and manufacturing operations on the Gateway Earth station were broadly classified into the following for patent analysis: In-space Manufacturing, Satellite Payload Health Monitoring, Satellite Payload Performance Monitoring, Satellite Freighters, and In-Space Recycling and Reuse Technology.

Further to this classification, keywords were formed, and a full-text patent search was conducted in the World Intellectual Property Organization (WIPO) database. (Please note that patent applications are normally published within 18 months from the date of application, which means that the data for the previous 18 months is subject to change as new applications are published.)

While the field of payload performance monitoring has the maximum number of patents, in-space recycling seems to be just picking-up. The field of additive manufacturing is seeing an upward trend in the number of applications and can be attributed to the increasing interest in the field of 3-D printing and research on new materials.

Satellite freighters patent data shows an interesting insight; apart from Boeing and Trion World, other top applicants in this field are all individuals and not organizations.

Patent applications are classified based on their technical field of implementation, and they often give a glimpse of the major focus of inventions in our chosen technology. Based on the data collected, we see that most of the patents in monitoring of satellite payload health and performance fall under the category of "Transmission". This indicates that most inventions focus on Information and Communication Technology, as compared to electromechanical inventions.

As seen in Appendix I, the USA leads the pack with the most patent applications among the top jurisdictions, and the UK, Canada and Australia find themselves in three of the five technical fields. China appearing in the list for In-Space Manufacturing and Russia for Satellite Freighters are in-line with the traditional areas of focus of their respective research areas. South Africa and African Regional IP Organization appear in the list for Payload Performance Monitoring.

6. Preliminary GEO Station Architecture and Systems Engineering

The Gateway Earth GEO station is proposed to be modelled after the ISS, but using the most advanced inflatable models (such as Bgelow B330s) and connecting modules (of "ISS Tranquillity-like" variety). An ISS (ESA) Columbus-type science module and internal JAXA Kibo-like modules are proposed as the main science and R&D areas of the station, with internal and external laboratory and (satellite) manufacture and maintenance facilities. A schematic diagram of a possible station configuration is shown in the schema in Appendix J.

The central integrative precedent is the ISS, where modular architecture has enabled for seamless in-orbit assembly and energy efficient operations. The main difference is the self-sustainability of the B330 modules in comparison to the somewhat eclectic mix at the ISS and the overall smaller size of the Gateway Earth station.

Having modelled the interior environment and requirements as well as tracking emerging technological solutions, the smaller more compact GEO station can also have greater efficiency that ISS [4]. For example, due to water-filled thick walls, the B330 also offers decent radiation protection and is energy and heat efficient.

In addition to modular configuration of living quarters, research and docking facilities and the interconnecting modules, a special attention has been paid to core necessary technology for station assembly, operations and maintenance. As outlined earlier, with a combination of robotic technology (i.e. CanadArm successors), 3-D printing and other additive manufacturing techniques, the station can be built, maintained and can offer novel logistic and manufacturing services in-orbit.

Several costing models have been developed over the years, but the most consistent one puts its development, building and (25 year) lifetime operations costs on par with ISS at around 100 billion US dollars [49].

7. Business Model

Gateway Earth has a unique business model. Unlike other space stations such as Mir, the International Space

Station, and NASA's proposed Gateway, Gateway Earth is conceived as essentially commercial and self-financing. Gateway Earth harnesses the incredible growth of the new private space industry to build a ladder out of Earth's gravity well that will be accessible to all.

To generate the revenues needed to cover the high costs of activity in space, Gateway Earth offers solutions to multiple problems and meets several pressing needs of the new space industry, including commercial human spaceflight, satellite repair and removal or salvage of space debris, and on-orbit manufacturing and assembly. The added value for customers across the spectrum from private individuals to commercial space companies to national space agencies courts buy-in from all sectors of society and demands a high degree of collaboration. A key advantage of the Gateway Earth architecture is the lack of any need for additional technological innovation. Although future innovations will fit seamlessly into its architecture, Gateway Earth can be built wholly from existing technology.

Below we outline back-of-the-envelope calculations of revenue streams for the keystone of the Gateway Earth architecture, the space station in GEO (see pie-chart breakdown in Appendix K). These calculations are exemplary rather than comprehensive and serve to highlight the potential of the Gateway Earth concept.

7.1 Commercial human space flight

Commercial human space flight – or space tourism – is in the headlines this year thanks to recent flights by Virgin Galactic and Blue Origin. Virgin Galactic initially began selling ticket reservations at $250,000 and closed reservations at 600. Blue Origin auctioned a seat on its first flight for $28 million but has not disclosed the price of future tickets. Both companies have reported strong demand and already have a pipeline of customers. Earlier in the 21st century, Space Adventures, Inc. transported several private individuals for brief stays at the International Space Station. Ticket prices ranged from $20 million for the first space tourist, Dennis Tito, in 2001, to $52 million for Sarah Brightman in 2015. Space Adventures offered an additional spacewalk service for $15 million.

Several commercial human space flight companies have also begun to offer travel to the Moon in the near future. Space Adventures has indicated that it will transport tourists to within 100 km of the lunar surface within the next decade at a price of $100-150 million per ticket. SpaceX has also announced an intended tourist flight around the Moon, as well as the first passenger, Yusaku Maezawa. SpaceX founder Elon Musk quoted the price for a lunar flight to be around $70 million, similar to that for a trip to the ISS.

The "Space Tourism – Global Market Trajectory and Analytics" 2021 report by ResearchandMarkets.com [39] indicates that the space tourism market is expected to grow by 15.2% from 2020-2027, reaching a value of $1.7 billion in 2027. Space tourism is currently a high-end market with a small customer base. An increase in the supply of tickets to space may bring down prices as the sector grows but will also open up space tourism to a larger base.

