IAC-21,C3,1,5,x62540

The impact of EmDrive Propulsion on the launch costs for Solar Power Satellites

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Abstract

This paper addresses the problem of achieving the major launch cost reduction required for the economic viability of any SPS system. The EmDrive (Electromagnetic Drive) is a novel propulsion technology which has been the subject of worldwide Research and Development activity over the last 20 years. One of the early requirements was for a heavy launch vehicle which would, in the words of the USAF, "provide a space elevator without the cables". At the 2008 IAC conference an aerodynamic model of a spaceplane was exhibited. In a 2013 IAC conference paper, a hybrid EmDrive propelled, reusable spaceplane was described, with a 50 tonne payload to GEO. Using 3 spaceplanes for 134 launches, a 2GW SPS would take less than a year to build in orbit using tele-robot assembly. The total launch cost was then estimated at $1.5Bn.A further spaceplane concept, this time a single stage to orbit type, based on the USAF X37B outline, was described the following year. These early launch vehicle concepts used second generation EmDrive thrusters, with YBCO superconducting technology, cooled with Liquid Hydrogen. Although these engines would provide the required high levels of thrust, they suffered from acceleration limitations due to internal Doppler shifts. A solution was established using pulsed Doppler correction, circular polarisation and dual cavity thrusters. These third generation thrusters were incorporated into a number of design studies, including the Heavy Launch Vehicle described in this paper. The vehicle resembles the original spaceplane concept of 2008, and is unmanned and fully reusable, with a 500 mission lifetime. The launch mass is 116 tonnes and the payload capacity is a minimum of 50 tonnes to GEO. The acceleration levels are very low (.014 g mean) which allows a simple, low stressed, airframe, and the ability to carry an un-faired payload attached underwing. The maximum velocity through the atmosphere is a mere 70 mph, though 6 hours of continuous acceleration eventually gives GEO velocity. Both take off and landings can be carried out vertically, from any airfield. It is truly a space elevator without cables, with the additional advantage of precision manoeuvrability, to assist positioning and assembly of the SPS components in orbit. Early cost estimates give a specific launch cost to GEO of $11/kg. Clearly the use of EmDrive propulsion will make the economic case for SPS unassailable in the future.

1 Introduction and background

Although it is self-evident that Solar Power Satellites (SPS) are an ideal solution to the global requirement for sustainable electrical power, the launch costs are prohibitive. Chemical propulsion is not likely to bring down these costs to an acceptable level in the near future. An alternative propulsion system is clearly needed if the SPS concept is to flourish, as it should.

The problems with chemical propulsion are not new and many solutions for alternatives have been proposed. In his 1974 Royal Institution Christmas lecture, Professor Eric Laithwaite introduced the idea of propellant-less propulsion using a gyroscope, [1]. Although this caused great controversy, the idea was noticed by the UK Ministry of Defence, who were having propulsion problems on the Top Secret Chevaline project. There were major concerns over the safety of the liquid fuelled engines which were part of the re-entry system. These were raised at the highest government levels, as shown in the recently released cabinet papers, [2].

The Sperry Gyroscope Company at Bracknell UK, part of the US Sperry Corporation, was a major contractor on the Chevaline programme, and in early 1975 were tasked to look at unconventional solutions to the propulsion problems. The team were actually asked *"to think the unthinkable"*. Solutions based on purely mechanical systems, including gyroscopes, were eventually ruled out. However an electromagnetic (EM) solution was proposed by the author, which was considered possible, although the thrust would be low. A key reference used in the EM proposal, was the work carried out by Professor Alex Cullen of UCL, on the use of radiation pressure for microwave power measurement using fundamental physics, [3]. Further work had also been carried out at RRE Malvern by Dr Bailey, a former student of Cullen, [4]. Although the EM solution was not adopted for Chevaline, the ideas were followed up in the public domain. In October 1976 Professor Roger Jennison of Kent University published the first of a series of papers on aspects of EM momentum, [5]. The paper contains details of experimental equipment using a Gunn Diode source and an open resonant cavity. The Kent University work carried on through to 1989, and was one of the concepts considered in the British Aerospace Greenglow programme [6].

In November 1988, the first of the EmDrive patents was filed, based on a cylindrical resonant cavity with a shaped internal dielectric. The device gave thrust due to the different EM propagation velocities, and hence different radiation pressures, at each end of the cavity. The Patent was granted and published on 5 May 1993, [7]. A second patent was filed in April 1998 based on a tapered cavity, and showed how the thruster complied with both conservation of momentum and conservation of energy. This patent was granted on 19 April 2000, [8].

In early 2001, a small R&D company was set up, Satellite Propulsion Research Ltd (SPR). An 18 month contract from the UK government was won to design, build and test an Experimental Thruster. The contract was run under the Department of Trade and Industry SMART scheme, and technical monitoring was carried out by Dr David Fearn of The Royal Aircraft Establishment (RAE) Farnborough, a world expert in Spacecraft Electric Propulsion. This first contract resulted in a technical Report in September 2002, [9] and an independent review [10].

