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"Gateway Earth" – Low Cost Access to Interplanetary Space

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INTRODUCTION

The paper describes some aspects of a proposed space development whose aim is to dramatically reduce the cost of missions, both crewed and robotic, to anywhere in the solar system. The concept uses a funding mechanism combining governmental and commercial financing working in new ways together. The aim is to enable interplanetary space transportation and exploration within realistic funding projections.

The basic architecture uses a combined governmental/commercial space station ("Gateway Earth") located in geostationary orbit (near the edge of Earth's gravity well) and a logistical supply chain of reusable tugs going regularly between LEO (Low Earth Orbit) and GEO (Geostationary Orbit) and back. Part of the commercial station would be a GEO space tourist hotel. Other commercial uses of the Gateway complex would include servicing of GEO communications satellites. "Gateway Earth", the station at the edge of interplanetary space, would consequently be partly funded by space tourism revenues, as would also be the operation of the tugs. It's a way of exploring the solar system by using space tourism revenues to augment government funding.

The paper addresses some design implications of including an industrial scale 3-D manufacturing facility at the Gateway complex, for building and assembling components of craft intended for ongoing interplanetary travel. Elements of a business case framework are presented, using market analogs for this next destination of space tourists beyond LEO, which supports the argument that the "Gateway Earth" architecture represents a way to achieve relatively low cost interplanetary travel.

SUMMARY OF RATIONALE

The case has been made many times, going back at least to von Braun and Tsiolkovsky, for why we need to develop our capabilities to access interplanetary space (one reason is that, eventually, life on Earth will become unsustainable due to a range of inevitable long term astronomical factors). The initial robotic explorers will, therefore, eventually need to be followed by craft carrying human occupants. The difficulty in practice has always been in finding ways to finance such ventures. There has been an implicit miss-match between the associated time frame of government funding for such long time-frame eventualities (as, eg, stellar evolution of our star, the Sun) in relation to the short term presidential and budget cycles. Apollo, funded at about 5% of the US GDP throughout the 1960's, was conceived and funded as a reaction to a perceived *imminent* national threat. Current NASA funding levels are nearer 0.5% of GDP, and likely to remain at that level for the foreseeable future (since that level reflects the public's reaction in opinion polls). The way forward, it would seem, is to use the notion of economic development in space to augment the public funding contribution. Are there enough commercial markets in space to make this feasible? The author believes the answer is in the affirmative, provided enough time is allowed for their development. The first such markets are going to be in space tourism. Then there could be satellite servicing and refueling markets. And ultimately asteroid mining and other uses of the unlimited resources of space. References 1-9 provide further documentation on this joint governmental/private funding concept.

Reduced to its simplest form, the issue is how to regularly, and at low cost, get from the surface of the Earth, out of Earth's gravity well, and across the relatively flat geopotential plateau to the edge of the gravity wells of neighboring planets. Reusability becomes an essential element of any proposed architectural solution. Figure 1 provides an overview of the proposed architecture. Steps 3, 4, 5 are in fact interrelated and carried out in parallel. Although the Figure represents the near-Earth neighborhood, the approach is equally applicable to any interplanetary destination at any point across the relatively flat geopotential plateau.

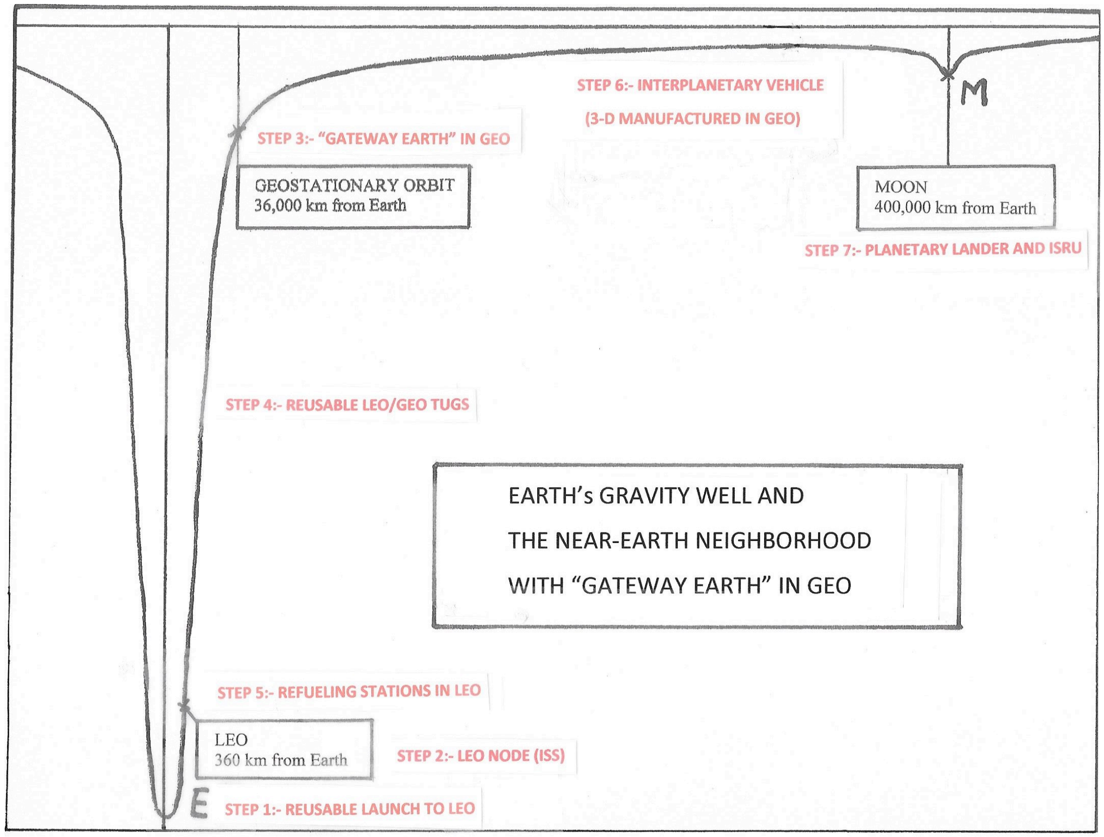

Fig 1. Overall 7-Step Process for Regular Interplanetary Travel (Credit: Author)

The proposed solution is a 7 stage infrastructure (Ref 9), a key focal point of which (Step 3) is to install "Gateway Earth" more or less near the rim of Earth's gravity well. This then becomes the effective start and end point for interplanetary missions. At the Gateway, the interplanetary vehicles are built and assembled (Step 6). The Gateway is also the place to where the vehicles return after their journeys. Therefore, the interplanetary vehicles themselves do not need to be built to withstand the rigors of a launch from Earth's surface, either from the point of view of structural strength or aerodynamics. And furthermore, they do not need to possess the weighty thermal control system associated with atmospheric re-entry, or the powerful motors needed to provide the energy for getting from the Earth to GEO. Another way of thinking from the "gravity well" perspective is to view the "getting to the edge" part of the operation as "powered flight", and traversing the vast interplanetary spaces as much more like "gliding". Much of the structure for the interplanetary "glider" craft can therefore be built using additive manufacturing techniques. The returning interplanetary space travelers of the future will consider "Gateway Earth" as "home" on coming back in an interplanetary Aldrin cycler from, say, the vicinity of Mars. Once they have docked at the Gateway they may return to Earth's surface using the regular tug service introduced as part of the proposed architecture (Step 4). How can the tugs be "regular'? This is because their main purpose is to shuttle back and forth between LEO and GEO to take space tourists, and their associated supplies, to their GEO space hotel. The tugs are in fact a business operation in their own right. They are refueled, and restocked, in LEO each time before they make their next trip to GEO. So a LEO refueling component is an important part of the logistical infrastructure (Step 5).

