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Bridgehead – Interplanetary Travel Becomes Routine

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Abstract

It is proposed that the world space community establish a bridgehead, which secures for future generations the ability to regularly leave Earth's gravity well. To this end, this paper provides details of a cis-lunar architecture operating via a joint government/commercial "Gateway Earth" complex in, or near, geostationary orbit. The complex, which partially operates as a space hotel and a base of other commercial space businesses, and partially operates as a combined governmental space station and port of entry/departure for interplanetary payloads, is supplied by commercial reusable space tourism tugs, cycling between low Earth orbit (LEO) and geostationary orbit (GEO), and making use of a refueling depot established in LEO. At the "Gateway Earth" complex, government astronauts will be able to assemble the spacecraft specially designed for interplanetary travel and not required to handle the rigors of Earth atmospheric transit. These spacecraft, furthermore, will require only relatively low energy propulsion because of the location of the starting point of their journey near the edge of Earth's gravity well. For the space tourists, the hotel established at or near GEO will enable them to view an entire hemisphere of the Earth at a time. Other commercial uses of the complex could include satellite servicing businesses related to the communications satellites operating in GEO.

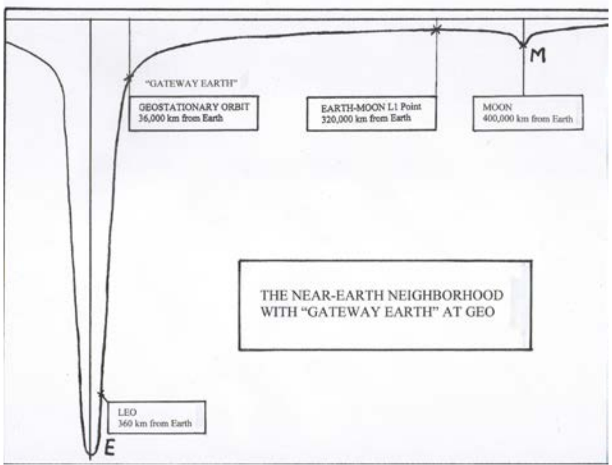
A rough order of magnitude (ROM) economic analysis is provided, which explores under which circumstances this approach is more economical than conventional expendable launch services for operating interplanetary missions. This proposed architecture, supported as it is by the regular flights of the space tourism business, therefore provides the bridgehead at the edge of Earth's gravity well, and thereby anchors the progress that has been established in the first half-century of the space program. This in turn makes it easier, less costly, and a matter of routine for future exploration missions beyond Earth. The work in this paper adds the economic assessment and dimension to the conceptual paper presented by this author at the 63rd International Astronautical Congress, Naples, Italy in 2012.

1. INTRODUCTION

Commercial and privately funded space ventures are becoming a significant factor in space, at least in the US. Moreover, governmental funding for space operations has reached a plateau at around $17B per annum for NASA, or around 0.5% of GDP, and there is no public appetite for increasing this amount. There has been much debate about what should be the purpose and direction of funding for future NASA activities. The focus should not now be on any single interplanetary destination, or any specific target timeframe, but should instead be on putting in place, within the available current budget allocations, *the enabling infrastructure* to make *any* such future missions possible and affordable. The most useful infrastructure, which would enable a whole range of future missions, is a crewed outpost in GEO, near the edge of Earth's gravity well, supplied by circulating tugs going in between LEO and GEO, and being regularly refueled in LEO. This would provide the bridgehead of the paper's title. In this paper, we begin to explore the economics of the proposed architecture. The data used is all available in the public domain, and has been assembled for convenience in an attached Data Annex to the paper.

2. OVERALL CIS-LUNAR ARCHITECTURE

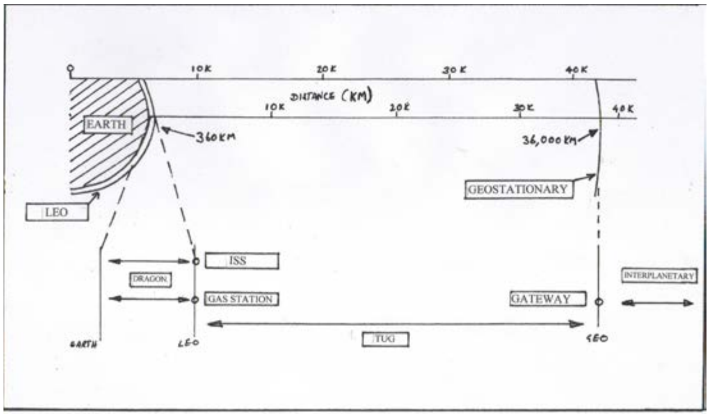
The papers [11.1 thru 11.5] provide the rationale for the proposed "Gateway Earth" architecture (the need for humans to find solutions to longer term problems of living on planet Earth). GEO was selected as the location because there will be a realistic probability of having private commercial businesses operating in parallel with the governmental astronaut activities. These commercial businesses are essential to making the overall architecture affordable, because their revenues are assumed to support the building and operating of the delivery tugs, and to partially fund the "Gateway Earth" outpost itself. Fig 1 shows this choice of location near the edge of Earth's gravity well. With a permanent base there, and assembly in orbit of the relatively flimsy craft that would be needed, subsequent interplanetary missions would require much less energy to get to their destinations.