The first public paper on EmDrive was given at a BIS symposium in October 2004, and subsequently published in their journal [11]. A three year UK government contract was won, to develop a Demonstrator Engine for satellite propulsion. In July 2006 a technical report was provided, [12] followed by a second independent review, [13]. The UK government reports and reviews were released in 2016, are now available on the SPR Ltd website.

Work continued on the Demonstrator Engine and a series of dynamic tests on a rotary air bearing successfully demonstrated compliance with Newton's second law. A video of one of the test runs, carried out on 31 October 2006 was released in 2015, [14].

Discussions with Boeing were started, and resulted in an End User Undertaking being submitted to the UK Export Control Office in June 2007, [15]. An export licence was granted on 14 January 2008. A paper was given at the IAC-08 conference held in Glasgow in 2008, [16]. In addition a 2m sized aerodynamic model of an EmDrive propelled spaceplane was brought from Gibraltar, where it had been tested, and was exhibited at the conference. The model is shown in Fig.1

Fig.1.Aerodynamic test model of EmDrive Spaceplane

The basic airframe design has been maintained through a number of design iterations, and the latest version is described in this paper. SPR Ltd were contacted by the USAF, to set up a meeting in the Pentagon. This meeting took place on 10 December 2008, chaired by the director of the National Security Space Office (NSSO). A separate meeting with DARPA also took place on 12 December. Following a suggestion from the Air Force Research Laboratory (AFRL), a test was carried out at SPR Ltd, using a long pendulum which gave no indication of thrust. This was the first confirmation of the need to load the thruster, in order to comply with the law of conservation of energy. Subsequent tests by a number of research groups have confirmed this finding.

On 29 May 2009 a Technical Assistance Agreement was sent to SPR Ltd by Boeing which enabled a transfer of EmDrive technology to the US to take place, [17].The transfer was carried out under the Boeing Purchase Contract No 9CS114H, which was completed in September 2010 with the acceptance of a final report. A mean specific thrust of 326mN/kW was reported for a series of 19 formal performance tests. Issue 2 of this report, describing the development and test of a Flight Thruster was released by SPR Ltd in December 2017, following the expiry of NDAs, [18].

Due to the initial public controversy the EmDrive concept generated, research work started at The North Western Polytechnical University in China and was completed with the publication of a paper in December 2010, where a maximum thrust of 315mN was reported at 1000W input power, [19]. The work was continued using a force-feedback thrust stand, normally used to test flight qualified microwave ion thrusters. A maximum thrust of 720mN, at an input power of 2500W was eventually reported in a paper in December 2012, [20].

With the completion of the basic experimental work, a number of application studies were carried out at SPR Ltd, and in a 2013 IAC conference paper, a Hybrid second generation, EmDrive propelled, reusable spaceplane was presented, with a 50 tonne payload to GEO [21].This spaceplane concept is illustrated in Fig.2

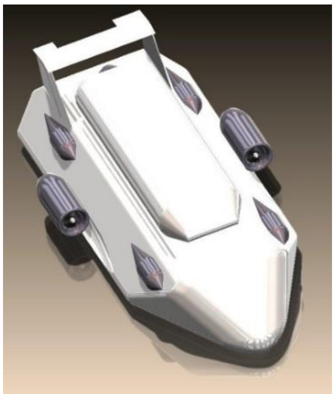

Fig.2 Hybrid Spaceplane Concept

The problem of Doppler shift in an accelerating high Q cavity was addressed in the 2013 IAC paper, and was also worked on by researchers in both the USA and China. A UK solution was established using closed loop Doppler correction, circular polarisation and dual cavity thrusters and a patent was filed in April 2015 and granted in August 2021 [22]. These third generation thruster designs were incorporated into a number of design studies including the Heavy Launch Vehicle described in this paper. This long R&D programme has finally resulted in a launch vehicle design, which is at last capable of fulfilling the need for *a space elevator without cables*, which was first described by the USAF in 2008.

2. Description of the Heavy Launch Vehicle.

The Heavy Launch Vehicle (HLV) outlined in Fig.3, resembles the original spaceplane concept of 2008 but is now based on a more detailed engineering design study. The HLV is an unmanned fully reusable vehicle with a 500 mission lifetime. The launch mass is 116 tonnes and the payload capacity is 50 tonnes to GEO. The acceleration levels are very low (.014 g mean) which allows a simple, low stressed, airframe, and the ability to carry an un-faired payload attached underwing. The maximum drag through the atmosphere occurs during vertical flight at 150mph, at an altitude of 10 miles, and both take off and landings are carried out vertically. It provides routine low cost access to space, with the additional advantage of precision manoeuvrability, to assist positioning and assembly of the SPS components in orbit. The vehicle length is 28.8m, with a height of 7.8m and a wingspan of 19.5m.

