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Gateway Earth Taking Off: Detailing Infrastructure and Mission Logistics

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Abstract

Gateway Earth Development Group is an international think-tank proposing new modular space access architecture, centred on operating a combined research space station and commercial space hotel in the geostationary orbit (GEO) – the Gateway Earth complex. At this location, robotic and crewed interplanetary spacecraft could be assembled, including through utilising in-situ (additive) manufactured components, and dock before they travel to, and return from, any Solar System destination. Moreover, space tourism and GEO satellite maintenance could provide a significant part of the funding to build and maintain the complex. Our current work is related to creating a detailed infrastructure development and mission operation programme, with particular focus on incorporating new technologies (such as electric propulsion, and inflatable/configurable habitats) and innovative efficiencies (re-usability and re-deployment of access vehicles and on-orbit assets). Specifically, a detailed deployment analysis is being undertaken as well as further valorisation of the complex market opportunity. In this paper we will present the current state of play in our proposal and solicit comments as to further improvements.

Keywords: Space Access, Modular Architecture, Future, Space Exploration

Nomenclature

Δv	delta-v, required impulse to perform maneuver
r	orbital radius
G	gravitational constant = 6.67408×10^{-11} m^3 kg^{-1} s^{-2}
M	mass of Earth = 5.972×10^{24} kg
α	required angle between spacecraft and target
t	time taken to perform orbital transfer
a	semi-major axis of orbit
v	speed of spacecraft
g_0	standard acceleration due to gravity = 9.80665 ms^{-2}
I_{sp}	specific impulse
m_0	rocket initial mass (including fuel)
m_f	rocket dry mass
m_{fuel}	fuel mass
Δi	change in orbital inclination
Δv_{Hn}	nth burn of Hohmann transfer delta-v
Δv_{Bn}	nth burn of bi-elliptic transfer delta-v
X_H	relating to Hohmann transfer
X_B	relating to bi-elliptic transfer
r_n	nth orbital radius in transfer
$v_{1/2}$	speed before/after engine burn

Acronyms/Abbreviations

GE	Gateway Earth
GEO	Geostationary Orbit
GMAT	General Mission Analysis Tool
ISS	International Space Station
LEO	Low Earth Orbit

1. Introduction

Gateway Earth (GE) is a proposed geostationary space station. It will be used for research and will generate revenue from satellite servicing and acting as a commercial space hotel. It is also an attempt to lower the cost of interplanetary travel by manufacturing spacecraft in space. Geostationary orbits are close to the top of the Earth's gravity well so it requires far less energy to reach other planets from here than launches from the Earth's surface. Since spacecraft won't need to withstand the Earth's atmosphere or be aerodynamic, they can also be made lighter, so less fuel is required to reach the same destination.

The planned GE architecture includes the station in geosynchronous equatorial orbit (GEO) as well as a station in low earth orbit (LEO). A reusable launch will carry space tourists and astronauts to the LEO node. There will also be regular reusable launches of supplies. Two types of tug will operate between the LEO and GEO node: a manned one to carry passengers, and a cargo one to carry supplies. There will also be a tug refuelling station in LEO which will receive regular fuel top-ups.

The journey from Earth to the LEO node will be outlined, with the optimal launch site discussed, and the possible ways the manned tug could transfer between the LEO and GEO nodes will be compared. As well as this, the supplies needed on each resupply mission and the method for refuelling both tugs along with potential positions for the station will be discussed.

2. Launch Sites

The ideal launch site would already have the necessary infrastructure in place and be as close to the equator as possible. It would also have a large vacant area to the east, such as an ocean or uninhabited land, where debris from launches can safely fall.

Launching east is advantageous as the rocket receives a boost from the Earth's eastward rotation, and this effect is greatest at the Equator [1]. Launching from near the equator also means that the inclination change required to reach a geostationary orbit is low. The lowest possible initial orbit inclination that can be achieved is equal to the latitude of the launch site [2], and the required delta-v to change orbital inclination is large and costly. This means that when launching from near the equator the delta-v, and therefore mass of fuel, required to reach the same orbit is smaller and payload mass can be increased. Therefore, it is cheaper and far more efficient to launch from near the equator.

There are three countries which are on the equator and have an expanse of ocean to the east. These are Brazil, Somalia and Indonesia.

Brazil already has a near-equatorial launch site, Alcântara Launch Centre, at 2.34° south of the equator. So far it has mainly been used for launching sounding rockets [3]. If launch facilities could be built to support each of the launch vehicles to be used in the running of GE then this could be an ideal launch site.

The same can be said for a spaceport which is planned to be built in Indonesia. Its location will be either Morotai in North Maluku or Biak in Papua [4], both within a few degrees of the equator.

Table 1 lists the launch sites for the baseline launch vehicles previously selected for the deployment and operations of GE [5]. Their latitudes are also listed. Of these sites, Guiana Space Centre is closest to the equator with latitude 5.26°N. It would also be worth considering building new launch facilities here to support the other launch vehicles.

Although Vandenberg Air Force Base lacks a large vacant area to the east, the launch vehicles with facilities here can also be launched from the other two more suitable sites in the USA.

Table 1. Launch sites for baseline launch vehicles previously selected for deployment and operations of GE.

Launch Site	Latitude
Cape Canaveral Air Force Station, Florida, USA	28.56197°N
Kennedy Space Center, Florida, USA	28.6082°N
Vandenberg Air Force Base, California, USA	34.74202°N
Guiana Space Centre, French Guiana, France	5.26258°N

The possibility of building an entirely new launch site even closer to the equator could also be considered, though this may not be cost effective.

Of course, building new launch facilities would be expensive and so may be something which can't be undertaken until GE has built up sufficient profit. The availability of suitable land and legal issues would also need to be taken into consideration.

Fig. 1 shows a map of the launch sites mentioned.

Fig. 1. Locations of rocket launch sites discussed. Red: Alcântara Launch Centre, Orange: Morotai, Yellow: Biak, Green: Guiana Space Centre, Blue: Cape Canaveral Air Force Station and Kennedy Space Centre (overlapping), Purple: Vandenberg Air Force Base

3. Station Positioning

The position of the GE station is an important part of the planning of the mission as placing the station in a non-optimal position may have serious effects on the efficiency of getting spacecraft to it or the ability of the station to perform commercial duties such as satellite servicing.

To make transporting spacecraft to the station and travelling to geostationary satellites in orbit as easy as possible, the station should be placed at zero inclination, so only the eastern coordinate above the earth's surface needs to be determined.