This might be provided as a separate commercial venture, or partly supported by government funding. There is a need for a continuing LEO station, such as the ISS, as the LEO node of the architecture (Step 2). Space travelers will take two effective shuttle rides to reach their interplanetary craft; first they ride up to the ISS node – then they transfer to the LEO-GEO tug. And of course the process is repeated on returning from their interplanetary trip; first they dock at "Gateway Earth", then they take the tug down to LEO, finally they take the last leg to the surface using the traditional aero-thermal braking approach for atmospheric re-entry. Only the craft designed for providing the service back and forward between Earth's surface and LEO (Step 1) needs to be designed to handle the demands of transferring each way through our atmosphere, and of course such vehicles already exist (eg Soyuz, Dragon, etc). Ongoing developments at this stage for the Earth to LEO craft are approaching the achievement of reusability, but are not discussed further in this paper.

In summary, therefore, what is proposed is a "Gateway Earth" station placed in the GEO orbit. The station itself is partly funded by space tourism and other commercial businesses; there is a regular tug service between LEO and GEO – again largely funded by commercial space businesses; and this Gateway may be used by governmental astronauts (NASA and other) both as a place to assemble interplanetary craft, and as a starting and end point for subsequent journeys across the solar system gravity plateau. Almost the entire system is reusable. The governmental space program budgets only need to provide funding for *part* of the "Gateway Earth" complex, and for paying the operators for "taxi rides" both from Earth to LEO and from LEO to GEO. The capital costs for government are therefore limited, and this, together with the consequential lightweight/low energy design of the interplanetary spacecraft, will thereby dramatically reduce the costs compared with missions performed in the "traditional" ways. Of course, a major challenge will be the coordination between the commercial and governmental aspects of the architecture, and this is discussed later in the paper. There is a need for a flexible, rather than a monolithic planning process which is perhaps more familiar in traditional space programs. In particular, for the approach to succeed, there must be an acceptance of a timeline that recognizes the need to allow the space tourism and other commercial businesses to develop and generate revenues.

This section has so far provided an overview of 6 separate elements of the proposed "Gateway Earth" – based architecture for interplanetary travel. The first two (Earth to LEO vehicles, and LEO space station node) exist already. The specific design features of the LEO orbiting refueling depots, and of the interplanetary craft, are *not* the subject of this paper. We here only concentrate on the LEO to GEO tugs, and the key multi-functional "Gateway Earth" complex itself. There is also a seventh element (Step 7), which would probably vary for each destination planetary surface, and that comprises the lander and associated ISRU technologies. This seventh step is also not addressed further in this paper, but is here simply noted for completeness. This overall 7-step architecture makes possible relatively low cost access to the Moon, the asteroids, Mars or any other interplanetary destination (Ref 9).

"GATEWAY EARTH" DESIGN ASPECTS

This complex has been described in earlier papers (eg Ref 2,3). Its main feature, apart from its location in GEO, is that it consists of a combination of government and commercial elements, and will *not* have a pre-defined shape. There will be a need to coordinate the chosen orbital slot for "Gateway Earth" with the ITU organization, which is the relevant international authorizing and regulating authority.

The ***commercial*** part will grow only as the demand for services grows. It is assumed that the commercial modules will be Bigelow-type, or maybe Galactic Suites - type structures. The Bigelow modules have already been demonstrated in space with orbiting prototypes, and one is soon to be added as part of a NASA contract to augment the operating volume of the LEO ISS facility (Ref 19). Some of the modules will be operated as a GEO space tourist hotel, possibly capable of supporting up to about 6 space tourists and a commercial astronaut "hotel keeper". Others will provide a base of operations for a potential GEO communications satellite servicing business. One might even be a kind of "general store" or eatery. The funding of the commercial part of the complex will be provided by the commercial operators, only as they are able, and as the markets develop. Tourists at this new space hotel in GEO will have views of an almost entire hemisphere of the Earth, while also being able to observe the operations of the government astronauts who will be constructing the interplanetary spacecraft on site (Fig 3, 4). Although not addressed further in this paper, it is a possibility that space tourists in GEO may wish to pay more to use a tug in which to travel around the complete geostationary orbit, (which requires very little fuel to achieve) and thereby would see all parts of the Earth below, both in day and night.

The ***government*** part of the complex is intended to be very small compared with the size of the existing ISS facility in LEO. It will be designed *a priori* only to provide a safe haven for astronauts going onward to, and returning from, interplanetary destinations, and will initially be used as a base for the construction crews building and assembling the interplanetary spacecraft. It will carry a manipulating arm to unload cargoes and also assist in construction. It is *not*, however, intended for the conduct of science experiments, which will remain the preserve of the ISS laboratory in LEO. It will, though, contain the solar arrays for power generation, waste management, docking ports, storage facilities for oxygen, water, fuel and printer supplies, and the 3-D manufacturing facility. It will effectively become "the 3-D printer at the edge of the universe". The traffic control inbound and outbound from the entire "Gateway Earth" complex could also be managed by the government astronauts in this part of the Gateway. This government part of the complex will be funded by the respective space agencies who are going to use it. The construction will need to be phased to align with national space budget cycles. Clearly, an initially minimalist government part of the complex will make its funding more probable. In any case, none of this "Gateway Earth" facility will ever be returning to Earth, and it will likely grow over time as the need arises, and as the budgets make possible. So it will make sense to initially consider only enough infrastructure to support a small number of government astronauts in preparing initial agency budgets.