Credit: author

Fig 1 The Earth's gravity well and cis-lunar space

The next critical part of the architecture is the reusable and refuelable tug. This craft can carry people and cargos and regularly cycles back and forth between LEO and GEO. The tourists will use it to get to their hotel; the governmental astronauts will use it to get to their part of "Gateway Earth" and conduct their activities related to missions of exploration. The tug will be refueled in LEO and so the architecture also requires that there be a permanent "gas station" in LEO. It would be operated by a commercial operator, probably a space tourism operating company. Figure 2 summarizes the main elements of the proposed architecture.



Credit: Author
Fig 2 Summary of cis-lunar architecture elements

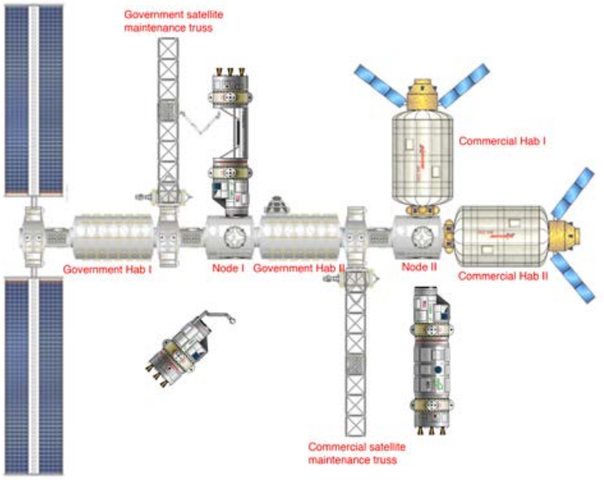
The artwork in Fig 3 shows the key elements of the proposal. In the foreground is “Gateway Earth”. The two nearest elements are the commercial modules, one of them a space tourism hotel, the other being the base for the potential commercial satellite servicing business. Further back are the governmental parts of the gateway, including various EVA access hatches and trusses and cranes for assembly work. Just arriving is one of the reusable tugs.


Artwork: Phil Smith
Fig 3 “Gateway Earth” in geostationary orbit, with arriving passenger tug.

Although the location of “Gateway Earth” will make it possible to routinely depart from there on interplanetary travels with minimal energy needs, we are not considering *landing* on any astronomical body, merely reaching its vicinity, and so we do not assume any landers or surface elements in the calculations.

3. FEATURES OF “GATEWAY EARTH”

In practice, the specific design and number of modules that constitute the “Gateway Earth” complex will emerge over time, and will not be the result of a centralized planning effort. This is because the commercial components can only be introduced as and when the respective commercial business revenue streams justify the expense. Equally, the governmental modules can only be delivered to GEO as the NASA (or other national space agency) budget will allow. It will be necessary for agreements to take place at the outset between potential commercial partners and space agency planners, with the objective of agreeing *not* the final shape of the outpost, or the number of modules, but rather the principles on which it would operate, the design of standard interfaces, etc, etc. For the purposes of this paper, however, a possible layout is suggested and is shown in Fig 4.

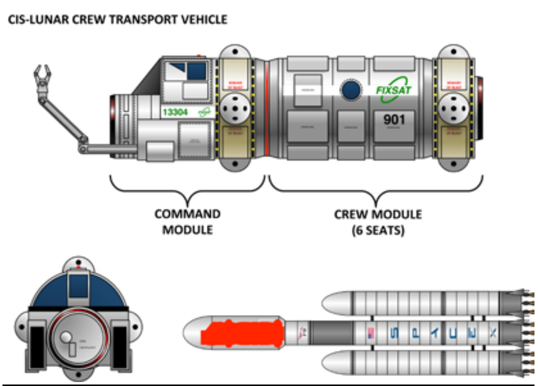


Artwork: Phil Smith

Fig 4 Features of the “Gateway Earth” joint commercial/governmental complex in geostationary orbit.

4. FEATURES OF LEO-GEO TUGS

The tugs are intended to be provided and operated by commercial operators. They will provide a “taxi-service” between LEO and GEO to both private and governmental users. They could be modular in construction, as suggested in Fig 5, and can carry people or cargos or both. Some cargos would be carried externally. For the economic analysis in the paper, it is assumed that, at least initially, only one tug will be required, constantly cycling between LEO and GEO. The tug would initially be injected into LEO as suggested in Fig 5, protected during launch by the launch vehicle’s fairings, and *never again need to experience the effects of the Earth’s atmosphere*. The tug will refuel when needed by achieving rendezvous in LEO with the gas station.



