

Chapter 20

Microwave Thermal Rocket Engine-Based Orbital Launch System Implementation



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Abstract Chemical rocket engines' specific impulse (Isp) limitations hinder the introduction of fully reusable single-stage launch vehicles with high payload mass-fraction. Modern launchers rely on multi-staging, face reusability difficulties, and resulting in a low payload mass-fraction compared to other vehicles. Microwave Thermal Rocket (MTR) method was explored as a more efficient solution but was abandoned due development cost risks. There are three types of rocket engines for orbital launch: (1) Chemical engines, (2) nuclear thermal rocket (NTR) engine, and (3) beam-powered engines (microwave or laser). Chemical engines provide low Isp, but high thrust-to-weight ratio (T/W). NTR engines offer high Isp but have low T/W and cause radiation pollution. MTR engines provide similar to NTR Isp and T/W similar to chemical engines without radiation pollution. MTR differ from conventional rockets as the power source is ground-based. The engine and ground-based beam director communicate to adjust power intensity and guidance parameters for autonomous ascent. This communication is to be done without human interaction, which is the ability of autonomy. However, as strong interference may put the viability of this essential feature in doubt. We propose a solution to address this problem. Research also proposes a commercially viable microwave-powered launch method utilizing reduced frequency Gyrotrons, air-launch method, and direct methane heating design to reduce research, development, and infrastructure costs. MTR engines can provide high Isp, enabling fully reusable single-stage vehicles with higher payload mass-fraction. Our approach trades off maximum performance for cost reduction, aligning with private investing market needs and supporting the trend of commercial space expansion.

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Keywords Microwave propulsion · Space launch · Beamed energy propulsion

20.1 Introduction

20.1.1 The Problem of Space Launch and the Need for a Step-Up from Chemical Propulsion

Traditional chemical propulsion-based launch vehicles lack payload lift capability due to the natural limits of their energy source—chemical fuel mixtures. Reaching an orbital velocity by burning chemical fuel mixtures requires multi-stage and semi-reusable or completely expendable vehicles to be applied. The payload ratio is meager, around 4%, especially compared to other vehicles; for example, cargo aircraft might have ten times for payload ratio [1].

Besides the lack of payload ratio, the expendable nature of rocket vehicles means that the launch cost heavily depends on manufacturing vehicles for each flight mission. Designing fully reusable rocket vehicles faces significant technological challenges due to an even more reduction of payload mass fraction; for small launch vehicles, it is barely possible at the current state-of-the-art material science [2].

Both factors mentioned above naturally lead to prohibitively high launch costs. The commercial side of the space industry focuses only on the products that can bring significant value [3] being launched on a costly launch service. Significant launch cost reduction to the levels comparable with other types of transportation will presumably open opportunities for massive use of space for commercial purposes.

The natural energy limitations of chemical propulsion are not a solvable problem at the current understanding of physics, and the typical way of improvement relies on (1) improving the dry-to-wet mass ratio of rocket stages, (2) reducing the cost of production, or (3) introducing reusability technologies. The above methods do not promise significant improvement and remain minor advancements [2]. The technology reaches its natural ceiling; the major leaps in space launch technology cannot be promised by chemical propulsion-based launch vehicles. An introduction of completely novel launch technology is needed to resolve the above-stated problems.

Nuclear Thermal Rocket (NTR) engines are among the options considered for space launch applications due to their extremely high specific impulse, reaching up to 900 s [4]. Despite this advantage, NTRs face drawbacks such as a low thrust-to-weight ratio, falling below 35 [1], and the considerable issue of radioactive pollution, which negatively impacts their overall appeal.

20.1.2 Beamed Energy Space Launch Technology

The method of powering rocket engines via external direct energy sources was first introduced by Konstantin Tsiolkovsky in 1924 [5], named “parallel beam of shortwave electromagnetic rays”. However, the author admitted that the (1) microwave generator, (2) beam focusing, (3) directing, and (4) receiver material science technologies were not mature enough.

An artificially generated energy beam, either a microwave or laser, might carry various energy densities. Which indeed far exceed what can be extracted from chemical combustion energy sources. Thus, it leads to an ability to design rocket engines with significantly higher specific impulse. With the current state-of-the-art material science, thermal-type rocket engines can reach specific impulse, similar to nuclear thermal engines, which are under 900 s of specific impulse [1]. However, it depends on the reaction mass, molar weight, and temperature (Fig. 20.1).