3-D manufacturing, otherwise known as additive manufacturing, is a newly emerging technology with great potential for space operations. Some parts for lunar rovers being built to attempt the Google Lunar XPRIZE challenge have already been constructed in this way. With a 3-D printer in orbit, for example, it becomes possible to manufacture on site replacement parts for failed systems, and tools, by uploading the design details. This will obviate the need to store pre-constructed spares inventory. And an industrial-sized facility at the "Gateway Earth" complex will be capable of manufacturing the main elements of interplanetary craft. Such craft do not need to be as complex or robust as a similar vehicle manufactured on Earth. They may even in the case of cargo variants use a "lightsail" for propulsion (Ref 15, 16, 17). The technology has already been demonstrated that quite large and complex shapes can be produced out of a variety of materials, and the resulting parts have the requisite structural integrity and strength. There have already been demonstrations of this capability in orbit (Ref 15), particularly using the Made in Space, Inc. equipment installed and operated on the ISS in 2014. Engine parts have been constructed of copper by Aerojet Rocketdyne. A joint New Zealand/US firm named Rocket Lab has manufactured a prototype engine largely using additive manufacturing techniques. Lockheed Martin is working on building propellant tanks using 3-D printing technology. NASA designers at Marshall Space Flight Center are also working on using 3-D printing, and NASA is even exploring converting plastic waste into high quality 3D printer filament for construction purposes. Fig 2 shows an example of a large scale industrial 3-D manufacturing capability.

Fig 2. Large Scale Industrial 3-D printing of Building Elements (credit: Edyta Zwirecka)

For the purposes of the "Gateway Earth" arrangements, we need a printer setup which can operate using a range of different raw material supplies. The printer will need to be big enough to effectively extrude structural elements of an interplanetary craft. Industrial sized 3-D printers are emerging, and will need to be demonstrated in space as part of the checkout of the proposed architecture. With the availability of the on-orbit 3-D manufacturing equipment, the supply logistics from Earth are considerably simplified, and storage at the complex may thus largely be relegated to a matter of bulk raw material. Such material needs no special handling during launch from Earth. Fig 3 is an impression by artist Phil Smith, showing the dual nature of the "Gateway Earth" complex, with the commercial modules (including the GEO space hotel) nearest the viewer, and the governmental part including trusses and robotic arms for assembly work.

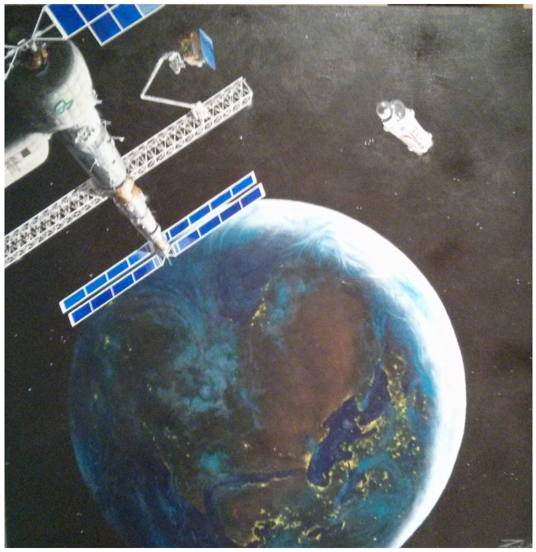

Fig 3. "Gateway Earth" in GEO, with Arrival of a LEO/GEO Tug (Credit: Phil Smith)

Fig 4 is another perspective, also by artist Phil Smith, of the "Gateway Earth" complex in GEO, with space tourists at the GEO space hotel observing the Earth behind the government modules, and the activities of governmental astronauts as they manufacture parts for an interplanetary craft using the Gateway's 3-D manufacturing facilities and then assemble them for onward exploration. A tug is arriving with more raw material for the manufacturing facility.

Fig 4. "Gateway Earth" Complex. Tourists Observe Construction Work in GEO (Credit: Phil Smith)

One of the main considerations in bringing a "Gateway Earth" facility into operation will be a joint working agreement between government space agencies and commercial operators. The main elements of such an agreement will resemble an interface agreement. This will be a heads of understanding about respective responsibilities, about the specification of interconnections, power levels, safety procedures, storage, training requirements, etc. The agreement will also need to specify the prices that the governmental users will pay for the ongoing use of the commercial LEO to GEO tugs.

DESIGN OF THE LEO-GEO TUG

The basic design of the tug has also been provided in earlier papers (eg Ref 2,3). The LEO to GEO tug does not need to ever return to Earth, and so does not need to carry any re-entry thermal controls or heatshield. Also, it will always be operating in the vacuum of space and does not therefore need to be aerodynamic (once it has been delivered into LEO). There may be more than one variant, perhaps one type for pressurized cargos and personnel transportation (including space tourists), and one for bulk cargo deliveries. For each type, the common features will be docking ports (for docking at the ISS serving as the LEO node, and at “Gateway Earth”), refueling ports (for linking up with the orbiting refueling stations in LEO (Ref 18)), the transportation space for the cargo and/or crews, propellant tanks, and a motor. For the cargo version, probably an ion motor will serve; for a crewed version a more conventional reusable in-space engine will be required. The tug could be based for example on an adaptation of the “trunk” section of the SpaceX Dragon spacecraft, or of the Orbital Cygnus transporter, or versions being developed by Lockheed Martin corporation.

What will be the cargoes that the tugs will be required to carry on a regular basis both up to the “Gateway Earth” complex, and back down again from the Gateway to the LEO node at the ISS? The human cargoes include the regular arrival and departures of the space tourists. Each group (of initially about 4 to 6) will probably be staying for one to two weeks at “Gateway Earth”. The space tourists will also have a “hotel manager” commercial astronaut in support. Other human cargoes include the governmental astronauts from NASA, and other space agencies, who are arriving and departing from their tour of duty at “Gateway Earth”, and who ultimately will include the crews of interplanetary missions.

There will be a mix of non-human cargoes. There will be oxygen, water, food and laundry for the humans. Also in the downward direction there will be trash. There will be a need to transport rocket and reaction control fuel. As the GEO satellite servicing business develops, then there will be spare or upgraded communications satellite modules. But probably the main bulk transport requirement will be for 3-D printer supplies, the raw materials for building the interplanetary craft. We will quite literally be “3-D printing our way to the planets”. These supplies may come in pellet form or in rolls of raw material. The raw material itself might be plastic or metal or carbon. Fig 5 is a notional design by artist Phil Smith showing two versions of the GEO-LEO tug, one for crew/space tourists, and the other for cargo, including 3-D manufacturing supplies.