Artwork: Phil Smith

Fig 5 Features of the refuelable and commercial LEO-GEO tug

5. FEATURES OF LEO FUEL DEPOT

The detailed design of the LEO fuel depot will emerge as work is refined on NASA docking and refueling experiments, and as iterations of the present proposal suggest the most appropriate capacities for each of the stored on-orbit propellants and oxidizers. The concept of a refueling gas station in orbit is well established eg [11.7]. Some developmental work and in-orbit demonstrations of the concepts have already been carried out. The Defense Advanced Research Projects Agency (DARPA) Orbital Express experiment took place successfully in 2007. NASA conducted a Robotic Refueling mission in 2011 using facilities outside the ISS. Another demonstration is planned for 2015 when a Canadian refueling craft will be orbited for tests. DARPA will be conducting the Phoenix program to rendezvous with retired geostationary communications satellites in 2016 [11.8].

6. SUMMARY CONCEPT OF OPERATIONS (CONOPS)

It is necessary to make assumptions about the likely utilization rate of the station and its tug and gas station support infrastructure. The assumptions for the commercial business elements need to be in line with expectations about space tourism pricing and utilization. Table 1 provides an initial view on these factors to use as a baseline

TABLE 1 Basic CONOPS summary for the whole system

BASIC CONCEPT OF OPERATIONS FOR THE OVERALL SYSTEM (Baseline Assumptions)

NODE	ACTIVITY	FREQ / UTILIZATION
"Gateway Earth"	Initial Arrival of components Arrival of prep crew Tourist flights to hotel (# of passengers) Tug arrivals with gateway supplies Tug arrivals with interplanetary craft parts Tug departures with crew and/or cargo	5 flights 1 flight 200/year (50 tug cycles) 12/year 3 arrivals/ mission 50/year
LEO-GEO Tug	Initial arrival in LEO Transfers LEO-GEO (crew and/or cargo) Transfers GEO-LEO (crew and/or cargo) Refueling in LEO Supplies arrivals	Once 50/yr with 4 passengers 50/yr with 4 passengers 25/yr 12/year
LEO Fuel Depot	Initial arrival in LEO orbit Top-up from Earth Tug refueling event	Once 5/year 25/year
Supporting launches from Earth	Launch of fuel depot to LEO Fuel transfer to Fuel Depot Launch of tug to LEO/ISS Launch of Dragon to ISS with tourists Launch of Dragon to ISS with Gateway Supplies Launch of interplanetary craft parts to LEO	Once 5/year Once 50/year 12/year 3 flights/mission
Re-entry flights from ISS to Earth	Return of Crews to Earth Return of tourists to Earth Return of Cargos to Earth Return of cargos for incineration	10/year 50/year 5/year 20/year

7. ECONOMIC ASSESSMENT OF INTERPLANETARY TRAVEL OPTIONS

Appendix 1, Appendix 2, Appendix 3A and 3B, and the Data Annex provide material used in this section to evaluate whether the “Gateway Earth” concept, with its associated tug and LEO refueling support infrastructure, leads to an economically beneficial means of conducting future interplanetary missions. Fig 6 conveys the general framework for leaving Earth’s gravity well and heading outwards on an interplanetary journey. Are the costs associated with A plus B (ie using the proposed new architecture) less than the more traditional alternative, shown as C?

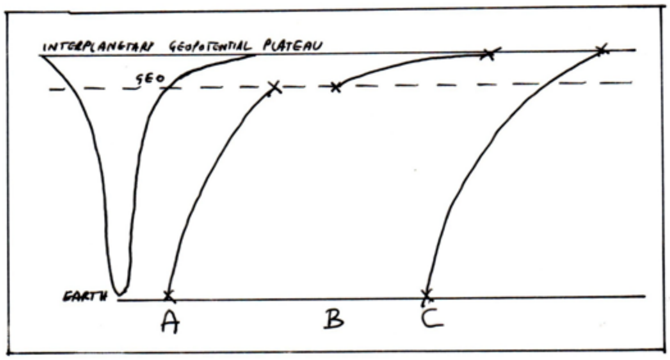


Fig 6 Routes to Interplanetary Destinations –A is totally reusable to GEO, B is GEO to Interplanetary via Lightweight Craft Assembled at Gateway, C is the SLS/Orion-type approach.

We are considering a "steady state" situation after the development costs of the "Gateway Earth" infrastructure have all been recovered. Therefore we are considering the *variable* costs per interplanetary mission (tentative evaluations in Appendix 1 and 2 suggest that this steady state could be reached after about 5 years of operations). Table 2 provides this economic assessment, with Appendix 3A and 3B giving schematics of the calculation sequence, and the values used for the assumptions in the baseline case.