The method is based on heating the reaction mass and then converting the energy of the heated gas into jet thrust. Various researchers suggest different types of realization of this method. It might vary from (1) pulsed bursts or (2) continuous flow of energy or be based on transferring energy on a (1) laser or (2) microwave beam. The pulsed beam concepts are typically (1) pulse detonation engines [6] or (2) ablative thrusters. On the other side, the continuous energy beam concepts are typically (1) thermal rockets, (2) light sails, or (3) photonic thrusters [7].

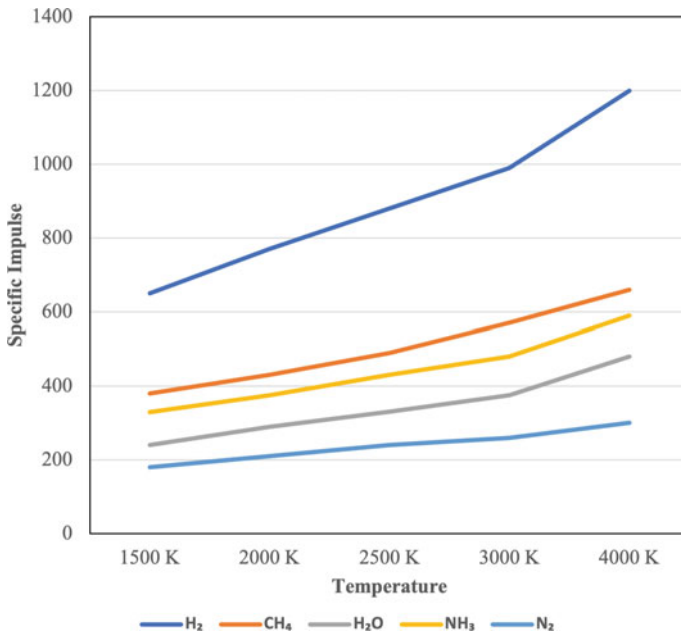


Fig. 20.1 Specific impulse parameters of different types of reaction mass

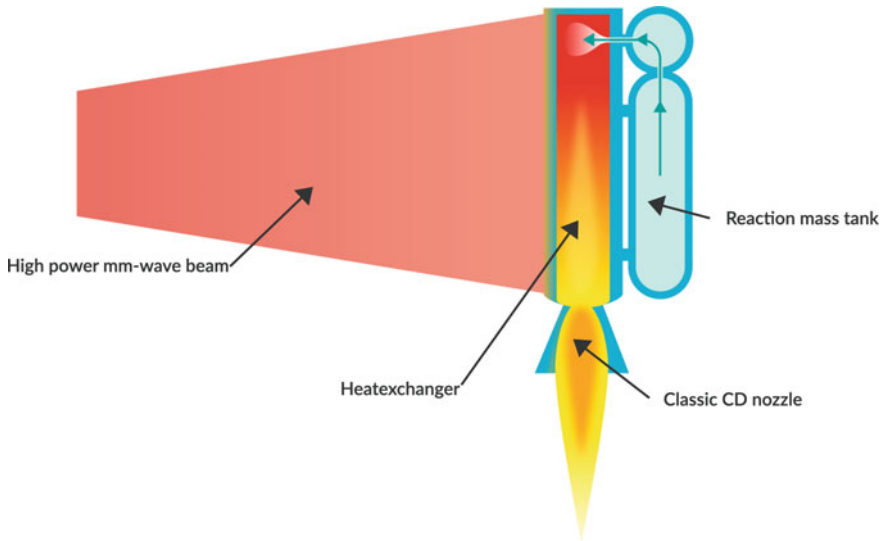


Fig. 20.2 Microwave thermal rocket engine schematic image

The (1) energy storage, (2) microwave generator, and (3) beam director are located on Earth and serve as a stationary energy source that transmits power wirelessly to the rocket engine system (Fig. 20.2) [7]. The core concept of beamed energy propulsion is based on leaving the energy source, which typically constitutes a significant mass, out of the rocket on the ground. As there is no theoretical limit to the energy source and the power of the beam, unlike in chemical fuels, the technology promises significant improvements with the improvement of material science, primarily via improvements in handling high-temperature gas flows.