3.1 Satellite Regulations

The basic rules for sending a satellite into outer space are outlined in the United Nations Treaties and Principles on Outer Space. This article sets out rules for the exploration of space in general as well as the responsibilities and liabilities of states that send objects into space. The only relevant information for this report is the section on sending objects into orbit, Section D. Article IV of Section D states that there is a registry kept by the UN Secretary-General that contains all relevant information about the satellites currently orbiting Earth. This registry is called the Online Index of Objects Launched into Outer Space [6]. There are over 8000 satellites orbiting Earth, with various different orbital heights

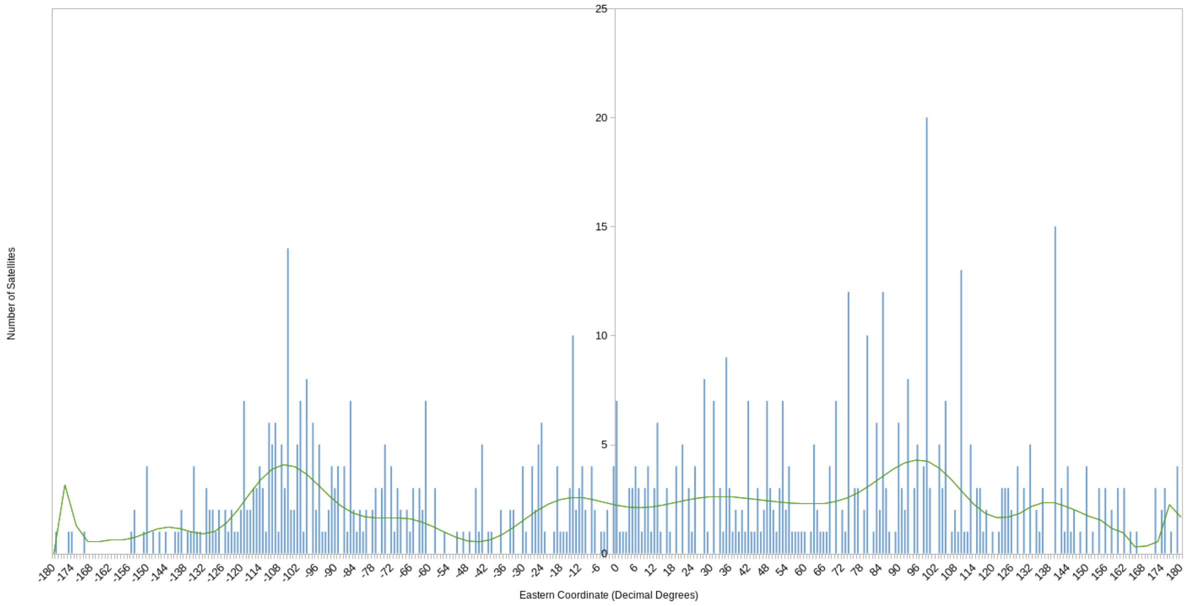

Fig. 2. A graph showing the density of satellites in GEO at each Eastern decimal degree above the equator.

and positions, however there is a filter function that can be used to narrow down the results.

Firstly, applying the filter that removes all as yet unregistered objects removes objects there is no information about and secondly, applying the filter to only return objects in Geosynchronous orbit is useful since that is the orbital distance proposed for Gateway Earth. Additionally, the Eastern coordinate for each satellite in Geosynchronous orbit is given, which can be used to rule out certain positions for Gateway Earth.

3.2 Optimal Station Position

Two positions suggested for the Gateway Earth station were above the Pacific and Atlantic Oceans. This gives a decimal degree coordinate of around 105° to -120° or -15° to -75° respectively assuming that the station is at zero inclination.

Using the data from the Online Index of Objects Launched into Outer Space on the UNOOSA (United Nations Office for Outer Space Affairs) website, a map of the density of satellites in Geosynchronous Orbit was created. Using a Python script to read the raw HTML code from the website, the Eastern decimal degree coordinate corresponding to each satellite's position above the Earth was extracted and collated in a histogram. Many of the satellites had no position data and the data in some entries was misleading or corrupt, so the density map created is not fully accurate. However, it is the best approximation possible with the available data.

There are far fewer other satellites over the Pacific Ocean than the Atlantic Ocean (see Fig. 2) and since the Gateway Earth station will be relatively large in comparison to a regular satellite, it may be advisable to position it in an area with lower satellite density to reduce the chance of collision while being positioned after launch. Using this as the main criterion for positioning of the station, it should be positioned somewhere around -160° East. This is above the Pacific Ocean which was one of the desired positions. However, since one of the main sources of income for the station is expected to be the repair of satellites also in geosynchronous orbit, being close to an area of high satellite density may make this job much easier. Using this, as well as collision chance reduction, as our positioning criteria, another possible position for the station is around -50° East. This is an area of relatively low satellite density with an abundance of satellites close by both above the US to the West and above Europe to the East. It is also just above the Atlantic Ocean, which was the other desired position.

Overall, it appears that there are advantages to placing the station over either the Pacific or Atlantic Oceans. The decision as to which is more suitable can be made once the exact functioning of the station and its commercial and governmental operations are better known as, by this time, the position criteria for optimal operation of the station will be clearer.

4. Getting to Gateway Earth

4.1 Orbital Transfers

The most fuel efficient orbit transfer is the Hohmann Transfer [7]. It requires two engine burns. The first burn moves the spacecraft into an elliptical orbit with periapsis at the initial radius and apoapsis at the desired radius. The second burn is performed at apoapsis and circularises the orbit so that the spacecraft is moving in a circular orbit at the desired altitude. The total delta-v requirement for a Hohmann transfer is given by Equations 1-3. The required angle between a spacecraft and its target when the Hohmann transfer is initiated is given by Equation 4. For safety, the transfer should be delayed until the angle is slightly smaller than this so that the spacecraft doesn't crash into its target. The time taken to perform a Hohmann transfer can be calculated using Equation 5.

$$\Delta v_{H1} = \sqrt{\frac{GM}{r_1}}\left(\sqrt{\frac{2r_2}{r_1+r_2}} - 1\right) \quad (1)$$

$$\Delta v_{H2} = \sqrt{\frac{GM}{r_2}}\left(1 - \sqrt{\frac{2r_1}{r_1+r_2}}\right) \quad (2)$$

$$\Delta v_H = \Delta v_{H1} + \Delta v_{H2} \quad (3)$$

$$\alpha_H = \pi\left(1 - \frac{1}{2\sqrt{2}}\sqrt{\left(\frac{r_1}{r_2}+1\right)^3}\right) \quad (4)$$

$$t_H = \pi\sqrt{\frac{(r_1+r_2)^3}{8GM}} \quad (5)$$

A Bi-Elliptic Transfer uses three engine burns. The first burn raises the apoapsis of the spacecraft to the "apoapsis radius" where the second burn is then performed to raise the periapsis to the target altitude. The third burn, performed at periapsis, then circularises the orbit. The total delta-v required for a bi-elliptic transfer can be calculated using Equations 6-9, where the semi-major axes of the first and second elliptical orbit are given by Equations 10 and 11 respectively. The time taken to perform the manoeuvre is given by Equation 12. The required angle between a spacecraft and its target when the bi-elliptic transfer is initiated is given by Equation 13. Again, for safety, the transfer should be performed when the angle is slightly smaller than this.