Table 2 Comparison of Recurring Costs for Interplanetary Missions

RECURRING COSTS OF INTERPLANETARY TRAVEL - COMPARISON OF APPROACHES			
ROUTE SEGMENT	**A**	**B**	**C**
DESCRIPTION	**Totally Reusable to GEO**	**From GEO to Interplanetary Trajectory via Lightweight Low Energy Spacecraft**	**From Earth Direct to Interplanetary via Expendable SLS/Orion**
CALCULATIONS	see Appendix 1 (BB plus DD) less development costs	Parts per mission $200M Delivery to GEO $315M (ie 3 times $105M)	see Appendix 2 (FF) less development costs
RESULT (2012)	$105M per mission	$515M per mission	$2B per mission

We find that by comparing (A + B), ie $620M per mission, with C, ie $2B per mission, variable costs per mission using the proposed architecture can be *about a third of* the traditional approach. But how critical are these assumptions?

8. CRITICAL ASSUMPTIONS

The viability of a space tourism industry, and its extension to new destinations, is the most important driving assumption for the entire architecture. With regard to the ***numbers of space tourism passengers***, we have assumed in the baseline case that there are 200/year who would pay the price anticipated to go up to the "Gateway Earth" hotel for a week's stay. Even when we reduce the number to 25 tourists per year the case still closes.

With regard to the ***development costs of the tug and gas station***, our baseline assumption was $1B each. If we assumed $20B each for development costs of the tug and the gas station, it would not affect the outcome. In the baseline case, we assumed that the ***fuel needs of the tug*** require refueling once per every two cycles, and that the ***depot itself has enough capacity*** for 5 tug cycles (and therefore the depot needed to be topped-up 5 times per year). We changed this to refueling twice as frequently and these new assumptions are not enough to change the original outcome. We halved the gas station capacity. This change also did not affect the outcome of the economic assessment. With regard to the ***"Gateway Earth" complex*** itself, in the baseline case the government part of the gateway would cost $5B. The sensitivity analysis indicated that when this was increased to $10B, the economic benefit was no longer apparent. This assumption is more critical than the tug or gas station development costs because we have allocated the "Gateway Earth" development costs over only 10 missions (5 years), whereas for the tug and gas station they were allocated over 50 cycles/year for 5 years. With regard to the ***interplanetary spacecraft***, the baseline assumption was that it would require 3 trips per mission ***to deliver the parts*** to GEO for assembly. We increased the amount until 8 trips per mission were needed, and only at this figure the new architecture costs per mission became identical with the more traditional approach. The assumption for ***the costs of the part kits*** for each interplanetary mission can be increased from $200M to $800M per mission before the benefits of the proposed new architecture are canceled out.

9. FURTHER WORK

This paper represents only some very preliminary assessments, and suffers from a lack of real data in several areas. There is a need to conduct primary market research into the likely demand, at reasonable prices, for space tourism up to a GEO outpost. It is crucial to establish as soon as possible, and to a high level of statistical credibility, whether adequate demand exists. From a planning and policy standpoint, it would be beneficial to have a workshop with representatives from the potential commercial businesses, from insurers, from NASA and/or other national space agencies, and from spacecraft manufacturers to discuss the viability of the concept as a whole. There are possibilities for using a few SLS/Orion vehicles within this architecture, especially during the initial setting up of the "Gateway Earth" complex, and work needs to be carried out to integrate the SLS/Orion operations with the setting up of "Gateway Earth" and its support infrastructure.

10. CONCLUSIONS

"Gateway Earth" and its support architecture is a viable economic proposition. Therefore, we can create the bridgehead of the paper's title, which will make subsequent interplanetary missions simpler and cheaper, by using a reusable and regular tug taxi approach. Using this approach, interplanetary travel becomes routine, anchored on the frequent commercial trips of reusable and refuelable craft which are regularly following the highway to GEO, which they have opened up through the creation of a new stage in the space tourism business. Journeys beyond GEO, heading to a whole range of interplanetary destinations, might be conducted at *about a third of* the recurring cost of traditional (ie SLS/Orion) methods. Discussions need to take place between interested parties to determine whether such a joint commercial/government architecture could be managed.

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APPENDIX 1 - DEVELOPMENT COST RECOVERY FOR THE TUG AND REFUELING STATION

Will the tug and refueling station architecture make possible economic savings compared to more traditional ways of getting up to GEO? If so, we can estimate the savings and how many years of operation are required in order to recover their development costs? In Appendix 2, we carry out a similar economic savings analysis for the missions beyond GEO, and explore how many would be needed in order to recover the development costs of the government part of "Gateway Earth". Appendix 3A and 3B provide a detailed flowchart of the relevant calculations and assumptions used. We lay out the alternative ways to achieve insertion into geostationary orbit. Fig App1 shows how the parts of this task may be assembled. Four route segments are considered. Route AA is an expendable rocket launch to LEO. Route BB represents a reusable route to LEO. Route CC is to capture a launch all the way to GEO using an expendable rocket. Route DD is to represent the reusable tug approach from LEO to GEO (and back again).