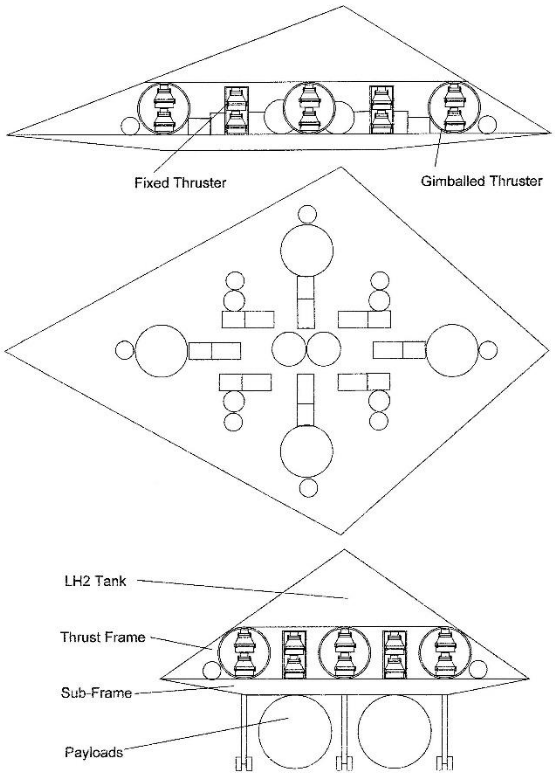

Fig.3. Outline of SPS Heavy Launch Vehicle

The outline shows the Heavy Launch Vehicle carrying two rolled up solar arrays underwing. The lack of any payload fairing due to low velocity through the atmosphere allows immediate docking with the SPS under construction. Once in orbit, attitude control and manoeuvring are carried out using the four fully gimballed thrusters. The four fixed thrusters are used for continuous lift during the 7 hour launch phase.

Each thruster comprises two superconducting microwave cavities operating in TE211 mode at 530 MHz. The cavity diameters are 900mm and 550 mm with an axial cavity length of 940mm. The cavity is illustrated in Fig.4.

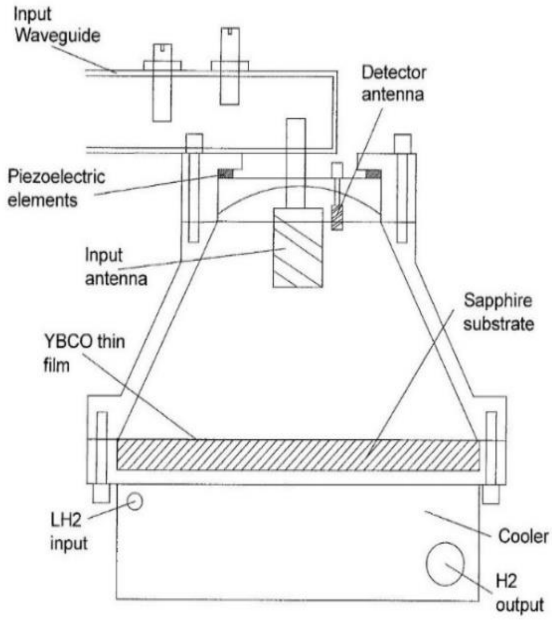

Fig. 4. Superconducting Cavity

The cavity is cooled by liquid hydrogen (LH2) which ensures that that the Yttrium Barium Copper Oxide (YBCO) superconducting coating remains well below critical temperature. Some of the boiled-off hydrogen gas is used to cool the microwave Solid State Power Amplifiers (SSPA) and Fuel Cells and then used, together with liquid Oxygen, to provide the electrical power to the thrusters. Circular polarisation of the microwave input power is used to enable instantaneous Doppler Shift to be detected which is compensated in real time using piezoelectric elements to extend path length. Application of DC voltage to piezoelectric elements gives control of end plate alignment. Square wave modulation is used to reset path length extension, as illustrated in Fig.5.

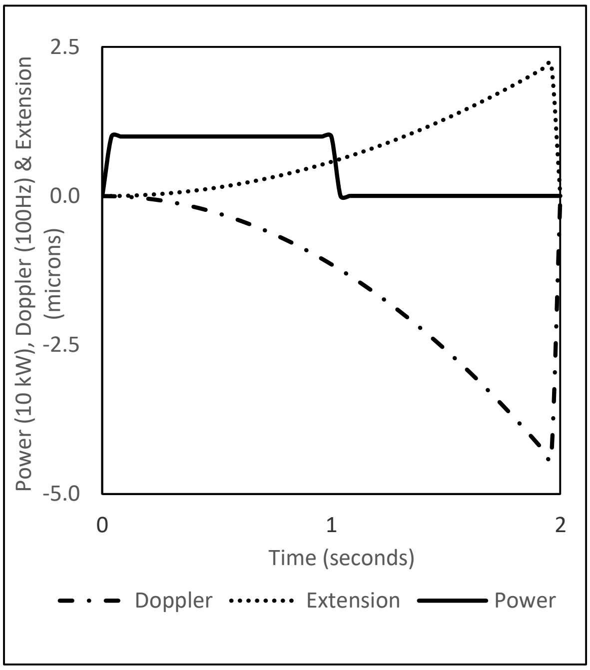

Fig.5. Cavity Operation Under Acceleration

The two cavities are mounted in line and powered using alternative pulses. This allows reset of the cavity length, whilst still maintaining constant thrust. This is illustrated in Fig.6.