$$\Delta v_{B1} = \sqrt{\frac{2GM}{r_1} - \frac{GM}{a_1}} - \sqrt{\frac{GM}{r_1}} \quad (6)$$

$$\Delta v_{B2} = \sqrt{\frac{2GM}{r_2} - \frac{GM}{a_2}} - \sqrt{\frac{2GM}{r_2} - \frac{GM}{a_1}} \quad (7)$$

$$\Delta v_{B3} = \sqrt{\frac{2GM}{r_3} - \frac{GM}{a_2}} - \sqrt{\frac{GM}{r_3}} \quad (8)$$

$$\Delta v_B = \Delta v_{B1} + \Delta v_{B2} + \Delta v_{B3} \quad (9)$$

$$a_1 = \frac{r_1+r_2}{2} \quad (10)$$

$$a_2 = \frac{r_2+r_3}{2} \quad (11)$$

$$t_B = \pi\sqrt{\frac{{a_1}^3}{GM}} + \pi\sqrt{\frac{{a_2}^3}{GM}} \quad (12)$$

$$\alpha_B = 2\pi - t_{bi-elliptic}\sqrt{\frac{GM}{{r_3}^3}} \quad (13)$$

Changes in inclination can be costly in delta-v. It is more efficient to perform a combined manoeuvre instead of separately performing an inclination change and a burn to move to a different orbit (e.g. circularisation). The delta-v requirement of a combined manoeuvre is given by Equation 14. Equation 15 gives the velocity of the spacecraft at a specific point in its orbit.

$$\Delta v_{combined} = \sqrt{{v_1}^2 + {v_2}^2 - 2v_1v_2\cos\Delta i} \quad (14)$$

$$v^2 = GM\left(\frac{2}{r} - \frac{1}{a}\right) \quad (15)$$

Equation 16 is the Tsiolkovsky Rocket Equation. It gives the maximum total delta-v which can be provided by a rocket. This equation can be rearranged to give the mass of fuel required for a given delta-v (Equation 17).

$$\Delta v = I_{sp}g_0 \ln\frac{m_0}{m_f} \quad (16)$$

$$m_{fuel} = m_0 - m_f = m_f\left(e^{\Delta v/g_0 I_{sp}} - 1\right) \quad (17)$$

4.2 Earth to LEO

The journey from Earth to the ISS is well-established, with several launches per year [8]. This was used as the basis for the launch to the LEO node [9] [10]. It is most efficient to launch just after the LEO node orbit passes over the launch site so that the spacecraft is aligned with the target orbit. Fig. 3 shows the path taken as simulated in NASA's General Mission Analysis Tool (GMAT). A breakdown of the manoeuvres and timings is given in Table 2 (See Appendix A).

The launch of the spacecraft into orbit is shown in red. The exact altitude of the insertion orbit, shown in yellow, isn't known precisely in advance due to unpredictability in the launch, but it is around 220 km.

From the insertion orbit, a Hohmann transfer (light blue) is performed to reach the phasing orbit (purple). While in the phasing orbit, the angle between the spacecraft and the LEO node is decreased to the desired value.

Then a bi-elliptic transfer (first ellipse orange, second ellipse green) is used to move up to the LEO node orbit (dark blue). A bi-elliptic transfer is used since the final burn is significantly reduced when compared to that of a Hohmann transfer. The very small increase in fuel required for this manoeuvre is worth the decrease in risk to the LEO node and crew members.

The rest of the rendezvous process is fully automated, carried out by the on-board computer. This is not shown in Fig. 3.

When the apoapsis radius was varied there was little difference in the total delta-v, but a higher apoapsis altitude reduced the final delta-v. The radius was therefore chosen to be 10km below the LEO node orbit to keep the final burn small but also to maintain a safe distance from the LEO node.

The mass of fuel required for this launch depends on the hardware used and can be calculated using Equation 17.

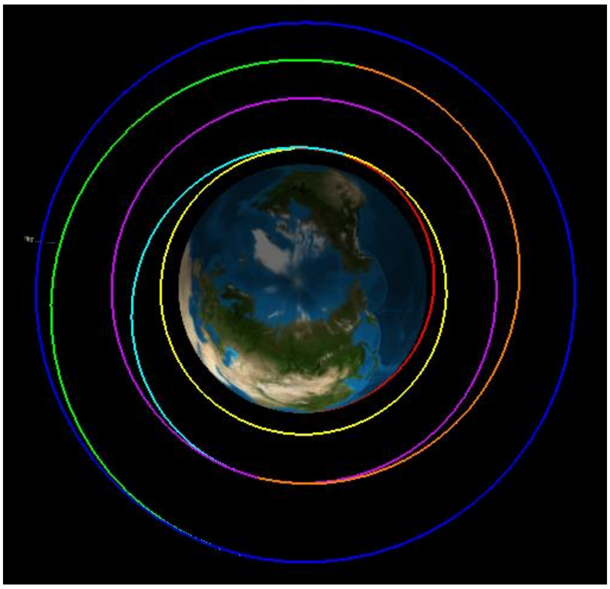

Fig. 3. Path from Earth at 0° Latitude to LEO node at 0° inclination, as simulated NASA's General Mission Analysis Tool (GMAT). Not to scale – orbital radii have been made larger to make each manoeuvre clearer.

4.3 LEO to GEO

The spacecraft for the manned tug has previously been assumed to have a dry mass of 6t, including security margin and crew [5]. The engine chosen for the manned tug was Rocketdyne's XLR-132 which has specific impulse 340s.

A couple of constraints were set on the journey of the manned tug [5]. The first was that no more than 56t of fuel should be used for a return journey to keep the number of refuelling launches sustainable. The second was that the journey time one way should be under 12 hours to reduce exposure of passengers to radiation and in the interest of tourists' comfort.

The most efficient way for the manned tug to travel from the LEO node to the GEO node is through a Hohmann transfer, as shown in Fig. 4. A breakdown of the transfer is given in Table 3 (See Appendix A). For a Hohmann transfer, the journey from GEO to LEO is the journey from LEO to GEO performed in reverse [11].

A Bi-Elliptic Transfer is less efficient than a Hohmann Transfer. However, it is still worth considering due to the increased safety. Fig. 5 shows a bi-elliptic transfer between LEO and GEO as simulated in GMAT and Table 4 (See Appendix A) gives a breakdown of the transfer.

The apoapsis radius was chosen as the value which minimises the final delta-v while keeping journey time under 12 hours.

For the journey from GEO to the LEO node a lower apoapsis radius was chosen so that the final delta-v was minimised. This also led to a shorter journey time and lower total delta-v. A breakdown is shown in Table 5 (See Appendix A).

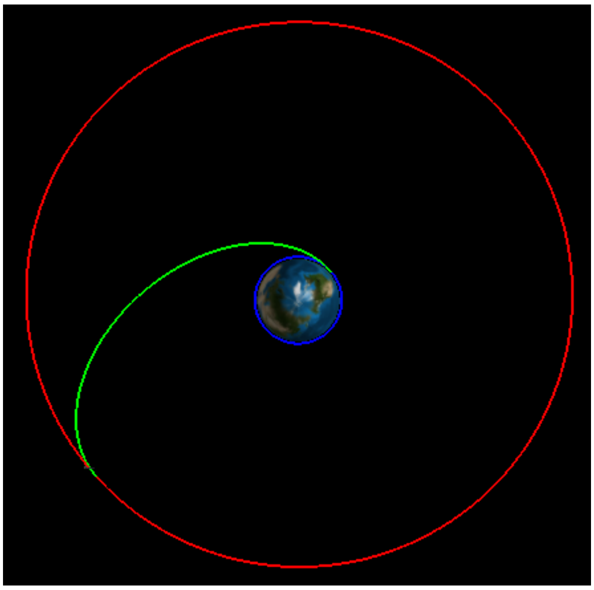

Fig. 4. Hohmann transfer from LEO Node to GEO Node with no inclination change, as simulated in GMAT.