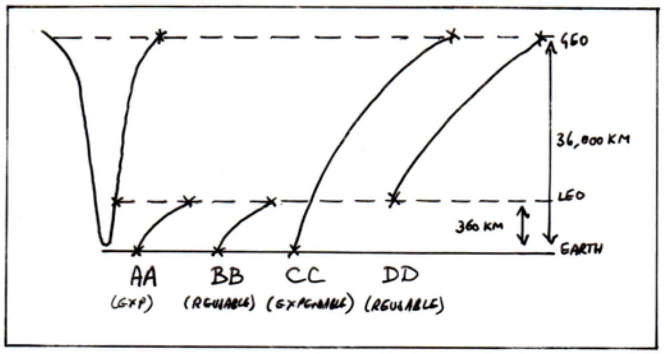


Fig App 1 Comparison cases for various ways of getting crews or cargo out of Earth's gravity well and up to GEO

We find cost data in the public domain which is reliable enough to be used. The Data Annex has been assembled for this purpose, and in Table App1 below we use published data from the relevant part of the Annex.

TABLE App 1 Results of comparison of various routes from Earth's surface up to GEO

SUMMARY RESULTS OF COMPARISON FROM EARTH TO GEO – FULL COSTS				
ROUTE SEGMENT	**AA**	**BB**	**CC**	**DD**
DESCRIPTION	**Expend to LEO**	**Reus to LEO**	**Expend to GEO**	**Reus Transfer from LEO to GEO**
Costing Assumptions	Soyuz L/V + capsule	Falcon 9 + Dragon	Proton L/V + Soyuz	Tug + launch once to LEO + launch of refuel
Calculation	\$50M + \$180M equals \$230M	\$54M + \$86M or \$14M + \$86M	\$112M + \$180M ie \$290M (2008)	\$4M/cycle (devt) + \$0.2M/cycle (launch) and \$5M/cycle (fuel) \$4M/cycle gas stn dvt
Result (2012)	\$230M	\$100M- \$140M	\$310M	\$13M/cycle

Various simplifications have had to be made. In order to derive costs for an expendable trip to GEO, ie Route CC, an entirely notional Proton/Soyuz combination has been assumed, which is a combination that has never been used in practice, although Proton is regularly used to place geostationary communications satellites directly into their operating orbit. Also, for Route BB, the reusable transportation to LEO, two possible values are provided. The first assumes that the SpaceX Falcon 9 is expendable; the second assumes that it proves possible to make it reusable – and Elon Musk's quoted expectation for the price impact of doing this has been used.

In determining the frequency of the LEO to GEO cycles for the tug in route DD, the space tourism traffic forecasts in [11.6] have been used. It was assumed that with around 14,000 space tourists per annum willing to pay around $0.5M to go to LEO, then there would be around 200 space tourists per annum, ie 1% of them, willing to pay more to go to GEO. Of course, at this stage, we do not know the price of a ticket to GEO, but we do know that tickets to the Moon for a circumlunar flight are available (from Space Adventures) for around $150M each and therefore the assumed price to GEO will be somewhere around $50M to $100M. The assumption we have used implies that the space tourists wanting to explore this new destination of "Gateway Earth" are willing to spend about 10% of their net assets to do so. At the present time, there are over 1,000 billionaires and 10 million millionaires, and so the assumption *of just four wealthy individuals/week wanting to take the trip* seems to be supportable, although of course it would be better if we had some direct market research to support this assumption. So, we come up with an interim solution for getting from Earth to GEO represented by combining AA and DD. The representative figure, in 2012 economics, using the stated assumptions, is **$240M** per trip. Eventually, when the launch into LEO becomes reusable, we get an even better cost figure for the trip to GEO represented by combining BB and DD. This result, in 2012 economics, with the stated assumptions, would be **$150M**, or down to as low as **$110M** if the Falcon 9 becomes *fully* reusable. All of these figures turn out to be *only about half of the costs* of the traditional approach (**$310M**).Thus, we have demonstrated that we can recover the development costs of the tug and LEO refuel depot, through the economic savings generated *over a period of 5 years*, given the key assumptions used.

APPENDIX 2 - DEVELOPMENT COST RECOVERY FOR THE “GATEWAY EARTH” COMPLEX

We may now extend the same approach that we have just used for reaching GEO to considering interplanetary transfers beyond GEO. Appendix 3A and 3B provide the calculation flowchart and the assumptions used for the baseline case. Fig App 2 describes the two main alternatives – either we use the Route FF approach, which employs a single giant rocket all the way from the surface of the Earth, or we use the new approach made possible by the architecture proposed in this paper, viz we start off assembling the interplanetary craft at the “Gateway Earth” complex in GEO, and send it onwards with the relatively small amount of fuel it requires.

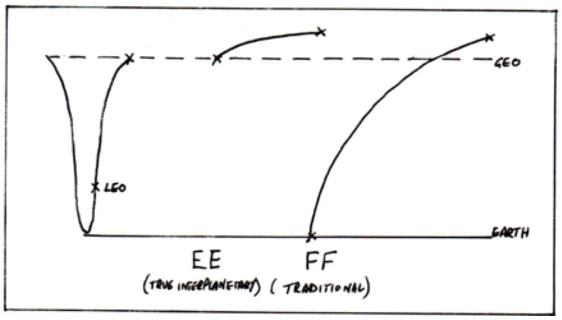


Fig App 2 Comparisons beyond GEO heading with crews or cargo to interplanetary destinations

Table App 2 below provides the results of this comparison, under the stated assumptions.