The Gateway Earth architecture will tap into the market for space tourism by offering travel to and accommodation at the Gateway Earth space station. The space hotel will accommodate six guests at a time, in addition to one hotel manager who will accompany them on arrival and departure. Vidmar et al. 2017 plans for 24 return trips per year, giving a total of 144 available tickets per year. Using the recent ticket prices for private travel to the ISS and lunar flights as a basis, tickets are estimated at $50 million.

Customer base: Private individuals
Revenue stream: $7.2 billion per year

7.2 Satellite repair & servicing

On-orbit satellite servicing is a nascent market. The satellite industry makes up the bulk of the global space industry, offering services such as telecommunications, remote sensing, navigation, and national security applications. As the number of satellites in orbit has grown, issues of sustainability have raised their heads, particularly concerns about space debris and collisions, extending the lifetime of existing satellites, and decommissioning of old satellites. The leading body in this area is the Consortium for Execution of Rendezvous and Servicing Operations, a US-based, DARPA-funded initiative that researches, develops, and funds standards and best practices for on-orbit satellite servicing.

Satellite services are increasingly being provided by satellite constellations in low-Earth orbit, which has opened up greater opportunities for servicing because these constellations are easier to reach than GEO. However, for both technical reasons and to avoid overcrowding lower orbits, GEO satellites will remain part of the space ecosystem for the foreseeable future. 2020 saw the first successful servicing of a GEO satellite when the Space Logistics Mission Extension Vehicle (MEV-1) docked with the satellite Intelsat-901 in geostationary orbit. MEV-1 will extend Intelsat-901's service life by five years. This achievement demonstrates the viability of on-orbit satellite servicing in GEO; however, Gateway Earth offers substantial improvements over this approach to OOS.

The GEO space station will act as a hub for satellite repair, servicing, refuelling, and salvage. A unique selling point of the Gateway Earth station is the absence of the need to launch additional repair craft. Gateway Earth will be a permanent installation. Vidmar et al. 2017 produced an estimate of the GEO repair market of $8.75 – 17.5 billion per year based on the service life and replacement costs of the current GEO satellite population. If Gateway Earth captures 20% of this market, the resulting revenues would be $1.75 billion – 3.5 billion per year.

Customer base: Commercial satellite companies
Revenue stream: Conservative estimate at 20% market share $1.75 billion per year

7.3 On-orbit manufacturing and assembly

In 2014, the company Made in Space Inc. partnered with NASA to send a 3-D printer to the International Space Station. The mission was a proof of concept that additive manufacturing in zero gravity is possible. It successfully used polymer feedstock to print test objects and remains an ongoing experiment in the ISS National Lab. On-orbit manufacturing and assembly of satellites, spacecraft, and equipment offers enormous potential for cost savings and efficiency gains. Currently, payloads must be designed to withstand the stresses of launch (vibrations, thermal loads, etc.) as well as the environment of space. On-orbit manufacturing can reduce this engineering burden – as well as the physical mass of the product, which can be less robust and require less packaging than one manufactured on Earth. On-orbit manufacturing could be used for individual parts or entire satellites, spacecraft, and space telescopes.

In 2017, the IDA Science & Technology Policy Institute produced a report titled "On-Orbit Manufacturing and Assembly of Spacecraft" [38] which investigates the cost savings from on-orbit manufacturing and assembly in several case studies. The report finds that:

- A cost analysis by the Jet Propulsion Laboratory indicated that on-orbit assembly of a space telescope on the scale of the James Webb Space Telescope would save $12.8 billion in comparison to current procedures.
- Assembling additional antennas onto an existing GEO comsat (from three antennas to six) could increase the annual revenue by $5.4 million per year, or $81 million over the satellite's lifetime.
- Upgrading the technology on an older GEO comsat through on-orbit manufacturing and assembly of technology innovations could result in an increase in total revenue over the satellite's lifetime of $300 million.

Gateway Earth will act as a permanent manufacturing and assembly platform in GEO. If Gateway Earth provides the assembly hub for one space telescope with a 30-year project timeframe, assembles antennas for 10 GEO comsats in a year, upgrades 10 more GEO comsats in a year, and captures only 10% of the cost savings from these ventures through fees, the resulting revenue stream will be $68 million per year. These case studies do not cover the full range of on-orbit manufacturing and assembly activities, which will also include assembly of interplanetary spacecraft such as future Mars orbiters and commercial space vehicles.

Customer base: Commercial satellite companies, commercial human space flight vehicles, national space agencies; potentially in-situ resource utilisation and asteroid mining companies in the longer term
Revenue stream: $68 million per year+

The NASA's Office of the Inspector General report "Extending the Operational Life of the International Space Station Until 2024" [40] cites the annual operating costs of the ISS at $2.9 billion (for the fiscal year 2013). Our revenue streams, based on conservative estimates using figures from the present small private space industry, already come to $9 billion, or roughly 300% of these running costs. Although these figures represent only rough estimates and markets will no doubt shift in the coming decades, it is clear that a commercial space station supported by revenues from private industry is likely to become viable. The Gateway Earth architecture offers the opportunity to tap into these varied markets while promoting public interests in the form of benefits to science and future interplanetary space travel.

8. Consortium Set-up

Analysis of the available legal frameworks for Gateway Earth development and operations point toward the need to establish parent organisation's headquarters in a jurisdiction with a favourable legal regime as well as progressive interest in space exploration and industry, for example a country like Luxembourg or Singapore [49]. As discussed previously, the station is to be located above GEO, which also allows operations uninhibited by the protected orbital slotting within the 200km GEO frequency band allocation zone.

Furthermore, our analysis shows that the most optimal organisational configuration is as an non-for-profit international (potentially intergovernmental) organisation, modelled after large scientific facilities operators, such as European Organisation for Nuclear Research (CERN), European Southern Observatory or the upcoming Square Kilometre Array.