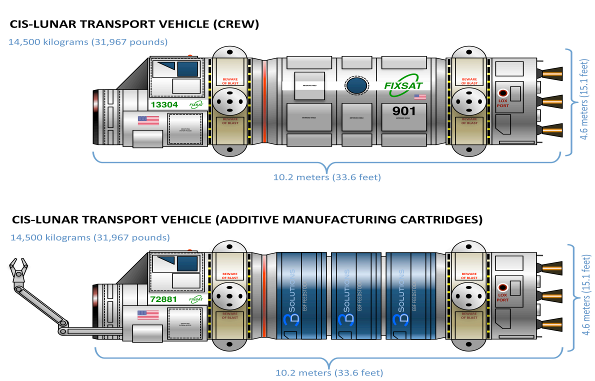

Fig 5. A Notional LEO-GEO Tug, Operated by Space Tourism Company (Credit: Phil Smith)

On arrival at the "Gateway Earth" complex, the tugs will rendezvous and dock, and the supplies will be transferred to their storage locations using the Gateway's manipulating arm. Human cargoes will, of course, enter the complex via one of the docking ports. The tugs operate in both directions, and will also carry materials and people back to Earth via transfer in LEO at the ISS node, before taking on their next load of people and supplies for returning back to GEO.

BUSINESS CASE FRAMEWORK

For this proposal to succeed, a combination of government and private industry resources, working together – towards the same aims but not necessarily, or even likely, in unison – will be needed. This is a non-traditional way of working in a number of respects, but offers great benefits if it may be achieved. It will require working agreements between, eg, NASA, other space agencies, and the members of The Commercial Spaceflight Federation.

In the case of the ***governmental*** work, this may be achieved by a judicial phasing of a series of tasks within budget projections over a sufficiently long timeframe to be politically supportable. The tasks needing to be achieved and funded by governments include (1) basic research and design development of LEO fuel depots and fuel transfers for a range of fuels, (2) further in-orbit testing of 3-D manufacturing capabilities, (3) Earth-based demos of ISRU capabilities for a range of end products, and (4) various planning and design activities – especially those related to interface specifications for power cabling, fluid transfers, access ports, and the structural elements needed for the governmental part of the "Gateway Earth" station – including (5) the costs of launching the elements into GEO, etc. The Agency planners therefore need to begin to sketch out the likely costs of these activities, and determine how they might be phased and shared between separate international agencies. It has been pointed out by Grey (Ref 27) that the difficulties of funding long-term expensive governmental space activities can be handled by accepting that the *total* costs are unknown, but that the costs can nevertheless be covered by budgeting a regular fixed *proportion* of the total budget, with the duration of the activities being the independent variable. The proportion itself would be determined by what to Congress seems acceptable. This allocation agreement will be made more palatable by a simultaneous recognition that commercial revenues are assisting in the overall funding plan, as described below.

For the ***commercial*** part of the architecture, it will be necessary to allow sufficient time for the new GEO-based commercial businesses to emerge. And a pre-requisite for that to happen is for a highly rigorous market assessment of likely demand to be performed. In particular, this is an extension of our knowledge of existing space tourism markets to a new destination. Previous results of financial evaluations of this "Gateway Earth" – based infrastructure are provided in Ref 3, where it was determined that the costs of interplanetary travel would conservatively be at least a third cheaper by using this approach. The Appendices to this paper contain the material that further addresses the market demand question. First of all there are analogs which provide some guidance on relative demand levels for different tourist attractions at increasing heights and increasing price levels. Then data is provided that is relevant to the now well-established requirement for getting from LEO to GEO in delivering communications satellites into their GEO slots. And finally an initial data set is provided that pulls together what we know about the various commercial business opportunities supporting the seven steps of the proposed "Gateway Earth" infrastructure. This work is clearly very preliminary and is based solely on desk research, and some elements remain of necessity completely unknown at this point. New statistically valid demand-based primary market research will be needed to further explore the validity of the notion that a combined governmental/commercial complex at "Gateway Earth" is viable, and therefore this need is noted in the next section. For a complete business case assessment, of course, we shall also need cost data – and this is also noted at appropriate places in the Appendices to assist future economics software modelers. As a first step, some of the most critical revenue elements have been scoped. And therefore we have been able to obtain some insight just by using the desk research described in the Appendices. What we find is that there is probably a peak market for about 150 tourists a year at "Gateway Earth", and they would generate about $4.5B revenue, assuming an optimum sized tug and hotel, both supporting 6 occupants at a time, and a ticket price of $30M to GEO.

NEXT STEPS

There are a number of identifiable next steps. As has been stated earlier, the *time frame* for instituting this "Gateway Earth" – based infrastructure must be fluid, because of historically low governmental space budgets and the need to allow time for the commercial businesses to emerge and develop their revenue streams. Furthermore, it should be acknowledged that the primary need for this capability is premised on a *very long term view* of planetary and solar development that does not require an urgent response. That having been admitted, there are nevertheless many nearer-term reasons for building the capability for regular low-cost interplanetary travel, including the beginnings of using the resources of space (such as the mineral content of asteroids) as part of Earth's economy, and the continued extension of public access to space through the development of a geostationary space tourism market segment. And there is the need to begin to develop methods to protect Earth from future catastrophic asteroidal or cometary impacts, with imperfectly known urgencies. Therefore, at the very least, we should endeavor to maintain the momentum by conducting a range of low cost, low risk, preparatory activities related to the establishing of the "Gateway Earth" infrastructure at the edge of Earth's gravity well. Listed below, in no particularly relevant order, are a number of tasks needing to be funded, performed, documented, videod and authenticated in order to convince Congress and the public that the proposed architecture is achievable. Some of them require relatively small amounts of funding, and might even be fundable via crowd-sourcing and crowd-funding approaches. Some would be the responsibility of the commercial sector, some would be in the remit of governmental space planners; some would benefit from joint activities. However it is done, we make a plea for transparency and sharing:

- Commercial operators conduct statistically relevant and valid market research into demand amongst wealthy individuals for space tourism in GEO to confirm or challenge the estimated $4B market opportunity, with results placed in the public domain (estimated $150K)
- Commercial and/or governmental space planners conduct full economic model analysis of the "Gateway Earth" infrastructure proposal, using software to compare the costs of doing space exploration via "traditional" methods, compared with doing so using the proposed infrastructure to confirm or challenge that the approach produces major cost savings, with results placed in the public domain
- Joint governmental/commercial operations continuing to develop and space-rate 3-D manufacturing facilities, leading to the extension of capabilities, the development, orbital trials and demonstrations of industrial-scale equipment
- Earth-based demos of ISRU capabilities for creating water, oxygen, rocket fuels, building bricks, solar cells, etc, from soil samples (governmental and commercial interests – eg markets for water on Earth)
- Joint governmental/commercial work to establish the terms of a Heads of Agreement (including interface specs) that could be used to regulate the joint international, governmental and commercial interests involved in setting up and operating the "Gateway Earth" infrastructure
- Further preliminary design work for the tugs and station modules, including the layout and *modus operandi* for the space hotel modules to be installed in GEO (governmental and commercial operators)
- Governmental and/or commercial providers conduct essential design work for the LEO-based propellant depots, and the demonstration in orbit of effective and safe fuel transfers
- Further work, including market research and business case analysis, is needed to explore the feasibility of a commercial geostationary communications satellite repair and refueling service, with some capabilities co-located at the "Gateway Earth" complex (commercial operators)

It would seem that crowd-sourcing and crowd-funding approaches might yield results for eg modeling the economic assessment of using a "Gateway Earth" - based manufacturing approach compared to one that launches interplanetary vehicles from the Earth, or for conducting the new statistically valid primary market research, and the author will be pursuing this approach in 2016 via an Incubator website currently being constructed for the purpose.