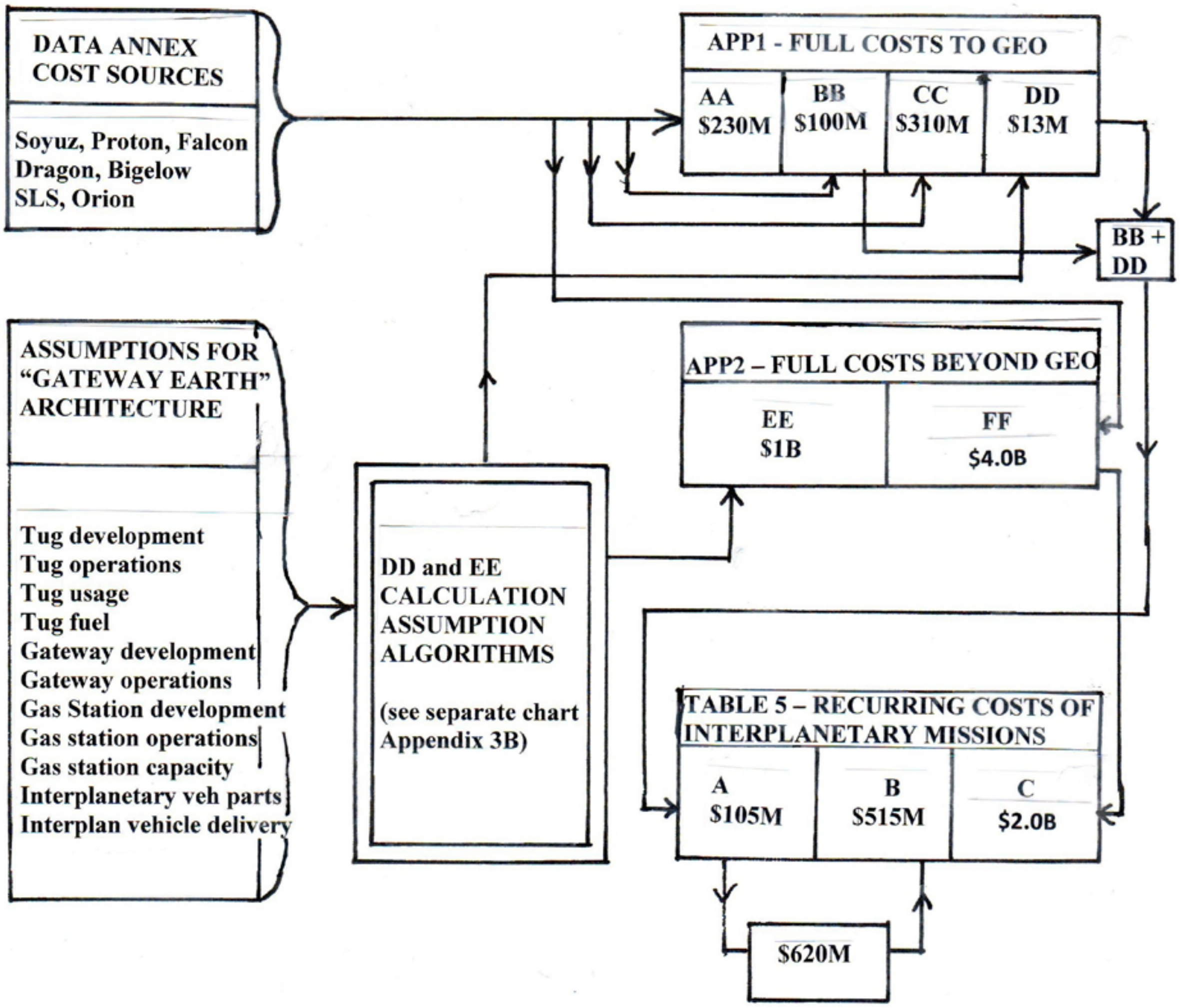
Table App 2 Results of comparisons of various options for taking crews or cargo beyond GEO

RESULTS OF COMPARISON BEYOND GEO - FULLY LOADED COSTS		
ROUTE SEGMENT	**EE**	**FF**
DESCRIPTION	**True Interplanetary Pass/cargo from GEO on outwards**	**All the way direct from Earth on interplanetary mission**
Costing Assumpts	Mix of govt and commercial parts for "Gateway Earth" + Assembly of true interplanet Vehicle	Apollo costs or SLS/Orion costs
Calculation	Gateway $5B development (based on 2 missions/yr and 5 yrs) Interplanetary vehicles $200M parts plus $340M for delivery to GEO	$24B (1969) X 6.2 = $150B (2012) is $25B(2012) per mission or $30B (2012) based on SLS and Orion spread over 10 yrs (ie 10 missions)
Result (2012)	$1.0B per mission	$25B (Apollo) per mission or $4B - $14B (SLS/Orion) per mission