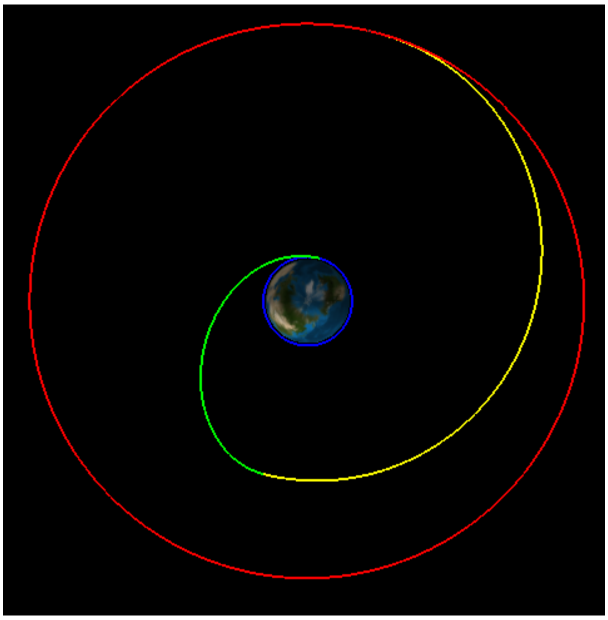

Fig. 5. Bi-Elliptic transfer from LEO Node to GEO Node with no inclination change, as simulated in GMAT.

Table 6 shows the total mass of fuel required for a return journey of the manned tug for each transfer type. The journey remains under the 56t limit for a Hohmann transfer, but is 5t above it using a bi-elliptic transfer.

Table 6. Mass of fuel required for a return journey between the LEO and GEO nodes using Hohmann and bi-elliptic transfers.

Transfer	Return Δv (kms^{-1})	Fuel (t)
Hohmann	7.719	54.56
Bi-Elliptic	8.048	61.02

These calculations assume that the LEO and GEO nodes are both at the same inclination. A change in inclination can be combined with the burns in an orbital transfer. Tables 7 and 8 (See Appendix B) show the delta-v required for an inclination change from ISS to zero inclination combined with a Hohmann and bi-elliptic transfer respectively. Tables 9 and 10 (See Appendix B) show the delta-v requirement changing inclination from that of the French Guiana launch site to zero combined with a Hohmann and bi-elliptic transfer respectively. The inclination changes are spread over the different burns so as to minimise the total delta-v requirement.

An inclination change from ISS to zero inclination greatly increases the amount of fuel required for a return journey to well over the 56t limit for both types of transfer. For the inclination change from the French Guiana site to zero inclination the fuel required changes very little from the return journey without inclination change, and is still under 56t for the Hohmann transfer. The maximum inclination change that can be performed during a Hohmann transfer while remaining under the 56t limit was found to be 9.17°. So that these reductions in inclinations can be performed in conjunction with the transfer burns, as well as achieving a specific angle at the start of the transfer, the spacecraft must also be at a point where its orbit intersects that of the target inclination. This reduces the number of opportunities for the tug to travel between nodes.

Overall, the Hohmann transfer is more fuel efficient, remaining under the 56t limit even for some small inclination changes. The journey time is also shorter than for a bi-elliptic transfer.

However, the bi-elliptic transfer has the advantage of being able to minimise the final delta-v for increased safety. It can also remain under the 12 hour limit for journey time, taking not much longer than a Hohmann transfer on the return to LEO from GEO.

The bi-elliptic transfer does exceed the 56t limit. However, this number was based on the average performance mass to LEO (62t) of New Glenn (70t) and Falcon Heavy (54t) accounting for 10% of that being the mass of the tank [5]. If New Glenn could be used for all refuelling launches then, including the 10% tank mass, the fuel limit for the manned tug return journey could be raised to 63t. This is enough for the bi-elliptic transfer to be feasible, even with small inclination changes. Other ways of sending fuel to LEO are also possible (see Section 6).

The increase in safety from using a bi-elliptic transfer is arguably worth the additional fuel required. It is definitely worth at least using a bi-elliptic transfer travelling from GEO to LEO as it is only slightly less fuel efficient and the final burn is significantly reduced compared to a Hohmann transfer.

4.4 Potential Solutions to Cost of Inclination Change

Inclination changes are very costly and requiring the tugs to transfer between ISS inclination and zero inclination every journey is clearly unsustainable. The ideal situation would be to have the launch site, LEO node and GEO node all at the same inclination. Small inclination changes are also worth considering since they don't have too large of an effect on the total delta-v requirement, so don't make costs and fuel requirements completely unreasonable.

The GEO node of the GE architecture should remain at zero inclination. Part of the business model includes generating revenue from satellite servicing. The geostationary orbit, rather than geosynchronous, is better suited for this activity.

It is clear that the ISS cannot realistically be used as the LEO node. At the time of writing, no plans for a LEO space station at zero inclination have been announced, though they may be in the future. It may be necessary to construct a new LEO space station for GE at either zero or low inclination. The cost of doing this needs to be researched further

Using the same mass and specific impulse values as for the manned tug, it appears that it would be more efficient to do a small inclination change in the Earth to LEO phase than in the LEO to GEO phase. Further calculations need to be done using the relevant values for the different launch vehicles to confirm whether this is the case.

If the LEO node were at a low inclination instead of zero, a wider range of launch latitudes could be used which wouldn't require an inclination change from Earth to LEO. However, overall the best option seems to be to launch from sites close to equator, such as those in French Guiana, Brazil and Indonesia, to the LEO node at zero inclination.

5. Supply Tug Cargo Manifest

Deciding what supplies to take on resupply missions and how much of each one is a complex process. As well as how much of each supply is needed per day, the maximum payload mass of the spacecraft used to make the deliveries must be considered.

Up until now Gateway Earth has assumed that one resupply mission every 10 weeks with a 5.9T payload would be sufficient, using the follow supply breakdown [12]:

- 2964kg for commercial activity supplies
- 2098kg for food
- 315kg for waste collection and management248kg for clothing
- 232kg for housekeeping supplies
- 85kg for personal hygiene supplies

However, there does not appear to be any evidence from other sources to back up these figures. A more in-depth calculation of the required supplies is carried out below.

5.1 Food

NASA reports that, on the ISS, an average astronaut eats 0.83kg of food per meal [13]. This means that, based on 14 astronauts eating 3 meals a day for 70 days plus a 15% margin, 2806kg of food are required. This is over 700kg more than what was first thought, which will result in either cuts to other supply types or more frequent resupplies.

5.2 Water

The initial Gateway Earth study into the payload of the supply tug did not include provisions to replace the water on the station. The ISS has one of the most efficient possible water processors, but there are, as yet, no 100% efficient water recycling options available. So, even if the Gateway Earth water processing system is as efficient as that of the ISS, water will still need to be transported to the station to make up for what is lost during recycling.