CONCLUSIONS

We have demonstrated some features of the “Gateway Earth” station proposed to be installed in geostationary orbit, and of the commercially designed, built and operated GEO/LEO tugs needed as a logistical supply channel, and have provided some preliminary business case analysis (suggesting a $2B - $4B market), then identified further steps required to refine the concept.

The main idea behind the “Gateway Earth” infrastructure is to use the combined resources of government and private industry to fund future interplanetary space travel and exploration via the shared use of a facility near the edge of Earth’s gravity well. By so doing, the costs of interplanetary travel will be significantly reduced in comparison with more ‘traditional” ways of proceeding. By its very nature, this will require a very different approach to managing future space developments and exploration, and it is an open question whether there exists enough of the combined technical and negotiation skills to enable the approach to succeed. In any event, there is an absolute *a priori* requirement for the nascent space tourism businesses (both in LEO and in suborbital experiences) to succeed in order for the revenue stream to emerge which could make the venture possible. There is another key requirement, and that is for the continued existence in LEO of a base station – which is currently considered to be the ISS, or any subsequent replacement beyond 2020 or 2024. The preliminary business case framework presented in this paper indicates that there is enough of a viable opportunity to consider the idea further (and indeed the author intends to progress this work in 2016 via an Incubator website approach currently under development). There is, moreover, short-term work enough for both governmental and commercial players to undertake, if a choice is made to pursue and refine the approach. Is $4B enough of a potential market to encourage the space tourism firms to consider supporting the concept? If so, will government agencies begin to do their part by making minor deviations to their current plans to make the “Gateway Earth” approach possible? Can both parties find ways to jointly move forward informally and explore these concepts?

Many authors over the years, and even centuries, have pointed out why the human race needs to open up interplanetary space to economic development in order to counteract depletion of resources on Earth and to provide a back-up plan for life itself in the very long term. The problem was initially one of technology. That was resolved by the Apollo program during the 1960’s. The problem then became one of funding and political will, which to a certain degree were interrelated. The joint governmental/commercial “Gateway Earth” infrastructure, described in this paper, represents an attempt to address the funding issue, and incidentally provides a new focus for national governmental endeavors related to space development. Building the “Gateway Earth” complex in GEO, if this could be achieved as a joint governmental/private commercial venture, would provide a new platform for the economic continued exploration of space during the 21st century, and would thereby be a fitting contribution from the first generation of space explorers to their grandchildren and descendants.

ACKNOWLEDGEMENTS

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APPENDICES

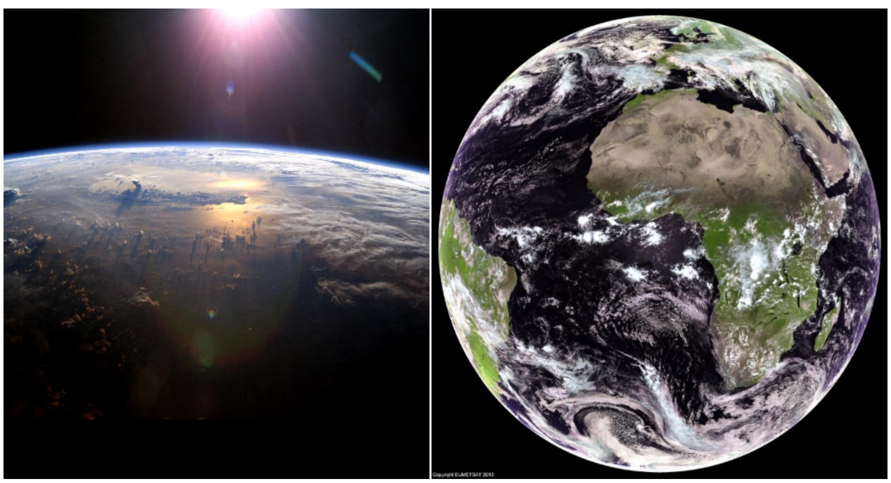
APPENDICES

Primary market research is needed to assess the likely demand and revenue potential for a new space tourism destination in GEO.

Until this research is funded and conducted, we can, however, make some progress by pursuing desk research using market analogs, as developed below. We must of course not assume too high a level of confidence in the resulting findings – and this point is discussed in the course of the analysis.

- *I* *MARKET ANALOGS*

How attractive will a hotel in GEO be for space tourists? Given an equivalence of other factors, the main difference compared with a LEO hotel will be the view.



View from a LEO space tourism hotel (left) and from a GEO space tourism hotel (right) credit: NASA

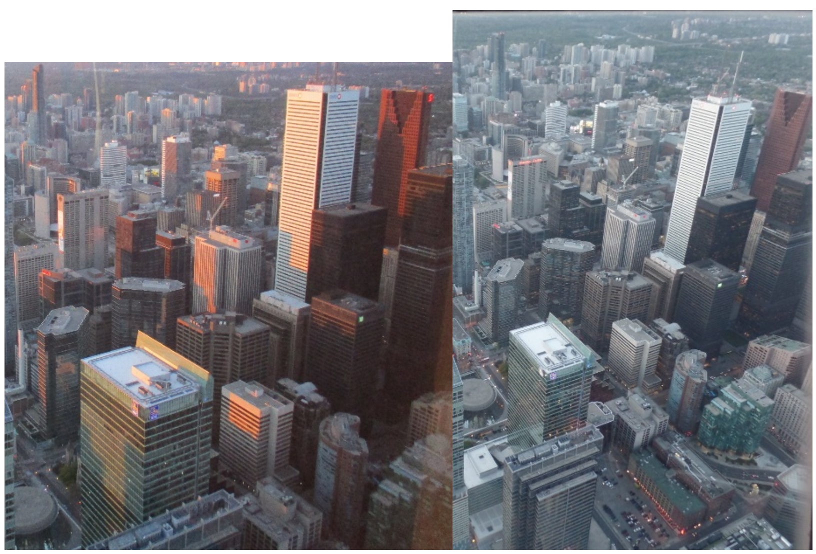
Would tourists be willing to pay a sufficient price increment over and above the already high price to LEO in order to reach the GEO hotel? Though clearly an imperfect analogy, in the absence of more relevant primary market research, the following terrestrial tourist attractions provide some insight into price elasticity of demand with increasing altitude. Basic data is collected and presented with some analysis for both the CN Tower and the Tour Eiffel experiences.