9. Stakeholder Engagement & Outreach

The participation of Medium, Small & Micro entities in space related industries has seen a boom in the last decade. The key factors contributing to it are:

- increased successes of space missions (SpaceX re-entry missions)
- access to allied technologies (microgravity implementations)
- relaxing of regulations & opening of space sector to private players (India)

The outreach can be done in four phases:

- Identifying potential players for collaboration
- Working out synergies and defining the scope of collaboration
- Pilot projects, followed by larger projects
- Reaching-out and awareness activities

While phases 1 and 4 will be continuous, 2 and 3 will be specific to a particular partner.

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References

[1] Webber. D. (2015). “Gateway Earth” – Low Cost Access to Interplanetary Space. Proceedings of the 13th Reinventing Space Conference.

[2] Weber. D. (2014). Bridgehead – Interplanetary Travel Becomes Routine. Proceedings of the IAA Space Exploration Conference.

[3] Vidmar. M & Weber. D. (2017). A Pragmatic Modular Architecture for Space Access and Exploration. Proceedings of 68th International Astronautical Congress (IAC).

[4] Vidmar. M, et al. (2017). Developing the Technical and Operational Framework for Gateway Earth Space Access Architecture. Proceedings of 15th Reinventing Space Conference.

[5] Molitch-Hou. M. (2017). One Small Step for 3D Printing Satellites in the Vacuum of Space. Available: https://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/15455/One-Small-Step-for-3D-Printing-Satellites-in-the-Vacuum-of-Space.aspx

[6] Nogales. C, Et Al. (2017). MakerSat-0: 3D-Printed Polymer Degradation First Data from Orbit. Proceedings of the 32nd Annual Small Satellite Conference.

[7] Medium. (2017). Dream on Earth. Build among the stars. Available: https://medium.com/made-in-space/new-space-based-manufacturing-technologies-demonstrated-by-made-in-space-79000e771ac4

[8] Wikipedia. (2018). Sidereal Time. Available: https://en.wikipedia.org/wiki/Sidereal_time

[9] NIST. (2018). Fundamental Physical constants. Available:https://physics.nist.gov/cgi-bin/cuu/Value?bg|search_for=abbr_in!

[10] International Earth Rotation and Reference Systems Service. (~2008). General definitions and numerical standards. IERS Technical Note. 36, 15-20.

[11] Longstaff. R & Hempsell. M. (2017). A MISSION TO DEMONSTRATE THE PRESERVATION OF THE GEOSTATIONARY ORBIT. Proceedings of the 7th European Conference on Space Debris.

[12] Sam Jarman. (2018). Space drones will give satellites a new lease of life. Available: https://physicsworld.com/a/space-drones-will-give-satellites-a-new-lease-of-life/

[13] ESA. INTRODUCING GOCE. Available: https://www.esa.int/Our_Activities/Observing_the_Earth/GOCE/Introducing_GOCE

[14] Hirt. C, Et Al. (2013). Geophysical Research Letters. New ultra-high-resolution picture of Earth's gravity field. 40 (16).

[15] Borissov. S, Wu. Y & Mortari. D. (2015). East–West GEO Satellite Station-Keeping with Degraded Thruster Response. Aerospace. (2), 681-601.

[16] Amos. J. (2011). International Space Station in debris scare. Available: https://www.bbc.co.uk/news/science-environment-13949956

[17] Inter-Agency Space Debris Coordination Committee. (2014). Support to the IADC Space Debris Mitigation Guidelines. 04 (06).

[18] Ostrove. B (2015). Average Commercial Communications Satellite Launch Mass Declines, Again. Available: https://blog.forecastinternational.com/wordpress/average-commercial-communications-satellite-launch-mass-declines-again/

[19] Dvornychenko, V. (1990). The generalized Tsiolkovsky equation. National Institute of Standards and Technology. 449-457.

[20] European Space Operations Centre (2018). ESA's Annual Space Environment Report. ESA Space Debris Office. 2.

[21] Weedon, B. (2010). Dealing with Galaxy 15: Zombiesats and on-orbit servicing. Available: http://thespacereview.com/article/1634/1

[22] United Nations. (2008). United Nations Treaties and Principles on Outer Space. UNITED NATIONS OFFICE FOR OUTER SPACE AFFAIRS. 2.

[23] ESA. (2011(updated)). THE GEOSTATIONARY SERVICING VEHICLE. Available: https://www.esa.int/Our_Activities/Space_Engineering_Technology/Automation_and_Robotics/The_Geostationary_Servicing_Vehicle_GSV

[24] Lothar Gerlach. (2009). INSIDE A SOLAR CELL. Available: https://www.esa.int/Our_Activities/Space_Engineering_Technology/Inside_a_solar_cell

[25] Rodiek, J & Brandhorst, H. (2008). SOLAR ARRAY RELIABILITY IN SATELLITE OPERATIONS. Acta Astronautica. 63 (11).

[26] SpaceX. (2018). CAPABILITIES AND SERVICES. Available: https://www.spacex.com/about/capabilities

[27] NASA. (UPDATED 2017). About the Space Station Solar Arrays. Available: https://www.nasa.gov/mission_pages/station/structure/elements/solar_arrays-about.html

[28] Boeing. (2018). Cells & CICs. Available: https://www.spectrolab.com/photovoltaics.html

[29] Northrop Grumman Corporation. (2018). Ultraflex Factsheet. Available: https://www.northropgrumman.com/Capabilities/SolarArrays/Documents/UltraFlex_Factsheet.pdf

[30] ESA. (2016). Tim and Tim Safely Back in Space Station After Spacewalk. Available: https://www.esa.int/Our_Activities/Human_Spaceflight/Principia/Tim_and_Tim_safely_back_in_Space_Station_after_spacewalk

[31] McNelis, A, et al.. (2014). Simulation and Control Lab Development for Power and Energy Management for NASA Manned Deep Space Missions. Proceedings of the 50th AIAA/ASME/SAE/ASEE Propulsion and Energy Forum and Exposition.