According to NASA data, astronauts have an allowance of 2.42kg (equivalent to 2.42L) of water per day: 1.62kg for drinking and 0.80kg for cooking, plus a small margin of around 0.5kg per day [13, 14]. If we assume gateway earth astronauts use around 3kg of water per person per day including a margin to ensure stock never runs out, the mass of water used in 70 days for 14 astronauts will be 2940kg. This is obviously a huge percentage of the resupply payload mass, but the use of a water processing system can recycle a lot of water, severely reducing the need for water resupply.

The water processing system on the ISS processes between 9.17kg and 13.60kg of water per person per day, giving an average of 11.39kg of water per person per day. From this, the water processor produces an average of 10.52kg of water per person per day. These figures result in the ISS recovering 92.36% of its waste water on average [15].

If these figures are extrapolated to Gateway Earth, we find that, with a water usage of 2940kg including margin and a recovery rate of 92.36%, the net water loss of the station over 70 days is 225kg. Therefore, if this amount of water is transported to Gateway Earth every resupply, then the station should never run out of water. There will also need to be a 20-week stock of water on the station, as for food, in case of two no-shows from the resupply tug. This will further reduce the chance of running out of water.

5.3 Clothing

NASA also provides information about the clothing required for astronauts on the ISS. There are no washing facilities on the ISS nor are there any plans to install them on Gateway Earth, so all clothing must be disposable. For this reason, clothing is worn for much longer on the ISS than it might be on Earth. Clothes are worn to the following schedule on the ISS:

- T-shirts -- changed every 10 days
- Work shirts and trousers/shorts -- changed every 10 days
- Underwear and socks -- changed every 2 days
- Thick socks -- changed every month (28 days)
- Exercise shorts and t-shirt -- changed every 3 days of exercising

In addition to this, the astronauts also receive two sweaters and two pairs of shoes (one for using the treadmill and one for using the exercise bike) for the whole trip [16].

Assuming Gateway Earth employs a similar policy on clothing, a resupply is carried out every 10 weeks and each astronaut exercises everyday as on all NASA missions [17], each astronaut would require:

- 7 t-shirts
- 7 work shirts
- 7 pairs of work trousers or shorts
- 35 pairs of socks
- 35 pairs of underwear
- 3 pairs of thick socks
- 13 exercise t-shirts (assuming one is worn for 4 days to remove the need for a clean one for 1 day)
- 13 pairs of exercise shorts (again, assuming one pair are worn for 4 days to remove the need for a clean pair for 1 day)
- 2 pairs of shoes
- 2 sweaters

It is feasible that, since the astronauts keep them for their whole stay, the shoes and sweaters could be transported in the manned tug, thereby reducing the load needed for each resupply. The mass of clothing required per resupply per astronaut is 22.47kg for men and 18.11kg for women where socks have been assumed to weigh 85g and 140g for a thin and thick pair respectively, work trousers have been assumed to weigh 700g per pair, work shirts have been assumed to weigh 300g per shirt and all other clothing was assumed to weigh the middle of the av1erage weight for that clothing type [118]. Assuming a half male and half female team of 14 astronauts, this equates to around 284kg of clothing per resupply. If it is not possible to take the sweaters and shoes on the manned tug, these will add around 2.55kg per astronaut (regardless of sex), bringing the total up to around 320kg of clothing per resupply. Adding a 15% margin to these numbers we get 327kg and 368kg respectively.

Again, the previous estimate for clothing is too low based on observations from the operation of the ISS; a further 79kg of clothing are needed even in the best-case scenario when the manned tug is used to transport some clothing.

5.4 Waste Management

There is no data available about the exact mass of waste management supplies are sent to the ISS per resupply. However, from attempting to consider all forms of waste that may occur and the methods by which the waste can be dealt with, the waste management mass given in Gateway Earth's report is possibly an overestimate.

The only waste management products that will be required are bags for collecting solid human waste, storage bags for used clothing and rubbish bags to collect used packaging from food and personal hygiene products. All of these things are relatively light: the total mass of storage bags for packaging and clothing should not be more than 10kg. In fact, if we assume a plastic bag is 30g, and one bag is required for packaging and one for clothing per week, then only 4.2kg of bags are required. Budgeting 20kg allows for heavier duty bags or more bags in case they are needed once the running of the station is better understood.

The human waste bags will weigh more since these need to be heavy duty to prevent contamination and more of them will be required since people digest food faster in microgravity. If we assume each bag weighs 100g and each astronaut needs up to 4 bags per day, then 28kg of bags are required.

This results in a total of 48kg of waste disposal products per resupply. Adding a 15% margin as has been done with previous estimations gives a total mass of around 55kg. This is significantly less than was previously estimated, with a saving of 260kg.

5.5 Personal Hygiene Products

Again, there is no real data for the mass of personal hygiene products required on the ISS. However, the only required personal hygiene supplies are toothpaste, a toothbrush and a means for astronauts to clean their bodies. On Earth, one person will use around two 150g tubes of toothpaste every 10 weeks, meaning only 300g of toothpaste are required per person. Also, allowing a total of around 4kg of soap and shampoo (2kg of each) per person for the 10-week period sounds reasonable. Only one toothbrush should be required for each person on the station for each supply run, about 50g per person.

This all totals to around 4.35kg of supplies per person per resupply while the original estimate was that 85kg would be required for everyone on the station. This leaves each person a budget of about 6.05kg, meaning that each person has 1.7kg of space available. This additional space could be filled with any specialist hygiene supplies that a given astronaut may want or require to make their lives on the station more comfortable.

The only addition to the budget that could be suggested is to add a 5kg allowance for medical supplies to be delivered to the station. There would not be any large equipment required but small first aid kits should be maintained on the station.

Overall, the budget for personal hygiene supplies seems reasonable and would supply all that is needed for the astronauts with enough left over to have a couple of luxuries. Adding 5kg for the medical supplies, the allowance becomes 90kg.

5.6 Housekeeping Supplies

Housekeeping supplies are vital on a space station to get rid of both physical and chemical contaminants as soon as possible. Things like dust and crumbs become a lot more dangerous on a space station where they can possibly float into astronauts' eyes and cause serious damage. Even strong smells can be an issue since the gases that make them up are recirculated and never leave the station. The same issue arises from anything that gives off any harmful gas because this will also recirculate, and the astronauts will continuously inhale it, possibly causing serious damage to health.

To keep the station clean, the astronauts will require a few supplies: paper towels and wet wipes to clean up minor spillages, a vacuum cleaner to remove dust from surfaces and air vents and a hazardous substance cleaning kit. If we assume that one packet of paper towels and one packet of wet wipes per week, and we assume that these weigh about 500g and 1kg each respectively, then 10.5kg of basic cleaning supplies are required per resupply. Around one vacuum cleaner bag per week will be required, resulting in 7kg of bags assuming they weigh around 1kg each. Assuming five hazardous waste kits are installed, each with a pair of goggles and a face mask, weighing about 1kg together, and 1kg of disposable gloves, 10kg of cleaning supplies are required for hazardous waste kits. Also, a set of heavy duty bags to dispose of the hazardous waste will be required. Assuming there are 1kg of these bags near each hazardous waste disposal kit, 5kg of these bags are required in total.

This means a total of 32.5kg of housekeeping supplies are needed; adding a 15% margin means that 38kg should be budgeted for these supplies.