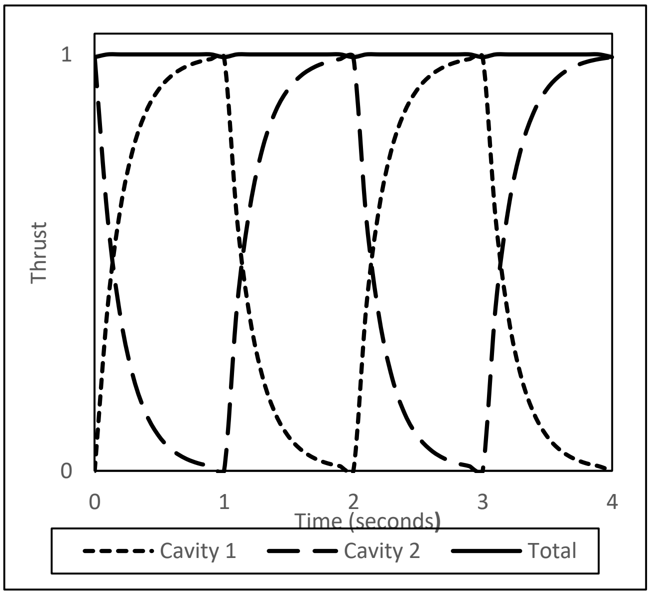

Fig.6. Two Cavity Thrust

A block diagram of the system controlling frequency, modulation and extension is shown in Fig.7.

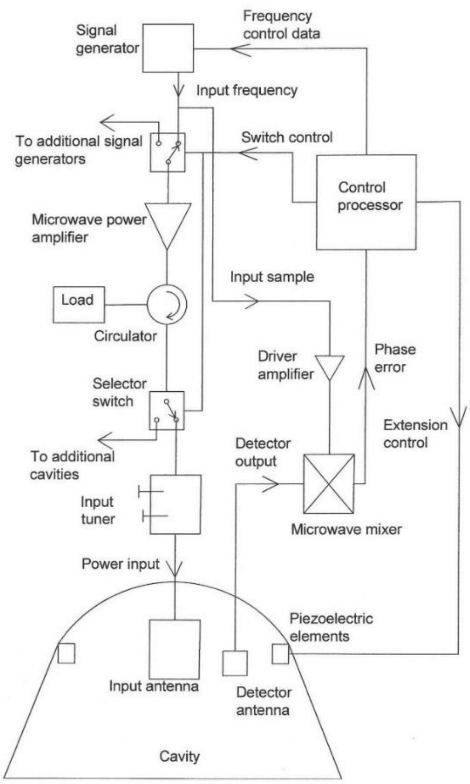

Fig.7. Thruster control system

The Thruster includes an input circuit with an input antenna capable of propagating a circularly polarised waveform inside the cavity. A second, much smaller detector antenna can then be used to detect the reflected wave, which will have the opposite polarisation to the input waveform. This opposite polarisation enables any phase difference between the input waveform and the reflected waveform to be measured and the measurement used to correct the phase of the input waveform. The system forms a phase locked loop, which corrects the Doppler shift caused by the acceleration of the cavity, and which if left uncorrected would cause a reduction in Q value and thrust.

A mass budget has been prepared for the SPS launch vehicle design and is the result of an iterative process where vehicle performance and mission parameters are varied to provide an optimum budget. The budget includes a 30% contingency factor for the major performance and mass parameters, as is consistent with good design practice for preliminary designs.

For the mass and dimensions of the solid State Power Amplifiers and Fuel Cells, which form a major part of the propulsion system mass, specific mass and volume data from commercially available equipment is used. The EmDrive cavity data is based on existing cavity designs and measured performance data.

The preliminary mass budget is given in Table.1

Table 1. HLV Mass Budget.

Item	Mass (Tonnes)
Payload	50
Fuel	22.59
Airframe	14.33
Thrusters	4.32
SSPAs	11.97
Fuel Cells	8.27
LH2 tank	3.53
LOX tank	0.99
Launch Mass	116

3.HLV Performance

The performance of the HLV is determined by the EmDrive thrust equation, derived in an IAC-08 paper [21].

$$T = \frac{2P_0Q_uS_0}{c}\left\{\frac{\lambda_0}{\lambda_{g1}} - \frac{\lambda_0}{\lambda_{g2}}\right\} \qquad (1)$$

Where:

$$S_0 = \left\{1 - \frac{{\lambda_0}^2}{\lambda_{g1}\lambda_{g2}}\right\}^{-1}$$

T = Static Thrust (N)

P_0 = Power (W)

Q_u = Unloaded Q

λ_0 = Free space wavelength

λ_{g1} = Guide wavelength at large end plate

λ_{g2} = Guide wavelength at small end plate

For the HLV thruster design, a static specific thrust of 3.2kN/kW is calculated for an unloaded Q_u of 6.23×10^8.