[32] OSCAR . (2015). Satellite: GOES 11. Available: https://www.wmo-sat.info/oscar/satellites/view/147

[33] ANON. (LAST UPDATED 2018). WIDE ANGLE SEARCH FOR PLANETS. Available: https://en.wikipedia.org/wiki/Wide_Angle_Search_for_Planets

[34] Borgmeyer, S. (2018). ORBITAL PROPULSION FLUIDIC EQUIPMENT. Available: http://www.space-propulsion.com/brochures/valves/space-propulsion-valves.pdf

[35] OSCAR . (2015). Satellite: DMSP-F13 . Available: https://www.wmo-sat.info/oscar/satellites/view/60

[36] STEVEN CLARK. (2015). DMSP satellite's break-up linked to battery failure. Available: https://spaceflightnow.com/2015/07/24/dmsp-satellites-break-up-linked-to-battery-failure/

[37] ESA. (2013). BUILDING A LUNAR BASE WITH 3D PRINTING. Available: http://www.esa.int/Our_Activities/Space_Engineering_Technology/Building_a_lunar_base_with_3D_printing

[38] IDA Science & Technology Policy Institute. (2017). "On-Orbit Manufacturing and Assembly of Spacecraft." Available: https://www.ida.org/-/media/feature/publications/o/on/on-orbit-manufacturing-and-assembly-of-spacecraft/on-orbit-manufacturing-and-assembly-of-spacecraft.ashx

[39] ResearchAndMarkets. (2021). "Space Tourism - Global Market Trajectory and Analytics." Available: https://www.researchandmarkets.com/reports/5141552/space-tourism-global-market-trajectory-and

[40] NASA Office of Inspector General. (2014). "Extending the Operational Life of the International Space Station until 2024." Available: https://www.oversight.gov/sites/default/files/oig-reports/IG-14-031.pdf

[41] IDA Science & Technology Policy Institute. (2019). "Evaluation of a Human Mission to Mars by 2033." Available: https://www.ida.org/-/media/feature/publications/e/ev/evaluation-of-a-human-mission-to-mars-by-2033/d-10510.ashx

[42] Atwell, W. and Matzkind, C. (2017). "Geostationary space: The radiation environment and effects on electronics under various shielding configurations." Available: https://ttu-ir.tdl.org/bitstream/handle/2346/72907/ICES_2017_81.pdf?sequence=1&isAllowed=y

[43] Lu, Y. et al. (2019). "A review of the space environment effects on spacecraft in different orbits." Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8758870

[44] Williams, J.R. and Yu, N. (2018). "Clock comparison and distribution beacon at cislunar orbits." Available: https://www.hou.usra.edu/meetings/deepspace2018/pdf/3088.pdf

[45] Chiow, S-w. and Yu, N. (2018). "Dark energy and gravity experiment explorer and pathfinder." Available: https://www.hou.usra.edu/meetings/deepspace2018/pdf/3040.pdf

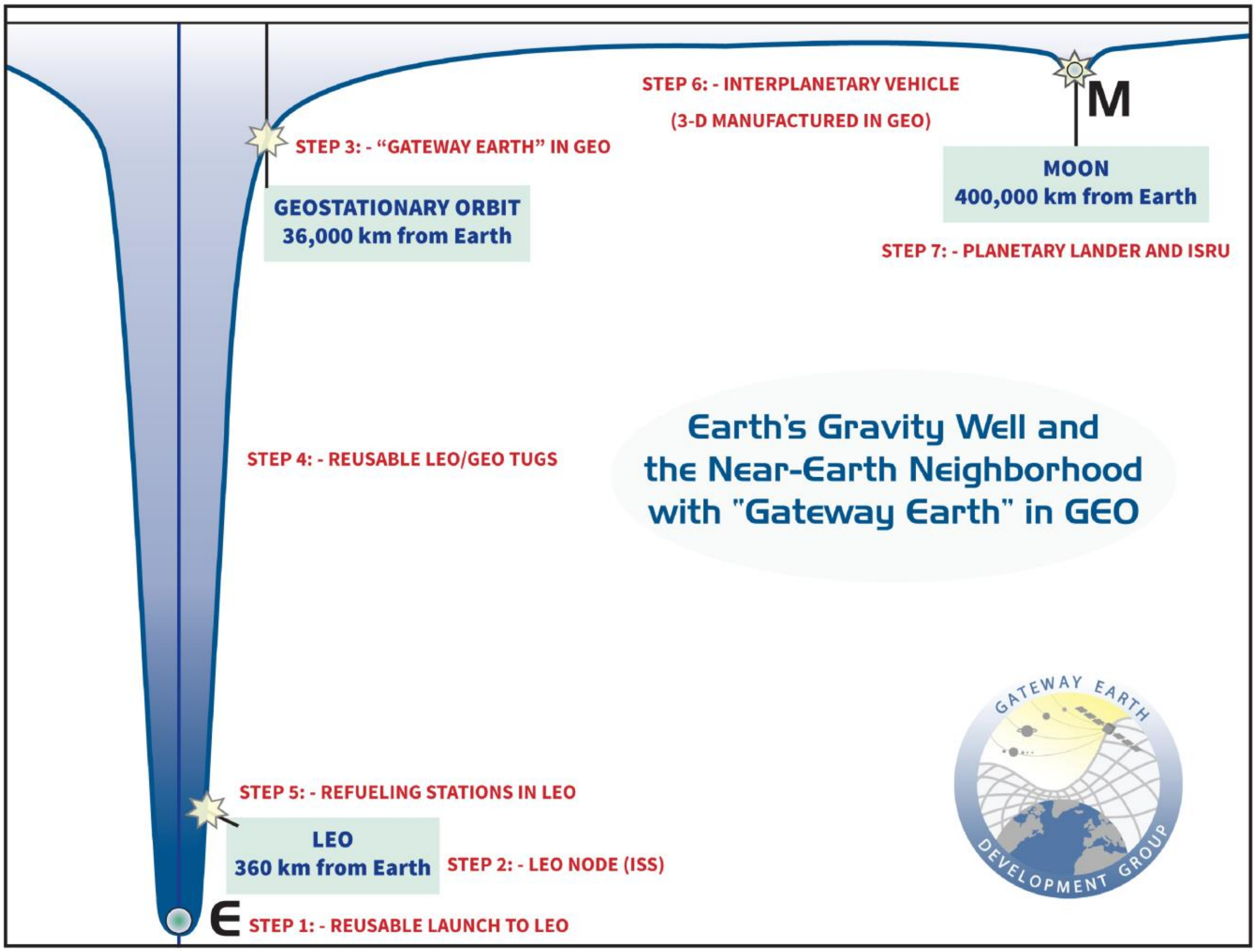
[46] Mohageg, M. et al. (2018). "Deep space quantum link." Available: https://www.hou.usra.edu/meetings/deepspace2018/pdf/3039.pdf