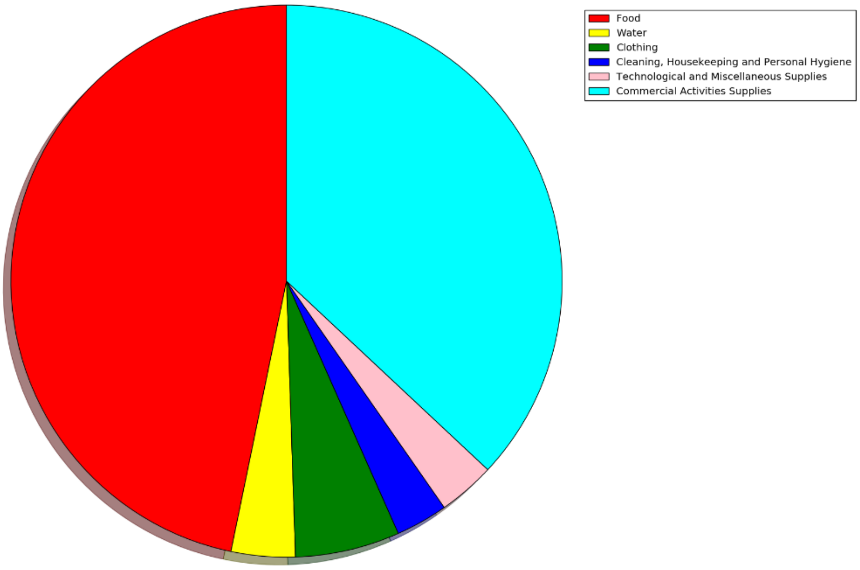

Fig. 6. A pie chart showing the relative proportions of each type of cargo to be transported on each supply tug.

This is much lower than the original estimate for housekeeping supplies of 232kg, with a saving of 194kg.

5.7 Technological and Miscellaneous Supplies

In addition to the other supplies, there will need to be a provision for some replacement parts for existing technology and parts to build new technology on the station. Also, some miscellaneous supplies may be needed, such as occasional oxygen deliveries to keep the pressure and oxygen levels inside the station safe.

The Russian Progress MS-03 resupply mission to the ISS took over 400kg of such supplies, however it seems that there was a large mass of parts for an upgrade to the water recycling system on the station on this mission [19]. Since large upgrades to the station will not be carried out every 10 weeks, it is not necessary to budget this much for every resupply. Therefore, a reasonable budget would be around 200kg.

5.8 New Proposed Cargo Manifest-

The new split of cargo is shown below:

- Food: 2806kg
- Water: 225kg
- Clothing: 327kg - 368kg
- Waste Management: 55kg
- Personal Hygiene Products: 90kg
- Housekeeping Supplies: 38kg
- Technological and Miscellaneous Supplies: 200kg
- Commercial Activities Supplies: 2218kg - 2259kg

The two options for clothing and commercial activities supplies masses depend on the method of transport for the shoes and sweaters. Also, in the case where more technological or miscellaneous supplies are needed, more mass can be taken from the commercial activities supply budget. For the purposes of visualization, the larger mass for clothing and, consequently the lower mass for commercial activities supplies, was used (see Fig. 6).

6. Orbital Refuelling

There are many advantages to using an refuelling the tugs in orbit. Doing so can significantly reduce the cost of sending repeat missions from Earth straight to GEO as this requires significantly more fuel and time. Keeping passengers travelling for too long in high-stress conditions such as flying a spacecraft can cause errors and end with injuries and damage to equipment.

6.1 Fuel Type

If a fuel depot is to be used, the type of fuel being stored must be carefully chosen. If a cryogenic fuel is used, such as hydrolox (liquid hydrogen and liquid oxygen) fuel, then it must be kept very cold. This then requires additional hardware to be added in order to cool the storage tank. If the tank is not kept cool enough, the fuel will slowly boil off, resulting in a lot of lost fuel and more resupply missions.

Other fuels, such as kerosene and monomethylhydrazine (MMH), do not need to be kept as cold as cryogenic fuels. This allows for a much larger payload of fuel to be stored in the same mass of tank since the tank does not need any special refrigeration equipment or a strong heat shield. They do, however, need an oxygen supplier due to the lack of oxygen in space.

This being said, cryogenic fuels have a much higher specific impulse. This means that a lower mass of propellant is required to fly the same mission. Since the missions from the fuel depot to Gateway Earth will be relatively common, cryogenic fuels may be a possibility because there will be less opportunity for boil-off.

The current plan for the Gateway Earth manned tug is to use MMH as the fuel and dinitrogen tetroxide (NTO) as the oxygen supplier. This is due to the optimal engine being powered by this fuel. [12] Changing the fuel to be used will likely result in having to find new engines, which may not exist. This would be a large setback and would require a new engine to be developed either by Gateway Earth or by another company before the launch of the station.

Therefore, it is likely best to stick with MMH and NTO as the combination of fuels to be used: it requires no special equipment to store and there is an engine optimal for powering the manned tug that already exists and is available.

6.2 Fuel Tank Design

The fuel tanks to be sent into orbit should be spherical, as spherical tanks are the best at holding pressurised fuel. Commercial tanks can hold MMH, on Earth, at around 25bar (2,500,000Pa) so it seems reasonable that a tank being used in space should be able to hold MMH and NTO at around 10 bar.

The ratio of the two fuels that is required can be found by examining the chemical reaction involved in the engine of the tug. The hypergolic (spontaneous upon contact) reaction between MMH and NTO is [20]:

$$CH_3(NH)NH_2 + N_2O_4 \rightarrow CH_3(N)NH + 2NOOH \quad (18)$$

From this, we can see that only one mole of MMH is needed for each mole of NTO. The molar mass of MMH is 46g mol^{-1} and the molar mass of NTO is 92g mol^{-1}, meaning that a 2:1 ratio of NTO to MMH by mass is required. With the 56T of fuel being used by the tug, this means that 18,666.7kg of MMH and 37,333.3kg of NTO are required on the tug.

The volume of the tanks needed to store these amounts of fuel can be found from the densities of the fuels. MMH has a density of 874kg m^{-3} (at 1atm, 25°C) [21] and NTO has a density of 1450kg m^{-3} (at 1atm, 20°C) [22]. Assuming a pressure of 10bar, the temperatures specified with the respective densities and the masses calculated earlier, the minimum radii of the tanks needed to hold the fuel (not accounting for any heat shielding or other extra material) are 0.802m for the MMH and 0.854m for the NTO. If we assume that the heat shield and other materials add around 20cm to the radius of each tank, then both tanks are close to 1m in radius and 2m in diameter. The whole payload section of a Falcon Heavy rocket is 5.1m in diameter and 13.1m tall (including all heat shielding and other material), meaning that the effective payload section will be smaller [23]. The exact payload area volume is not, however, published by SpaceX. Despite not knowing the exact figure for the diameter or height of the effective payload area, the tanks should fit easily as there is unlikely to be over 3m of shielding on the payload.

6.3 Refuelling Process

There are two options for refuelling the tugs in orbit: use a fuel depot structure to store fuel until it is required by the tug or use detachable fuel tanks that are sent into orbit and docked on to by the tug that needs to be refuelled.

The latter option is easier as it requires less manoeuvrability from the fuel tanks and also requires less infrastructure and fewer transfers of fuel from tank to tank. This makes it less expensive and more efficient.