This equation gives the thrust obtained from a static thruster, but as Q_u is the unloaded Q of a resonant cavity, then once the cavity accelerates under the effect of the generated thrust, then Q becomes loaded with the kinetic energy transferred to the vehicle. This can be appreciated by considering the definition of Q which is:

$$Q = \frac{\textit{Stored energy}}{\textit{Energy lost per cycle}} \qquad (2)$$

Thus EmDrive is fundamentally a stored energy device, and under acceleration the kinetic energy is an additional loss, and therefore Q will decrease, and thrust will decrease.

Following switch on, stored energy is built up over a time constant τ, given by:

$$\tau = \frac{Q_u}{\pi F} \qquad (3)$$

Where F = Resonant Frequency (Hz)

Typically the pulse length of a third generation EmDrive thruster illustrated in Fig.5 is 5τ.

It is therefore necessary to limit the acceleration of the vehicle over the pulse length, to ensure that the kinetic energy transferred to the vehicle does not significantly reduce the stored energy and thus the thrust. It is important that the thruster design and operation takes into consideration both vehicle mass and mission acceleration requirements.

This is illustrated in Fig.8 which shows the effect of vehicle mass on thrust, for a constant power input of 7.4 kW.

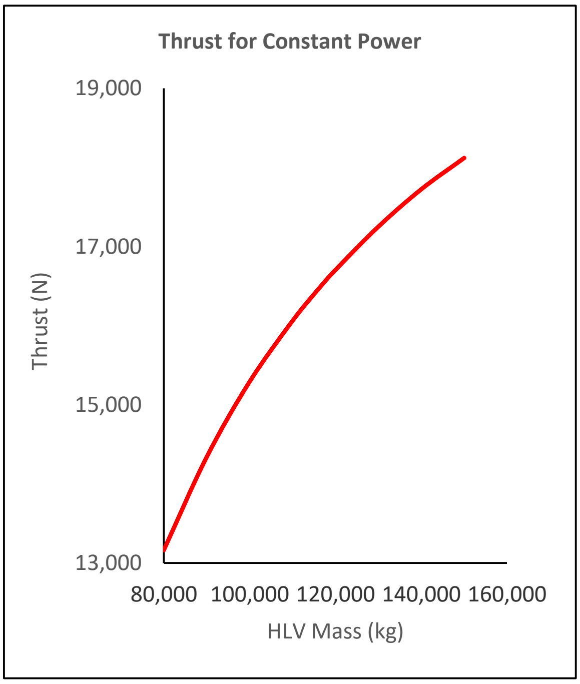

Fig. 8 HLV thruster performance under acceleration

For the thruster performance given in Fig.8, a mean acceleration of 0.142m/s/s is achieved for a vehicle mass of 116,000 Kg, when the thruster is producing a specific thrust of 2.2kN/kW.

A further mission input is the maximum acceleration of the vehicle in the direction opposite to the direction of thrust. For any vehicle within the Earth's gravity this is 9.81m/s/s. In this situation the Kinetic energy loss does not occur because the accelerating force is not due to the EmDrive thrust. However if the Doppler shift, which in this case is positive, causes the frequency to move outside the bandwidth of the cavity frequency control system, the thrust will be significantly reduced. Thus if the vehicle momentarily lost lift, and was subject to full gravitational acceleration, recovery could be compromised. Clearly this is an unacceptable condition.

Fig. 9 shows the loss of specific thrust as the control loop response time increases, for an acceleration of 10m/s/s.

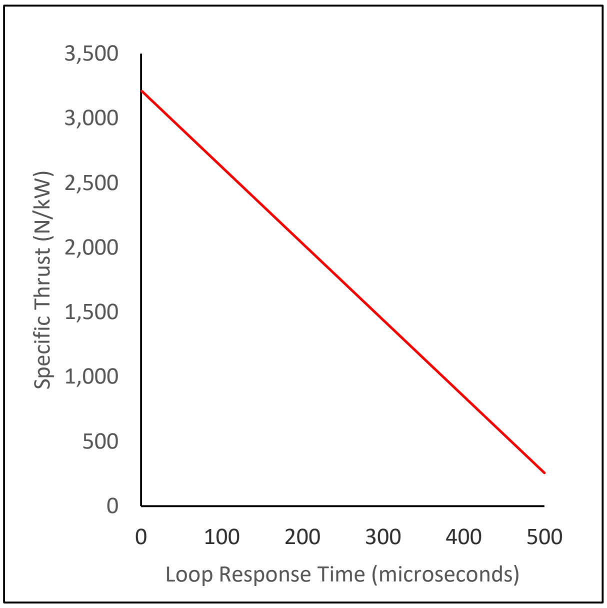

Fig.9 Control loop response

For the HLV thrusters the loop response time is set to 10 microseconds meaning that even under full Earth gravitation acceleration, the specific thrust remains at 98% of maximum. With the thruster design compliant with operation under Earth's gravity, and with a forward acceleration of 0.142m/s/s, for a vehicle launch mass of 116 Tonnes, a mission analysis can be carried out.