1) CN Tower

The CN Tower in Toronto, Canada, is 553m high, and receives 2 million visitors annually. Tourists are offered an opportunity to see the view of downtown Toronto from each of two observation platforms – the main platform is at 346m, and the Skypod is even higher at 447 m altitude. Whilst all tourists are taken up to the 346m level, there is an additional charge to the tourists who wish to go even higher, to the Skypod level at 447m. Distant horizon views of up to 160km are possible from the Skypod. Views are dramatic from each of the observation levels. What are tourists willing to pay for the *additiona*l ride up to the Skypod level, and how do the views differ? Below is the CN Tower and the tourist entry ticket.

CN Tower showing main observation deck and higher Skypod deck, and entry ticket (credit: author)

Below is a comparison of the views obtained by tourists, looking at the same section of downtown Toronto, from each of the two observation deck levels.



Contrasting views from (left) Main deck and (right) Skypod at CN Tower (credit: author)

Are the two views significantly different? Certainly not so significantly different as are the views from LEO and GEO as shown above. At any rate we can note that the Skypod is **29% higher** than the Main deck, and that the tourists who opt to go up the incremental stage from the Main Deck pay **41% more** for the experience (ie a $12 increase over the $29 basic charge). In the space tourism context, GEO is **100 times higher** than LEO, and of course, importantly, offers a whole-Earth hemisphere view rather than just a slice with a slightly curved horizon.

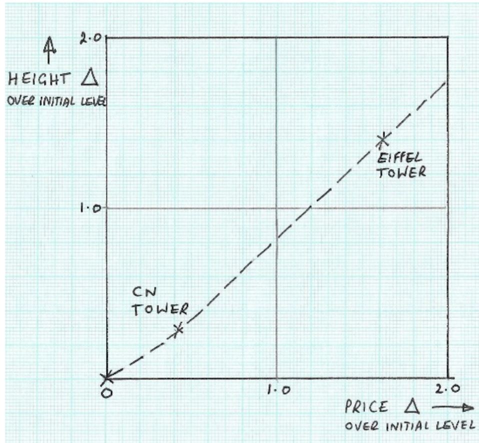
2) Tour Eiffel

Tour Eiffel showing the three levels for visitor access. (Credit: French Tourism Agency)

We gain a similar insight from viewing the Eiffel Tower's tourist statistics. The tower, in Paris, France, is 324 m high, and has over 6 million visitors per year, the most visited paid monument in the world. Tourists again pay more as they ascend higher in the structure. The first floor is at 57 m, the second floor is at 115m (**2 times higher** than the first floor) and the third floor is at 276m (**1.4 times higher** than the second floor). Initial prices in 1889 were 2 francs for the first level, 3 for the second and 5 for the top (ie the second floor cost **2 times** the price for the first floor, and the top/third floor cost **1.5 times** the price to the second floor). More recent pricing (2015) has simplified the price structure, and now the first ticket goes all the way to the second floor at 9 Euros, and all the way to the top for 15 Euros (ie it now costs **1.6 times** the price to the second floor to reach the top).

We may summarize the market analogs data with the following charts, which indicate that tourists will certainly pay for a more "enhanced" experience at greater heights:

Summary Data on Tourist Pricing at CN Tower and Tour Eiffel				
TOURIST DEST'N	VISITORS/YR	PRICE 1st LEVEL	PRICE TOP LEVEL	DELTAS
CN TOWER	2 million	$29	$41	41% price increase for 29% height increase
TOUR EIFFEL	6 million	9 Euros	15 Euros	1.6X price increase for 1.4X height increase



Price elasticity chart for increasing elevations at tourist destinations

- ***COMSAT DATA***

Some useful insights are also provided by analyzing, in energy terms, the relative costs of inserting satellite communications spacecraft cargoes into both LEO and GEO orbital destinations. Because of the use of the geostationary orbit for commercial communications and broadcasting satellites, a great deal of experience has been built up over the decades in getting between LEO and GEO. And this experience can provide some perspective into the relative distances and difficulties in getting to GEO, right at the edge of Earth's gravity well, compared with simply getting to LEO. Sometimes the pricing data is hard to come by, because of commercial confidentiality, but a good surrogate is the relative payload masses. Note that GTO refers to geostationary transfer orbit, not GEO itself. Spacecraft require to carry part of their mass for circularization burns on reaching the apogee of the GTO. Therefore the ratios developed in the table below would be even higher if this were taken into account. The data source for the following table was the FAA's Annual Compendium of Commercial Space Transportation (Feb 2013 version).

RATIO of MASSES to LEO and GEO ORBITS				
Orbit	Falcon 9	Ariane 5 ECA	Proton M	Atlas V
LEO	13,150kg	21,000kg	23,000kg	18,510kg
GTO	4,850kg	9,500kg	6,920kg	8,900kg
RATIO	2.7X	2.2X	3.3X	2.0X

Thus, we can see that it is almost **three times as hard**, in energy terms, to get to GEO (near the edge of Earth's gravity well) than it is to simply get into LEO (still relatively near the bottom of the well).

- ***ADVENTURERS' SURVEY COMPARISON DATA (ref 12)***

This survey was conducted in 2006 amongst approximately 1,000 visitors to the website of the adventure travel firm Incredible Adventures. Amongst the questions asked was an assessment of what respondents considered to be "fair" prices for a range of possible space adventures. The question about a visit to GEO was unfortunately not foreseen at that time as being of interest, so that specific question was not asked. However, in addition to the LEO orbit experience, a question was asked about a circum-lunar tourist flight, and so it is possible to draw some conclusions from comparisons of the respective responses, as tabulated below:

COMPARISON OF LEO AND CIRCUM-LUNAR "FAIR PRICES"				
SOURCE	PRICE	PROPORTION AGREEING THAT PRICE IS 'FAIR"		MULTIPLIER
		LEO	CIRCUM-LUNAR	
Adventurers' Survey (Ref 12)	$20M	8%	18%	**2.2X**
	$5M	14%	n/k	n/k
	$1M	30%	30%	1X

Thus, we can see that it was considered by twice as many respondents to be fair at a given price to go into lunar orbit than to go to LEO, or alternatively, approximately the same proportion thought $5M to be fair for LEO and $20M fair for circum-lunar (ie **4X more**).

- ***OTHER ANALOG SOURCE***

One other source of circumstantial evidence exists in the public domain, for pricing of tourist flights above LEO. The space tourism firm Space Adventures announced a price of $150M for a circumlunar ticket (for each of two tourists) for an Apollo 8 type mission proposed using Soyuz technology, at a time when LEO ticket prices were about $50M.