6.3.1 Basic Principle for Use of Detachable Fuel Tanks

The system would work by launching two spherical tanks, containing MMH and dinitrogen tetroxide, on a Falcon Heavy rocket into LEO. The tanks would be left in an orbit behind and below the LEO node to reduce collision chances and to allow for the tug to transfer from the LEO node to the drop site more easily.

The tug will need to use residual fuel from the last set of tanks to propel itself from the LEO node to the new tank drop site. It may, therefore, be sensible to have a small fuel tank inside the tug to store enough fuel to make the journey from the LEO node to the tank drop site. This would allow the old fuel tanks to be removed on the LEO node and placed in the Dragon spacecraft that was last used for a resupply mission to be taken back to earth for reuse. This would also get rid of the need for a heat shield on the tanks, leaving only the material necessary to protect the tank from space debris and to maintain the tank pressure throughout the journey from LEO to GEO.

6.3.2 Centre of Mass Issues

The issue with using attachable fuel tanks is that the rocket engine providing thrust to the tug must apply thrust in line with the centre of mass. This presents a problem as the masses of MMH and NTO being used are vastly different. If the thrust is not applied in line with the centre of mass, then the tug would veer off in the direction of the side with greater mass and the assumed trajectories and journey times would no longer be at all accurate. There are two solutions to this issue:

- Move the thrusters so that thrust is applied in the correct direction.
- Position the tanks in such a way that the centre of mass aligns with the predetermined thruster position.

Moving the thruster such that it is applying thrust in the correct direction is relatively easy in this case since finding the centre of mass is relatively easy if the tanks are simply attached to each side of the tug. If we assume that the centre of mass of the tug is approximately in its centre (which is a sensible assumption since it is close to being cylindrical) and we call the centre of the tug the centre of the system, then the centre of mass can easily be found from the ratio of mass between the two tanks if the tanks have the same volume. Since, in our case, the masses of the two tanks are in a 2:1 ratio, the thruster needs to be placed two times the distance from the lighter tank than from the heavier tank.

The provisional design of the tug lists the height of the tug to be 4.6m [24]. Using this figure and that the tanks have a radius of approximately 1m and their centre of masses at their centres, the thruster should be placed such that the overall thrust vector is perpendicular to the back of the tug, 4.4m from the lighter tank and 2.2m from the heavier tank.

This places the centre of the thruster 1.2m from the bottom or top of the tug depending on the orientation of the tanks. If the thruster is too large for this, then a backplate might need to be added to the tug for the thruster to be mounted on. If one is needed, the backplate should extend the same distance in all directions to ensure that the centre of mass stays on the same line as before.

The other option for ensuring that thrust is applied in the correct direction is not as practical: by moving the tanks further from the tug (and therefore the thruster), the fuel will need to be pumped further from the tank before it can be used. If, however, the first option becomes impossible, moving the tanks may be the only option.

This technique relies on the same principle as the other but involves moving the tanks such that the centre of mass lines up with the thruster instead of *vice versa*. Using the same numerical values as before, we can see that, if the lighter tank is attached to the top of the tug, the heavier tanks would have to hang 3.3m away from the bottom of the tug to ensure that the centre of mass is in the centre of the tug. While a 3.3m fuel line is not too problematic, it would likely be much harder to dock the fuel tanks at this distance away from the tug. Also, the structure needed to support the tank and dock it would have its own mass which would skew the centre of mass further, therefore requiring more complex calculations to work out how far from the tug the tank needs to be.

Overall, the need to have a longer fuel line, more complex docking and a centre of mass that is harder to calculate make this method of ensuring the correct thrust much harder than the last. Therefore, the thruster should be moved to meet the centre of mass if at all possible.

6.4 Explosion Risk Mitigation

Rocket fuel is highly combustable and could cause a significant explosion if it were to ignite. This could pose a threat to both people and expensive equipment if an explosion were to occur too close to the LEO node.

Realistically, the chance of an explosion happening with the current suggested fuel type is extremely low. In order for an explosion to occur, the fuel tanks holding the MMH and dinitrogen tetroxide would have to collide with enough force to rupture both tanks and allow the fuels to mix sufficiently and even then a spark would be needed at the exact right time after the initial collision and the mixing of the two fuels to actually cause ignition.

First of all, it is incredibly unlikely that the two tanks will collide in the first place: they are to be launched in the same rocket and dropped off just after one another. Even if the tanks were accidentally dropped off at the same time, they would be moving in the same direction and at the same speed, making collision impossible. Secondly, even if a collision were to occur with some amount of force, the likelihood of both tanks rupturing is very low; it is much more likely that one of the tanks would rupture instead of both. The contents of either tank alone are not explosive in space and therefore do not represent a threat. Finally, after a collision, the tanks are very likely to quickly separate from one another while the fuels leak out and spread out very quickly. This would mean that the fuel, while it may mix a little just after the collision, will not likely reach the point at which there is a high enough concentration of fuel to cause an explosion and where the fuel is mixed well enough for the MMH to combust.

Overall, the risk of explosion from the fuel tanks is essentially negligible. However, that being said, to avoid collisions between the LEO node and the rocket carrying the fuel tanks, the tanks will likely be deposited a few kilometres behind the LEO node at a slightly lower altitude. This in itself should be enough to mitigate any damage to people of equipment in the extremely unlikely event of an explosion.

6.5 Alternative Method for Transporting Fuel Tanks into Orbit

The current plan for getting the fuel into space is to use some SpaceX Falcon Heavy and some New Glenn rockets to launch large fuel tanks into LEO to be docked straight on to the tug, with the option to send an expendable SLS rocket carrying fuel in the case of an unexpected launch [25]. This is an extremely high-cost method but it does not require any further infrastructure.

Another option would be to use a railgun to launch smaller fuel tanks into orbit. Railguns use massive currents through huge rails to create Lorentz forces great enough to accelerate objects to very high speeds. In theory, a railgun could be used to fire objects into space, however this has not yet been done.

A relatively old paper, by Pearson, sets out a detailed plan for refuelling using railguns, suggesting that it is possible for small cylindrical (apart from a heat shielded aerodynamic cone at the top and stability fins on the side) tanks of radius 0.2m and length 6m to be fired into orbit with one [26]. These tanks are too small for the purposes of GE and to store fuel at the pressures previously suggested would require spherical tanks. However, the same basic principle applies.

There is a simplified equation for the force produced by a railgun as a function of the current in the rails, the distance between the rails and the radius of the rails that can be obtained by making several approximations about its geometry. This equation is:

$$F = \frac{\mu_0 I^2}{2\pi} \ln\left(\frac{R+w}{R}\right) \quad (19)$$

Where F is the force on the railgun armature, μ_0 is the magnetic permittivity of the railgun material, I is the current in the rails, R is the radius of the rails and w is the width between the rails [27].