4. Mission Analysis

The HLV launch mission to GEO is analysed in a different way to a typical ballistic rocket launch. The launch mass is overcome by a direct lift force generated by the four fixed thrusters. The vehicle is therefore vertically launched from a standard horizontal aircraft-like attitude. The fixed thrusters give additional thrust to provide an acceleration force to give the specified 0.142m/s/s vertical acceleration. The fixed thrusters are capable of giving pitch and roll control in one of the many thruster redundancy configurations. The four gimballed thrusters provide horizontal acceleration force as well as primary pitch, roll and yaw control. Each gimballed thruster is rated the same as the fixed thrusters. Each thruster, complete with its associated SSPA and fuel cell is rated at a maximum thrust of 370kN, at a maximum acceleration of 0.142m/s/s, for input microwave power of 166kW and a DC electrical power of 369kW. This allows any four thrusters to provide full lift to the launch mass, with 30% design margin.

The numerical analysis is therefore carried out a by calculating velocity in the horizontal axis, and rate of climb and altitude in the vertical axis, for increments in mission time. The launch objectives are to achieve an orbital velocity (horizontal) of 3,075m/s at an altitude of 36,000km with a final rate of climb of zero. The launch mass of 116 Tonnes is reduced during the flight, as the fuel mass decreases. LH2 is initially used for thruster cooling, and the rate of LH2 use is dependent on the total microwave power input to the thrusters at any given point in the flight, and the latent heat of LH2. The flow rate of LOX is dependent on the DC electrical output of the fuel cells, whilst the H2 input is some of the boiled off gas from the thruster cooling process. The remainder of the cold H2 gas is used for SSPA and fuel cell cooling, before being vented from the top of the vehicle. Clearly the analysis needs to be run a number of times in an iterative process to achieve the launch objectives whilst optimising total fuel use.

The launch dynamics are shown in Fig.10.

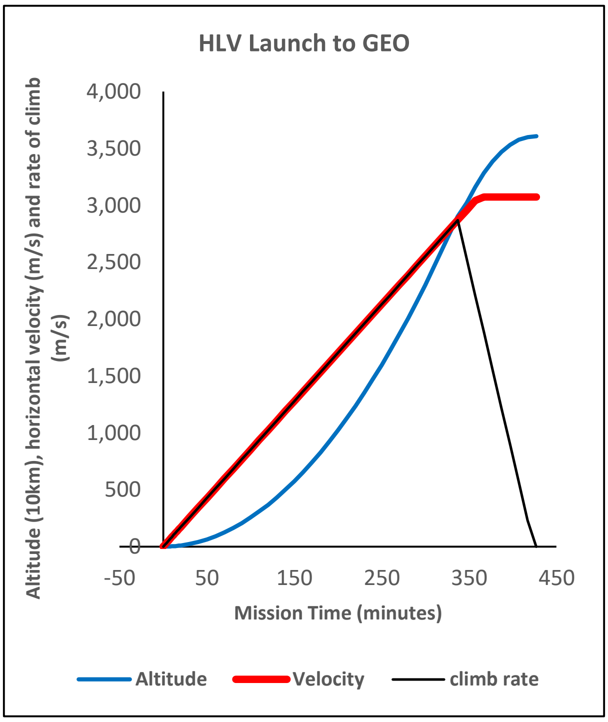

Fig.10 Launch profile.

The return flight is analysed in the same manner, with the initial return mass taken as launch mass minus payload and fuel mass used for launch.

The return flight dynamics are shown in Fig.11.

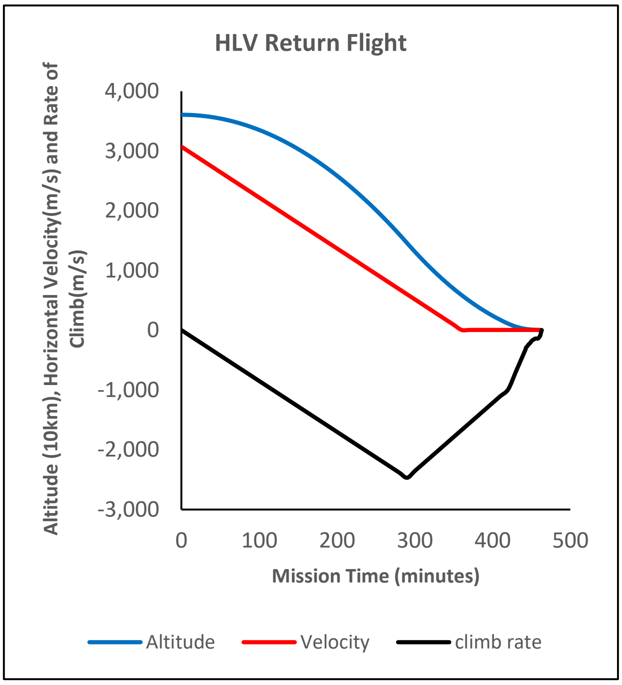

Fig.11 Return Flight Profile

Whilst the minimum time to achieve GEO orbital velocity at a constant acceleration of 0.142m/s/s is 6 hours, the need to optimise climb rate and altitude leads to a launch mission time of 7 hours 7 minutes, and a return flight time of 7 hours 43 minutes. The analysis assumes the SPS orbital slot and launch site position are optimised to minimise flight times. Fuel usage is shown in Fig.12.