So that we can commence our demand assessment, we now attempt to pull together, in the following table, our findings on a reasonable assumption for pricing of a space tourism trip to the "Gateway Earth" station in GEO:

CONSOLIDATED PRICING DATA FOR SPACE TOURISM TO GEO		
SOURCE	MULTIPLIER	COMMENTS
ANALOGS	>2	from this paper
COMSAT COST BASE	~3	see above
ADVENTURERS' SURVEY	2.2 – 4.0	applies to Moon, not GEO
SPACE ADVENTURES' PRICE QUOTE	~3	applies to Moon, not GEO ($150 M quoted cf $50M LEO)

We shall therefore use, conservatively, for the purposes of developing this preliminary business case framework, an assumed ticket price for space tourists spending 2 weeks at the "Gateway Earth" space hotel in GEO, of **three times the LEO prices in the same time period.**

- *II PRELIMINARY MARKET ASSESSMENT AND COMMERCIAL ASPECTS (and Sources)*

In considering the non-governmental business opportunities that will emerge if the "Gateway Earth" architecture is introduced, we begin to see a framework of commercial funding sources which can augment governmental budgets at each of the seven stages of development. This therefore becomes the new funding mechanism for 21st century interplanetary exploration; a blending of governmental funds with revenues generated from commercial operations. The degree to which commercial funds can boost the governmental budgets will vary between the different segments of the architecture, and indeed through time for any given sector. In some cases we cannot know *a priori* whether a commercial operation will develop. Work may, eg, be initially carried out under governmental funding, and then transfer to commercial operations further down the road. So, the indications recorded here are necessarily broad-brush, and designed mainly to suggest the constituent elements. Much more work will be required to provide a better basis for the assumptions developed here. However, that being said, we can make some progress if we set out, and consider in turn, the separate phases of the operation. In some areas we have pretty good data; in others we have very little, and some new primary market research is needed. Where appropriate, we can judiciously use some of the data from the market analogs developed above. This paper's focus, it should be remembered, however, is mainly on the interrelated steps 3, 4 and 5 which in practice are developed simultaneously. Note that, as suggested by J Grey (Ref 27), it is not necessary for a business case to close at each step of the way; governmental expenditure may be provided by assuming simply a fixed percentage of the agencies' annual budget, with a duration of "as long as it takes" to get the job done. The commercial revenues developed in this section therefore merely help out the overall funding so that the "fixed percentage" figure can be set at an acceptably low figure for congressional oversight purposes.

Step 1: EARTH to LEO (Musk data Ref 20, 23)

Revenues and costs for this step come from commercial launch experience, with projected cost and price reductions due to gradual introduction of reusability. Examples of reusability which could be used are the SpaceX Falcon 9 (entire first stage) and Airbus Adeline (engine only).

Step 2: AT LEO NODE (ISS operations – orbital space tourists Ref 10, 19)

The costs of the operation of the ISS are available from NASA budget data. The cost of the Bigelow inflatable habitat being attached to ISS for more internal volume is $17.8M. Revenues will come from conducting research at the ISS, and from orbital space tourists. Ticket prices for tourists in LEO vary from $20M to $60M for two weeks as orbiting space tourist.

Space Tourist Anousha Ansari (credit: Space Adventures)

Step 3: AT "GATEWAY EARTH" in GEO

This is the focal point of the whole commercial space exploration architecture. Cost information will need to take account of two different kinds of modules. Bigelow "Sundancer" modules may be assumed as the costing basis for the *commercial* space hotel part of the complex (Ref 19). For the *governmental* part of the complex, cost data can be assumed using a subset of the ISS costing information (source NASA).

Bigelow "Sundancer" Module Prototypes (credit: Bigelow)

For this paper, the focus has been more on the revenue opportunities than the overall business case closure. In exploring the business cases for the *commercial* elements of "Gateway Earth", the revenue elements generated at the "Gateway Earth" complex are likely to come from two distinct businesses, namely space tourism and satellite repair and servicing. For the current paper, the focus has been on the former revenue source.

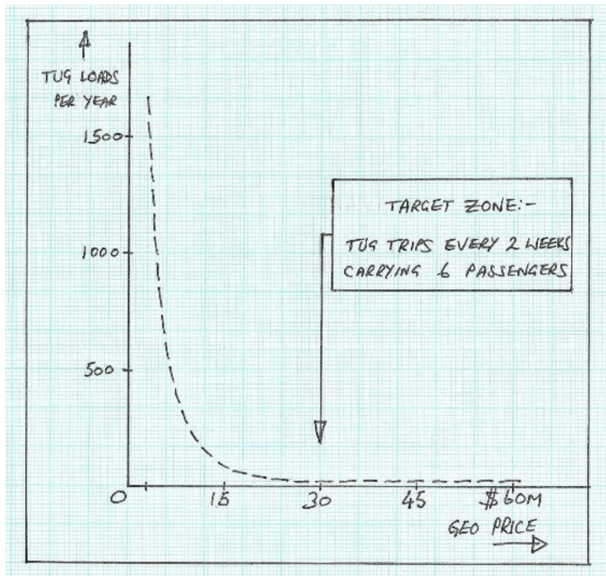
SPACE TOURISM (Extending public access to space at GEO – Ref 11, 12, 13, 14, 22, 26)

The following revenue analysis explores how many tourists are likely to want to go to a GEO space hotel at the assumed price. The hotel is assumed equipped with high quality and magnifying optical viewing ports. Note that Apollo astronaut H. Schmitt reported to the author that views of Earth from around GEO, a region through which he passed during Apollo 17, were fine using a monocular. It is assumed, therefore, that the "Gateway Earth" space tourist hotel will be equipped with suitable optical aids for its occupants.

The assumed starting point for the revenue analysis is the Futron/Zogby Survey (Ref 11). This was a statistically valid survey of potential space tourism demand amongst millionaires, conducted in 2002. The forecasting methodology took into account the numbers of millionaires available, and, despite the answers to the questions asked, only included in the calculation those for whom the ticket price would represent no more than 1.5% of their net worth. This means that eg at a price of $1M per ticket, we only assume that the demand can come from a population with an individual net worth in excess of $66M. The F/Z forecasts, moreover, only used those respondents who responded "Definitely likely" to the demand question at the stated price level. For context, we should note that the Futron/Zogby survey only considered sub-orbital space tourism and LEO orbital demand, however. At the time of the survey only a few space tourists (Akiyama, Sharman and Tito) had gone into space, all to LEO using Soyuz. Since then, LEO has become the regular destination orbit for space tourists. We now proceed to work with this base data, and our assessment of likely GEO prices, to infer demand for space tourism at the "Gateway Earth" complex in GEO.