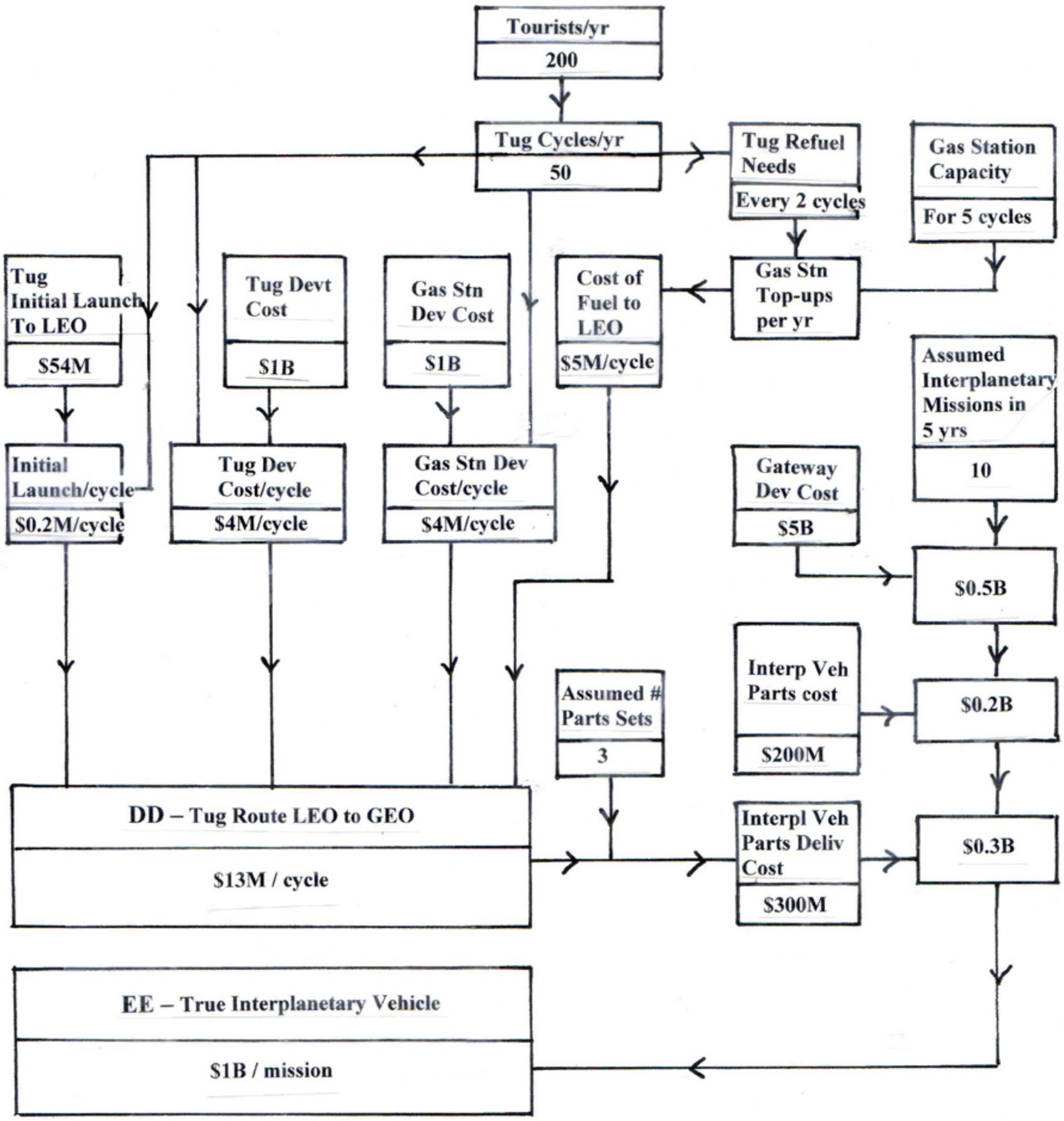
Note that we have used Apollo and SLS/Orion costings as a representation of the "traditional" way, for comparison with the proposed new approach using "Gateway Earth" and its supporting infrastructure. We assume as a baseline that a ROM figure for the governmental part of the gateway development costs would be $5B (since the government part is much smaller and simpler than the ISS, much more like the Skylab station) , and allocate these costs over an assumed 2 interplanetary missions per year and a 5 year lifetime of the Gateway. We also assume it takes six trips/year to deliver the parts of the two interplanetary spacecraft up to GEO. Thus, the allocated "Gateway Earth" development cost is $0.5B per mission, and we have allowed $515M mission-specific costs on average for the interplanetary spacecraft. For SLS/Orion we have assumed that Orion is reusable for 10 missions (ie 5 yrs).