Clearly the rate at which fuel is used depends on the thrust requirements and Fig.12 shows that the maximum fuel flow rates are at the beginning of the launch phase and at the end of the return flight. This is when Earth's gravity is at the maximum of 9.81m/s/s, whereas at GEO altitude it is a mere 0.22m/s/s. The bulk of fuel use is taken up by providing lift to counter vehicle weight, whilst acceleration uses only a modest fraction of the total.

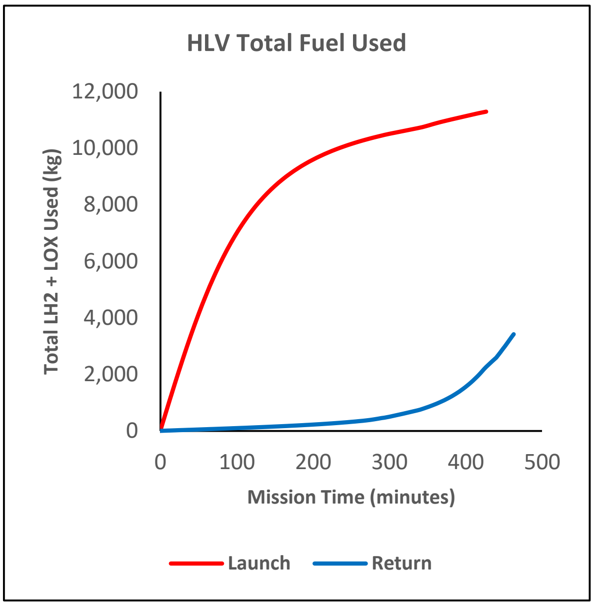

Fig 12. Total LH2 and LOX used for launch and return flights

Note that aerodynamic braking is not utilised in the return flight whilst drag is taken into account for the launch mission. The analysis gives a fuel margin for the total mission of 35%.

The overriding constraint is the maximum forward acceleration (0.142m/s/s) during launch, due to the stored energy nature of the thrusters, and the need to comply with the law of conservation of energy. During the return flight, deceleration rates are limited to a nominal 0.1g (0.981m/s/s) to minimise mechanical loading, and thruster cooling. The higher rate is obtained, without detriment to the specific thrust as deceleration means kinetic energy is added to the stored energy. The limit on stored energy then becomes dependent on cavity losses, and results in a small increase in LH2 coolant flow.

5.Operational Costs

The dominant cost of the overall operational cost of SPS launch is the initial development cost of the HLV. It has always been the objective to operate the vehicle for a minimum of 500 missions before major maintenance or replacement. For an unmanned vehicle, with a fully solid state propulsion system, and low mechanical and thermal stress during flight, this is considered a conservative approach.

Fig.3 shows that the HLV structure comprises a thrust frame with 8 thrusters, supporting a large Liquid Hydrogen (LH2) tank, with a sub-frame below the thrust frame. On the SPS launch vehicle the sub-frame includes the undercarriage and the payload attachment fixtures. However it is envisaged that there will be a family of vehicles where the sub-frame is replaced with a freight hold or two standard shipping container attachment points, to enable fast point to point freight transport at sub orbital altitudes. Inevitably military applications will also evolve, including global sub-orbital cargo delivery and hypersonic strike missions from a vehicle based on the HLV. This wide range of terrestrial applications will ensure that large numbers of vehicles will be built. The low acceleration and low atmospheric velocities result in low mechanical and thermal stress on the airframe. This means that conservative airframe design and conventional materials will lead to mass production techniques more familiar to the truck industry, rather than the aerospace industry. This approach will ensure that costs are reduced significantly compared to traditional aerospace programmes.

It is therefore estimated that the unit cost will be approximately $250M. This may be compared with the current quoted price of $185M for a 767-300F freighter aircraft which has a similar payload capacity, with higher take-off mass and fuel load. For 500 missions, the capital cost is therefore $500k per mission. This assumes no write-off costs per vehicle. This is conservative, as following a refurbishment, a second ownership sale will bring in additional revenue. The main operating systems on the vehicle (control and propulsion) are all solid state, and with the exceptions of cryogenic valves and thruster gimbals, are unlikely to require significant maintenance over 500 missions. It is assumed that with a total flight time of 15 hours, with efficient on orbit operations, and rapid ground refuelling and payload attachment, one mission per day would become routine.