Using this equation in a spreadsheet, various parameters can be altered to find the best way to launch fuel into space. The delta-v required to reach LEO is around 9300km s^{-1} [28]. Assuming that the tanks are launching from stationary and are accelerating at 1800g, a railgun of approximately 2450m in length with a rail separation of 10m and cylindrical rails of radius 0.1m is required to achieve launch velocity. Currents of approximately 18.90MA and 26.72MA are needed to launch the MMH tank (mass 18,666.7kg) and the NTO tank (mass 37,333.3kg) respectively using the railgun. These are very large currents, but they are only needed for 0.527s, which is possible with a large capacitor farm. Assuming that the current is supplied at 250,000V to reduce power loss over the long rails, the launches require approximately 691,000kWh and 977,000kWh for the MMH and NTO launch respectively. This results in a launch cost of £166,800 with an energy price of £0.10 per kilowatt-hour. A Falcon Heavy Launch to LEO costs $90,000,000 (£68,467,050 at exchange rate on 25/07/2018), so using the railgun costs about 410 times less per fuel launch than using rockets.

Pre-accelerating the tanks to 1km s^{-1} as suggested by Pearson [26] would reduce the time and the rail length required, meaning that the cost of infrastructure and the cost of energy per launch would be lower. It is possible that the infrastructure and gas for the gas accelerator may outweigh the advantages, but this is something that would need to be researched further.

Overall, it is feasible that, at some point in the future, railguns may be a possible means of launching fuel tanks into orbit once several issues are addressed. Firstly, there needs to be the available funds and land to build the railgun. Secondly, there must also be a means of charging the capacitors without draining too much power from the grid—possibly by building a power station on-site which could power the railgun when needed and sell electricity as a source of income at other times. Finally, plans for ensuring that the capacitors, rails, armature (firing mechanism) and payload can all take the huge forces being exerted on them without breaking needs to be implemented.

7. Conclusions

The proposed way to reach GE is as follows:

- The reusable launch vehicle takes off from a site close to the equator such as those in French Guiana, Brazil and the planned one in Indonesia. It may be necessary to use higher latitude launch sites for some launches until enough revenue has been accumulated to build new launch facilities near the equator to support each proposed launch vehicle.
- Inclination changes are performed in conjunction with the transfer burns on the journey from Earth to the LEO node, which is at zero inclination. It may be necessary to construct a completely new space station at this inclination, unless one is announced.
- If enough fuel can be transported to the refuelling station, a bi-elliptic transfer will be performed from the LEO to the GEO node and on the way back. Otherwise, a Hohmann transfer should be performed from LEO to GEO and a bi-elliptic on the way back. In this section, no inclination changes are required.

The GE station should be positioned above the equator at either 160° East or -60° East depending on the requirements for the running of the station that will be known better closer to launch.

After the station is in operation the resupply tugs should take a payload similar to the cargo manifest outlined in Section 5.8, allowing for minor changes as the specifics of the GE mission change over the course of its further development.

Finally, the tugs should be refuelled using reusable and detachable fuel tanks that will initially be sent into orbit on SpaceX Falcon Heavy rockets with the possibility of using a railgun to transport the tanks into orbit in the future should it become more feasible to install and maintain the infrastructure involved.

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Appendix A (Breakdown of Orbital Transfers, Tables 2-5)

Table 2. Breakdown of manoeuvres and timings on journey from Earth to LEO node.

Orbit	Orbital Radius (km)	Manoeuvre	Delta-v (ms^{-1})	Time (hours)
Insertion Orbit	6591	Hohmann		
		- Burn 1	25.16	
Phasing Orbit	6677	- Burn 2	25.08	
		Total	50.24	0.75
Achieve Angle from Spacecraft to LEO Node slightly less than 2.39°				
		Bi-Elliptic		
		- Burn 1	25.82	
Apoapsis Radius	6767	- Burn 2	28.56	
LEO Node Orbit	6777	- Burn 3	-2.83	
		Total	57.21	1.53
		Total	**107.45**	**2.28**

Table 3. Breakdown of manoeuvres and timings for Hohmann transfer from LEO Node to GEO Node.

Orbit	Orbital Radius (km)	Manoeuvre	Delta-v (kms^{-1})	Time (hours)
LEO Node Orbit	6777			
Achieve Angle from Spacecraft to GE slightly less than 100.42°				
		Hohmann		
		- Burn 1	2.398	
GE Orbit	42,164	- Burn 2	1.457	
		Total	**3.855**	**5.29**

Table 4. Breakdown of manoeuvres and timings for bi-elliptic transfer from LEO Node to GEO Node.

Orbit	Orbital Radius (km)	Manoeuvre	Delta-v (kms^{-1})	Time (hours)
LEO Node Orbit	6777			
Achieve Angle from Spacecraft to GE slightly less than 179.86°				
		Bi-Elliptic		
		- Burn 1	2.034	
Apoapsis Radius	27,164	- Burn 2	1.804	
GE Orbit	42,164	- Burn 3	(-)0.353	
		Total	**4.191**	**11.98**

Table 5. Breakdown of manoeuvres and timings for bi-elliptic transfer from GEO Node to LEO Node.

Orbit	Orbital Radius (km)	Manoeuvre	Delta-v (kms^{-1})	Time (hours)
GE Orbit	42,164			
Achieve Angle from Spacecraft to LEO Node slightly more than 335.62°				
		Bi-Elliptic		
		- Burn 1	(-)1.456	
Apoapsis Radius	6787	- Burn 2	(-)2.398	
LEO Node Orbit	6777	- Burn 3	0.003	
		Total	**3.857**	**6.06**

Appendix B (Fuel Required for Orbital Transfers with Inclination Changes, Tables 7-10)

Table 7. Mass of fuel required for a return journey between the LEO (ISS inclination) and GEO (zero inclination) nodes using Hohmann transfers.

Burn	**Δi (°)**	**Δv (kms^{-1})**	**Return Δv (kms^{-1})**	**Fuel (t)**
1	2.88	2.438		
2	48.76	2.348		
Total	51.64	4.786	9.572	99.90

Table 8. Mass of fuel required for a return journey between the LEO (ISS inclination) and GEO (zero inclination) nodes using bi-elliptic transfers.

	LEO to GEO		**GEO to LEO**			
Burn	Δi (°)	Δv (kms^{-1})	Δi (°)	Δv (kms^{-1})	Return Δv (kms^{-1})	Fuel (t)
1	3.73	2.110	48.75	2.347		
2	38.69	2.783	2.89	2.438		
3	9.22	0.584	0.00	0.003		
Total	51.64	5.477	51.64	4.788	10.265	124.35

Table 9. Mass of fuel required for a return journey between the LEO (French Guiana inclination) and GEO (zero inclination) nodes using Hohmann transfers.

Burn	**Δi (°)**	**Δv (kms^{-1})**	**Return Δv (kms^{-1})**	**Fuel (t)**
1	0.50	2.399		
2	4.76	1.468		
Total	5.26	3.867	7.734	55.04

Table 10. Mass of fuel required for a return journey between the LEO (French Guiana inclination) and GEO (zero inclination) nodes using bi-elliptic transfers.

	LEO to GEO		**GEO to LEO**			
Burn	Δi (°)	Δv (kms^{-1})	Δi (°)	Δv (kms^{-1})	Return Δv (kms^{-1})	Fuel (t)
1	0.58	2.035	4.76	1.467		
2	3.78	1.816	0.50	2.399		
3	0.9	0.356	0.00	0.003		
Total	5.26	4.207	5.26	3.869	8.076	61.63

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