[47] Parker, L. et al. (2018). "Evaluating space weather architecture options to support human deep space exploration of the Moon and Mars." Available: https://www.hou.usra.edu/meetings/deepspace2018/pdf/3170.pdf

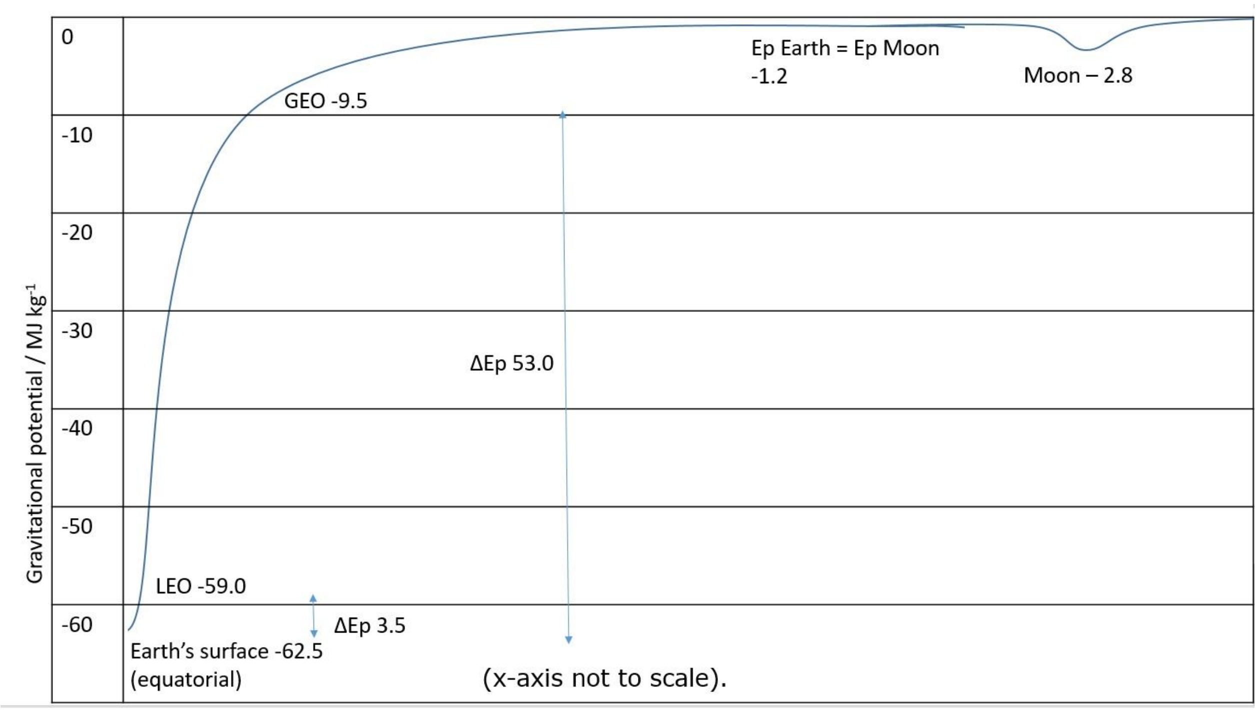
[48] Venkataraman, A., Leslie, L., Anderson, R., and Vidmar, M. (2020). Knowledge and Technology Building Blocks for Space Access Architectures. Proceedings of International Astronautical Congress.

[49] van Laar, M. and Vidmar, M. (2019). Legal, Business and Science Case for Modular Space Access and In-orbit Services Through Geostationary Orbit. Reinventing Space Conference, Belfast.

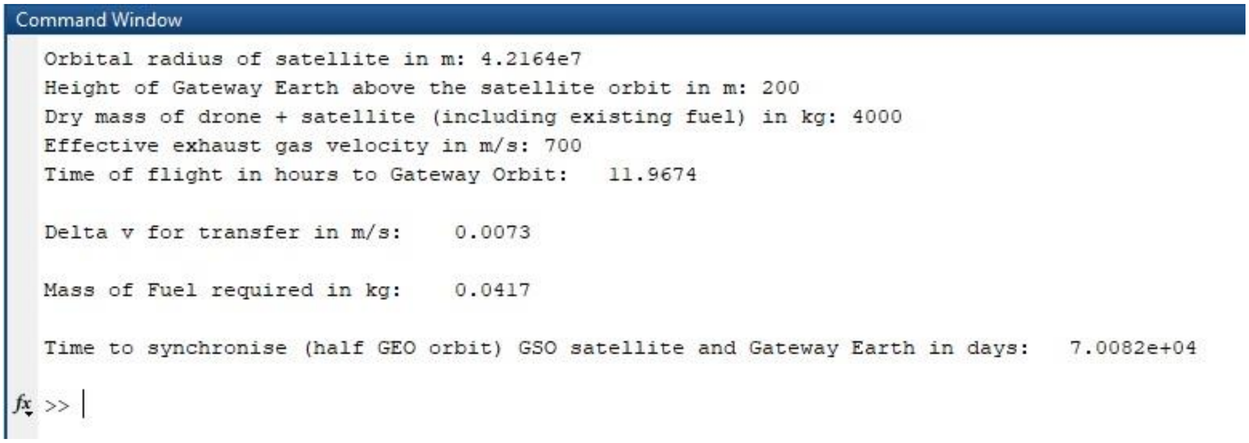
Appendix A (Gateway Earth Architecture)