Assuming LH2 cost is $0.7 per kg for manufacture at launch site, and LOX cost is $0.1per kg, then total fuel cost per mission is $12.9k. Assuming a shift team of 20, with each mission requiring 3 shifts, labour and overheads costs are estimated as $31.2K. Note the launch site consists of an area of tarmac of a size less than a supermarket car park, with an adjacent hanger for payload attachment and refuelling. Pre-flight checkout will be largely automated as are most flight operations, with manual tele-control only required for SPS docking and payload deployment. All ground operations would be modelled on routine airline practice.

The total cost per mission is therefore estimated as $544.1k which gives a payload launch cost to GEO of $10.9 per kg.

6.Conclusions

This paper has illustrated the progress of EmDrive development from the early concept, as a propulsion solution for a very highly classified defence problem, through to a solution to low cost access to space.

The technology has been shown to be compliant with classic physics, both theoretically and experimentally and it is therefore time for commercial development to start, and for EmDrive to come out of the shadows of the defence world.

The paper has described an unmanned, reusable Heavy Launch Vehicle, weighing 116 Tonnes, capable of carrying a 50 Tonne payload to GEO. A mission analysis has determined launch and return flight times of less than 8 hours with an overall fuel margin of 35%.

With a nominal 500 mission lifetime, a low technology airframe, and airline type operation, a cost analysis has resulted in a payload cost of less than $11 per kg.

A payload launch cost of $11 per kg to GEO would make Solar Power Satellites the prime choice for renewable energy supply, and thus a major solution to the ever closer global warming crisis.

References

1. Laithwaite. E. The gyroscope, an Engineer and the Christmas lectures. The Royal Institution. www.ribg.org

2. Chevaline: Polaris improvement programme. National Archives ref CAB301/734

3. Cullen. A.L. Absolute Power Measurement at Microwave Frequencies. IEE monograph No 23. 15 February 1952. www.emdrive.com/cullenpaper0001.pdf

4. Bailey R A. A Resonant–Cavity, Torque-Operated Wattmeter for Microwave Power. IEE

monograph No 138R. June 1955.
www.emdrive.com/baileyrrepaper.pdf

5. Jennison R C. and Drinkwater A J. An approach to the understanding of inertia from the physics of the experimental method. University of Kent J.Phys. A: Math. Gen Vol 10 No. 2 1977

6. Evans R. Greenglow and the Search for Gravity Control. Troubador Publishing. 2015. ISBN 978-1784620-233

7. Shawyer R. Electrical Propulsion Unit for Spacecraft. Patent No GB2229865B

8. Shawyer R. Microwave Thruster for Spacecraft Patent No GB2334761A

9. Technical Report on the Experimental Microwave Thruster. Issue 2. SMART Feasibility study Ref 931. DTI. Sept 2002
www.emdrive.com/FeasibilityStudytechnicalreportissue2.pdf

10. Spiller J W. Review of Technical Report on Experimental Microwave Thruster 29 October 2002
www.emdrive.com/reviewofexperimentalthrusterreport.pdf

11.The Development of a Microwave Engine for Spacecraft Propulsion Space Chronicle. JBIS Vol.58, Suppl.1 2005

12. Technical Report on the Development of a Microwave Engine for Satellite Propulsion. SEEDA R&D Project Ref.1939. DTI. Issue2. July 2006
www.emdrive.com/DemonstratorTechnicalReportIssue2.pdf

13. Spiller J W. Review of Technical Report on the Development of a Microwave Engine for Satellite Propulsion. 27 August 2006.
www.emdrive.com/ReviewofDMtechreport.pdf

14. Video of Demonstrator Engine dynamic test.
www.emdrive.com/dynamictests.html

15. End-User Undertaking. The Boeing Company, Huntington Beach to UK DTI. EmDrive demonstrator engine. 11 June 2007. Available from sprltd@emdrive.com on request.

16.Shawyer R. Microwave Propulsion-Progress in the EmDrive Programme. IAC-08-C4.4.7

17. Technical Assistance Agreement transmittal letter from The Boeing Company to SPR Ltd. 29 May 2009 Ref.YTD-SPR-090529. Available from sprltd@emdrive.com on request.

18. Report on the Design Development and Test of a C-Band Flight Thruster. SPR Ltd. September 2010.
www.emdrive.com/flighthrusterreportissue2.pdf

19. Yang Juan, Yang Le, Zhu Yu, Ma Nan. Applying Method of Reference 2 to Effectively Calculating Performance of Microwave Radiation Thruster. College of Astronautics, Northwestern Polytechnical University, Xi'an 710072,China.
Journal of Northwestern Polytechnical University Vol 28 No 6 Dec 2010

20.Yang Juan et al. Prediction and Experimental measurement of the electromagnetic thrust generated by a microwave thruster system. NWPU.
Chin.Phys.B vol. 22 No.5 (2013) 050301

21. Shawyer R. The dynamic operation of a High Q EmDrive Microwave Thruster. IAC-13, C4, P, 44. pl, x17254.

22. Shawyer R. Superconducting Microwave Radiation Thruster. Patent number GB2537119