"GATEWAY EARTH" PASSENGER DEMAND ASSESSMENT AND TUG TRIPS			
LEO PRICE ASSUMPTION	GEO PRICE ASSUMPTION (3 X LEO price)	PEAK ORBITAL PASSENGER DEMAND (F/Z)	LEO/GEO TUG LOADS at 6 PASSENGERS
$20M	$60M	60	10
$5M	$15M	600	100
$1M	$3M	9,000	1,500

We have determined, therefore, that at a price of $60M for 2 weeks in GEO there would be a peak demand for around 60 passengers. If we assume that the tug carries 6 passengers, then that implies 10 tug rides between LEO and GEO carrying passengers to the "Gateway Earth" hotel. If economies of scale make it possible to reduce orbital tourism prices into LEO to only $5M, then that would equate to a $15M ticket to "Gateway Earth" and 600 passengers to GEO in a peak year, or 100 tug journeys. The business case model, however, assumes that the GEO tourists will stay two weeks at "Gateway Earth", and that the hotel there can only support 6 tourists (plus attendant company astronaut). It is furthermore assumed that the tugs can only carry 6 tourists at a time. With these constraints, what would be the best pricing zone for the operation? The following chart makes it clear that for 25 tug trips a year to the GEO hotel, carrying a total of 150 GEO space tourists, the business case closes at a price level of about $10M for LEO and $30M for GEO:



Price Elasticity of Demand for tickets to the "Gateway Earth" Space Hotel

At this target price of $30M for GEO, the "Gateway Earth" complex, and its supply chain, would generate **$4.5B/ year in revenues**.

What is the level of confidence in these results? The original Futron/Zogby study primary market research (Ref 11) involved interviews with 450 millionaires, so that the findings at that time were expressed as being representative at a confidence level of +/- 4.7% of millionaires in general. Much has changed since 2002, some positive and some negative factors, adding to the uncertainty. Furthermore we have here extended the methodology by inserting additional steps with clearly stated but unverified assumptions. Nevertheless, it seems we are unlikely to be wrong in our assessment by as much as an order of magnitude – it might be reasonable to assume a factor of about two, though (ie the range in uncertainty in the $4B figure would probably be between $2B and $8B).

(GEO COMSAT SERVICING (Ref 24 – DARPA/Phoenix experiments)
At present, we do not have any useful data, either on the cost or revenue side, to provide for this potential commercial opportunity.)

Step 4: OPERATING THE TUGS (Ref 21)

For cost data with regard to refueling of the tugs in LEO (Ref 18, 21)
For revenue assumptions we need to separately assess each direction of the tug operation:

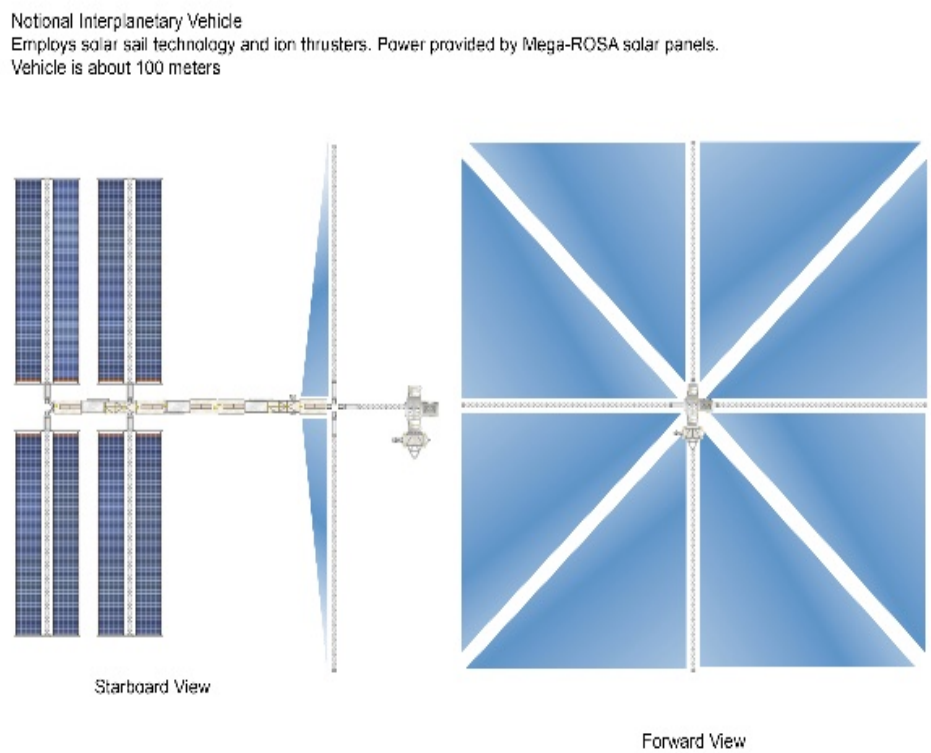
LEO TO GEO (service for transport of crews, tourists and cargoes)
For revenue estimates we may assume the above GEO tourist forecasts

GEO TO LEO (service for removal of trash)
For revenue estimates we may assume an operational frequency of once per two weeks period (at changeover of tourists).

Step 5: OPERATING THE LEO GAS STATIONS (Ref 18)

Costs are required for the building and launching of the stations into LEO orbit. Costs are also required of refueling the stations – we may use the frequency based on the tug trips calculated above.
Prices for providing the refueling service are yet to be determined, so no assessment of associated revenues is provided in this paper.

Step 6: THE INTERPLANETARY SPACECRAFT (Ref 16, 17)



Notional Interplanetary Spacecraft (Credit: Phil Smith)

Costs are required for building the craft (raw materials to GEO, 3-D manufacture, astronaut assembly)

No revenues are developed in this paper. They would ultimately depend on the prices charged for providing a service for crews and for (eventually) tourists.

Step 7: THE PLANETARY LANDER AND ISRU CAPABILITIES (Ref 25 – MOXIE/RESOLVE)

No useful cost or revenue data is available at this stage, except for the possible use of Bigelow surface infrastructure habitats (with associated published pricing).

(Note: Asteroid and planetary resource revenues have been excluded from the analysis at this stage)

- ***III COMBINED SUMMARY RESULTS of COMMERCIAL REVENUE OPPORTUNITIES***

  - Previous Results (Ref 3):-

    (Note: this analysis could be refined by software modeling, maybe using crowd-sourced software) The costs of interplanetary travel would be at least a third cheaper by using this approach, than by using the traditional methods.

  - Combined new results from the current analysis:-

    - A price to GEO of about $30M for two weeks is supported by market data
    - Logistically, 6 passengers occupy the space hotel at a time, and 6 passengers will fit in a LEO-GEO tug
    - Tugs arrive and depart every two weeks, ie 25 tug trips/year each way
    - **150 GEO space tourists at peak, generating $4.5B/year in revenues ($2B to $8B range)**
    - GEO Comsat servicing, or asteroid resource extraction, revenues not included