Appendix B (The potential wells of Earth and the Moon with energy requirements to move one kilogram from orbit to 'infinity' (x-axis not to scale))

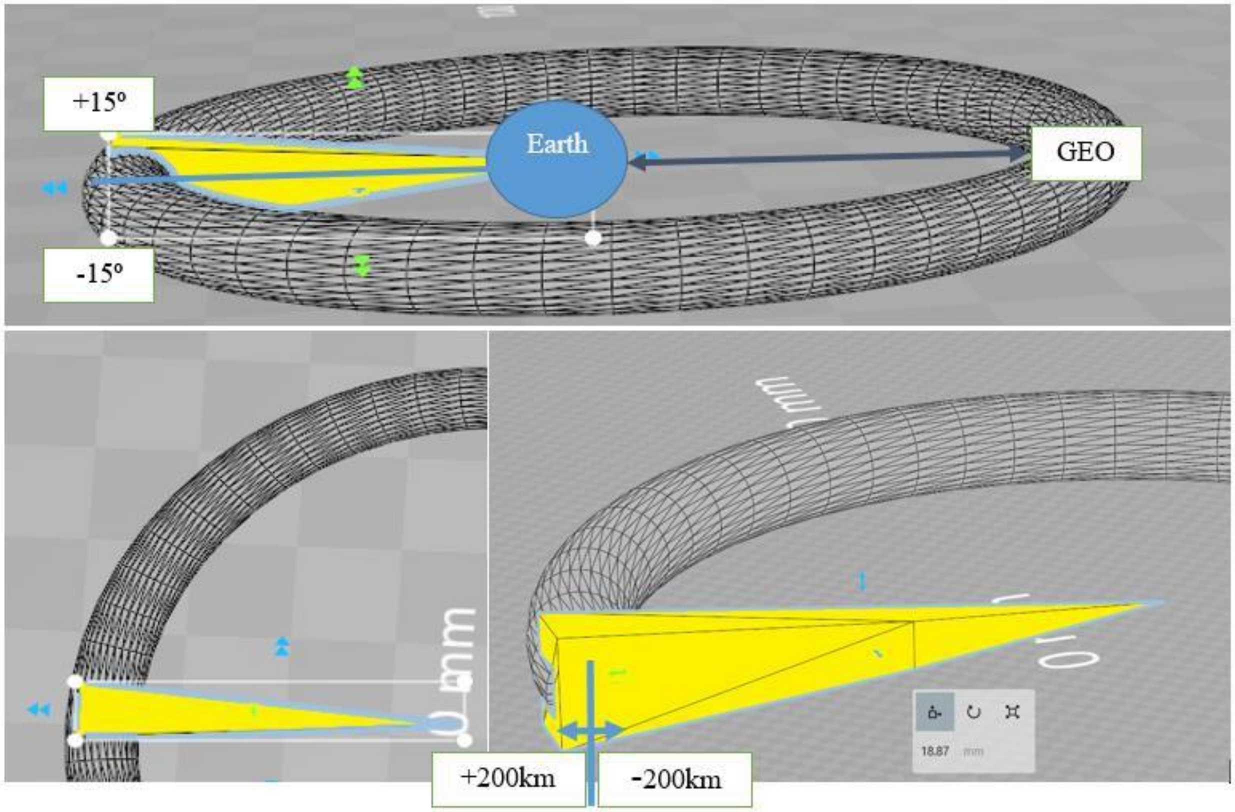


Appendix C (MATLAB screen shot showing Gateway Earth synchronisation time at 200 metres away from GEO)

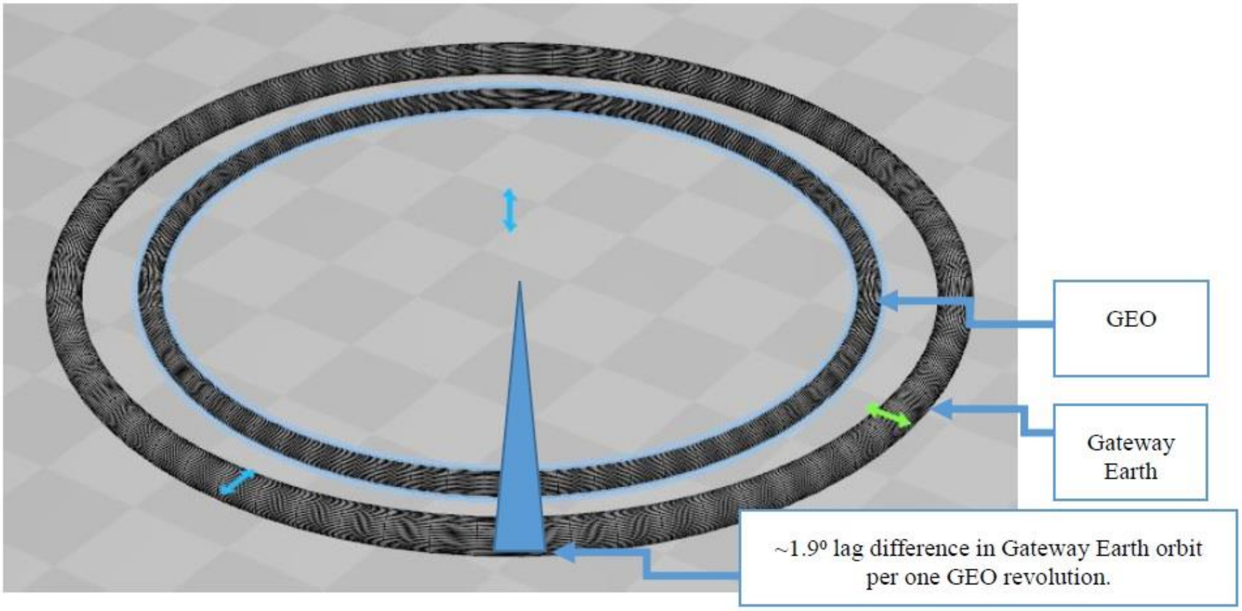


```
Orbital radius of satellite in m: 4.2164e7
Height of Gateway Earth above the satellite orbit in m: 200
Dry mass of drone + satellite (including existing fuel) in kg: 4000
Effective exhaust gas velocity in m/s: 700
Time of flight in hours to Gateway Orbit:   11.9674

Delta v for transfer in m/s:    0.0073

Mass of Fuel required in kg:    0.0417

Time to synchronise (half GEO orbit) GSO satellite and Gateway Earth in days:   7.0082e+04

fx >>
```