With these preliminary assumptions, we consider the full final interplanetary solution, which assumes an initial fully reusable launch to LEO, and results in a combination of BB+DD (from Appendix 1) + EE, producing a value of $1.1B/mission. And finally, for comparison, we have the traditional approach using a big booster to go all the way, and this assumes something like the SLS/Orion or Apollo approach, and this is the Route FF solution, with a value of $4B per mission.Thus we can say that, using our baseline assumptions, the full ROM cost per mission for interplanetary missions which use the "Gateway Earth" station and its reusable tug support infrastructure would be *less than a half* the cost of the traditional approach. It would be possible to recover the development costs of the governmental part of the "Gateway Earth" complex *within about 5 years of operation*, through savings in the costs of interplanetary missions during that period.

APPENDIX 3A
OVERALL BASELINE ECONOMIC COMPARISON SCHEMATIC



APPENDIX 3B
"GATEWAY EARTH" ARCHITECTURE ECONOMIC ANALYSIS
BASELINE ASSUMPTION ALGORITHMS AND SENSITIVITY VARIABLES



DATA ANNEX

1. Soyuz Launch Vehicle

Launch cost: $30M - $50M *2004* [1]; $40M *2008* [5];
Payload: 7,000kg to LEO [1]; 6,600kg [7]

2. Soyuz Capsule

Launch mass: 7,220kg [2];
Capsule cost: $63M *2011* per seat [10, 11]

3. Falcon 1 Vehicle

Launch cost: $50M *2004* development costs [1]; $5.9M *2004* per payload [1]; $7.0M *2008* per payload [5];
Payload: 670kg to LEO [1]

4. Falcon 9 Vehicle

Launch cost: $300M *2013* development costs [9]: $56M *2013*[7]; $140M *2013* including Dragon [10]; $50M *2013* to LEO [9]; $54M *2013* to LEO [9]; factor ¼ for reusable [9]; Falcon Heavy $83M (2012) to GTO [21]
Payload: 16,600kg to LEO [7]; 13,000kg to LEO [9]; 5,760 kg to GTO [7];
Fairing size: 17ft [4]

5. Proton Launch Vehicle

Launch cost: $60M - $75M *2004* for GTO [1]; Proton/Breeze M $112M *2004* [1]; $85M *2013* [7]; $70M - $75M *2008* [5];
Payload: 21,000kg to LEO [1]; 6,200kg to GTO [2]

6. Saturn V Launch Vehicle

Launch cost: $10B *1969* for 8 [8]; $1.2B *1969* [7];
Payload: 118,000kg to LEO [7]

7. Historic Capsules

Launch masses: Mercury – 1 man – 1,290kg [2]; Vostok – 1 man – 4,730kg [2]; Gemini – 2 man – 3,230kg [2];
Apollo Command and Service Module - 3 men - 44,000kg [2]

8. Apollo Costs

Overall program: $24B *1969* [8];
Breakdown: $8B *1969* spacecraft [8]; $10B *1969* launch vehicles [8]; $6B *1969* ground ops [8];
Spread: over 10 years with $3B *1969* per year max [3]

9. Dragon Capsule

Launch mass: 4,200kg (dry) [10];
Cargo capacity: 3,300kg [10];
Capsule cost: "Dragon plus Falcon 9 dev costs $800M to $1B *2013* " [10]; $20M *2013* per seat (out of 7) [10];
$80M *2013* per capsule – ie $133M *2013* - $54M *2013*[9]; $96M per capsule (crewed version).

Note: No incremental charges assumed for Dragon returns from LEO to Earth (due to minimal fuel requirements and ticket prices assumed 2-way).

10. SLS

Payload: 70,000kg to 130,000kg to LEO [7]; 5 meter fairing.
Launch cost: $500M *2013* [7]; $500M *2013* [13]; $1B - $2B [22]
Dev cost: $10B *2013*[13]; $2B/year *2013* [15, 22]

11. Orion/MPCV

Launch mass: 31,000 kg gross lift off [14];
Capsule cost: Dev cost $6B *2013* (crew of 4) [13, 14]; $1B *2013* per year [15, 22]
SLS/Orion combo: $4B/launch (at 1 launch/yr) or $10B per launch (at 1 launch/ 4 yrs) [22]

12. Historic Space Stations

Launch masses: Salyut 18,500kg [2]; Skylab 75,000kg [2]; Mir 137,000kg [2];
Capacity: Skylab 319 cub meter [18]; Mir 350 cub meter [19]; ISS 935 cub meter [20].
Dev cost: Skylab $2.2B *1970* [18]; ISS $100B *2013* [12]

13. Gateway Earth

Commercial parts are based on Bigelow modules (below), and government parts like ISS (see Sect 11 above).
Launch mass: Bigelow BA 330 at 20,000kg [17];
Capacity: Bigelow [17] Genesis 11.5 cub meter; BA 330 at 330 cub meter;
Bigelow cost: $26M *2013* [6]; $25M *2013* for 1/3 module for 60 days [6]: BEAM module for ISS at $17.8M *2013* [17]

14. Tug - Assumptions for tug based upon Dragon (see Sect 9 above)

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