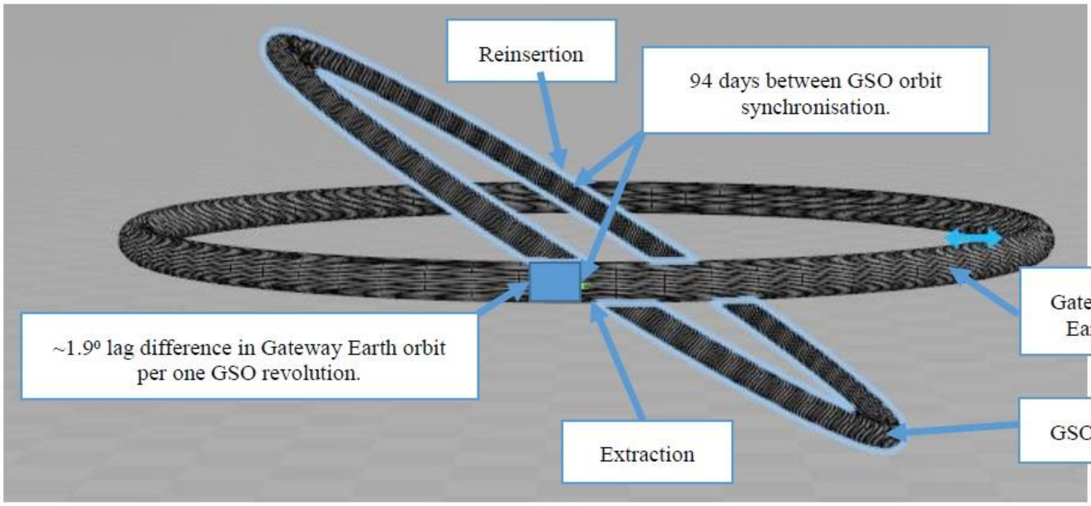
Appendix D (Protected GEO region (not to scale))



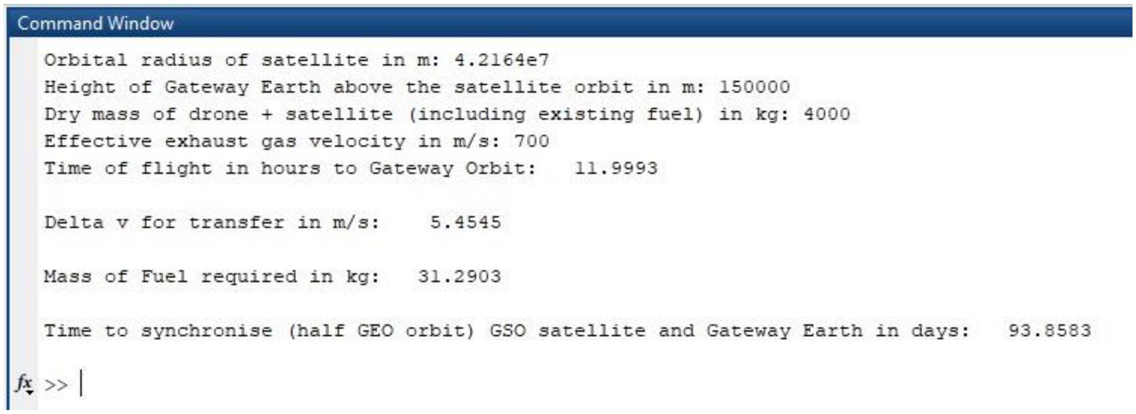
Appendix E (GEO and Gateway Earth orbital lag (not to scale))



Appendix F (Showing the GSO and Gateway Earth orbital lag (not to scale))

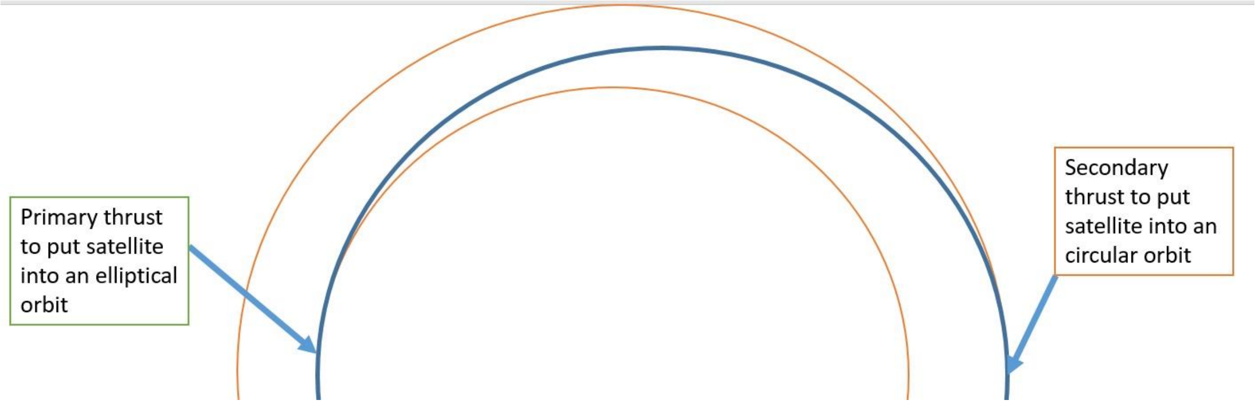


Appendix G (Screenshot of MATLAB command window for 150km from GEO and with an average 700ms-1 effective exhaust gas velocity for a typical chemical rocket engine)

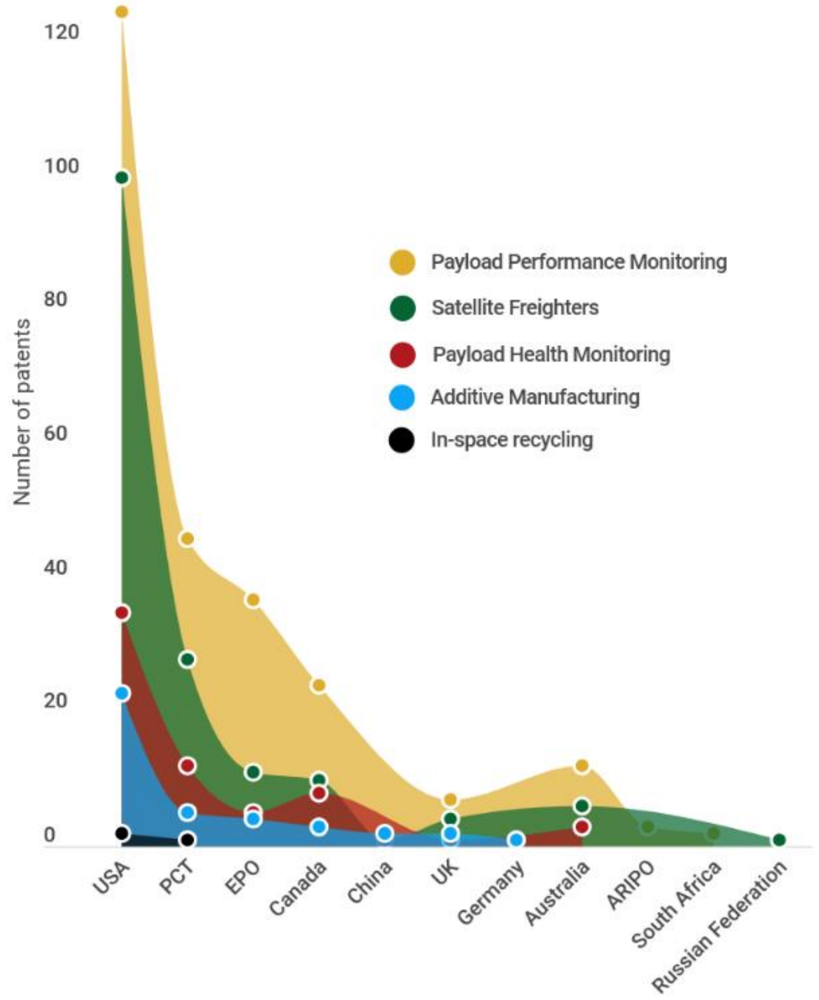


```
Orbital radius of satellite in m: 4.2164e7
Height of Gateway Earth above the satellite orbit in m: 150000
Dry mass of drone + satellite (including existing fuel) in kg: 4000
Effective exhaust gas velocity in m/s: 700
Time of flight in hours to Gateway Orbit:   11.9993

Delta v for transfer in m/s:    5.4545

Mass of Fuel required in kg:   31.2903

Time to synchronise (half GEO orbit) GSO satellite and Gateway Earth in days:   93.8583

>>
```

Appendix H (Homan Transfer orbit from GEO to Gateway Earth (not to scale))

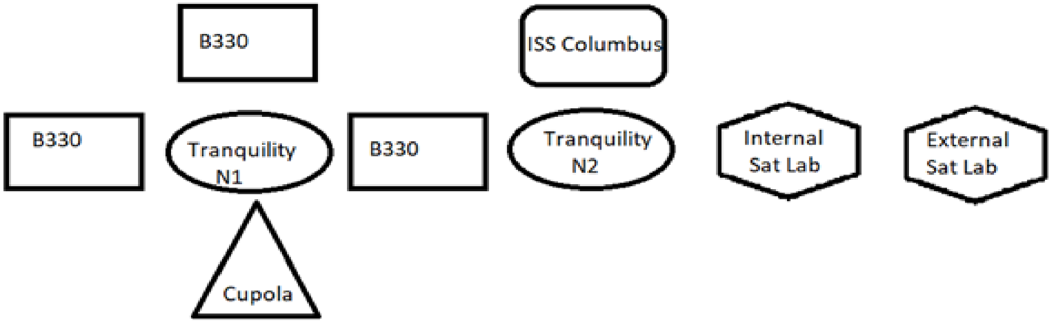


Appendix I (Breakdown of patents within the five target technical fields, broken down by jurisdiction)



Appendix J (Gateway Earth GEO Station Schema)

From Venkataraman, Leslie, Anderson and Vidmar (2020) [48].



Appendix K (Revenue Streams for Gateway Earth)