20.2 Benefits of Beamed Energy Propulsion Based on Microwave Thermal Rockets

Unlike other concepts, the microwave continuous thermal engine concept has an outstanding readiness level for realization. The (1) multi-megawatt continuous wave microwave generators, (2) beam combining, and (3) receiver material science have a Technology Readiness Level of 8–9 according to NASA classification [7]. This concept is typically proposed for the space launch application, as it is most suitable due to its mm-wave diffraction limits and the ability to generate and direct gigawatt scale beams, which are required for space launch [1].

Another differential point is that the microwave thermal engine concept allows multiple methods of energy absorption. Those can be (1) direct heating of heat exchanger, or (2) placing the microwave susceptor material inside of microwave

transparent cavity, or (3) direct reaction mass heating [1]. Unlike the continuous laser beam concept, where energy is absorbed directly by the outer side of the heat exchanger, above mentioned variety of energy absorption methods promises better performance and efficiency [8].

The higher specific impulse naturally drives a higher payload ratio. The thrust-to-weight ratio of such a thermal engine system is driven primarily by reaction mass density [1]. Thus, it does not disrupt the high specific impulse advantage as it happens with nuclear rocket engines [1, 7].

Considering the extra performance driven by higher specific impulse, a single-stage rocket becomes a preferred solution at some moment. From an economic point of view, adding reusability features is another option that optimizes launch costs [9].

As there is no combustion, the reaction mass is homogenous, thus requiring one type of onboard storage tank, valves, and pumps. Essentially, the factors mentioned above reduce vehicle complexity too [9].

20.3 Implementation Problems of Microwave Thermal Launch Systems and Proposed Solutions

20.3.1 Suggested Components of the Concept and System Description

The microwave thermal launch propulsion system consists of (1) ground and (2) onboard components. The ground component comprises (1) energy storage or source, (2) energy distribution, (3) microwave generators, and (4) beam director. The onboard component comprises a (1) reaction mass storage and (2) distribution system, a (3) planar power receiver, and a (4) jet nozzle [1, 7].

Most researchers suggest using hydrogen as a reaction mass due to its lowest molecular mass and significantly higher specific impulse [1, 7, 9]. The system design supposes that a thermal engine depends on a continuous external energy flow. At the stated conditions, the ground take-off scheme requires placing a (1) beam director close to the launch pad and another (2) beam director along the launch trajectory line to satisfy the propulsion system's tracking and power density requirements (Fig. 20.2) [9, 10].

The following methods are suggested for energy receiving and conversion (1) direct heating of the heat exchanger on board the launch vehicle, (2) cooling via transferring the heat to the reaction mass, and then (3) expelling it through the jet nozzle [10, 11].

20.3.2 *Launch Control and Monitoring*

Establishing feedback and control loop sequence for a microwave beam launch system is required for defining the critical parameters to monitor and control during the launch process. Control adjustments are critical according to these parameters as it is the key feature of adaptive launch control algorithms, for example Powered Explicit Guidance [12].

During the launch, the feedback and control system must continuously monitor the following critical parameters in order to adjust main microwave beam power intensity:

- Thrust to weight ratio
- Delta-v
- Spacecraft altitude and velocity
- Spacecraft attitude (pitch, roll, yaw) [12].

However, that's challenging to establish direct radio communication due to strong interference and highly probable damaging factor to on-board communication system from high power microwave beam that points onto the launch vehicle [7]. The satellite relay communication is viable due to the satellite communication antenna on the launch vehicle can be placed on top side of the vehicle in the shadow of high-power microwave beam, however this method possesses high latency (estimated latency might be up to 1000 ms) which considerably limits the guidance systems ability to respond accordingly to quickly changing conditions. Studied literature on microwave beamed launch method do not provide any viable solutions to the problem, mostly focusing on other problems.

Proposed solution

Using a combination of ground-based radar [13] and infrared telescopes [14, 15] to indirectly monitor the launch vehicle's performance and additional relay satellite-based data link [16] can be a viable approach. The proposed method would involve the following steps:

1. Ground-based radar: Tracks the launch vehicle's velocity, altitude, acceleration, and attitude using a radar system. This data would provide insights into the vehicle's trajectory and overall performance. Through knowing the acceleration, the system can analytically estimate the thrust to weight ratio:

$$\frac{T}{W} = \frac{a}{g} \quad (20.1)$$

where $\frac{T}{W}$ is the thrust-to-weight ratio, a is the acceleration, and g is the gravitational acceleration (approximately 9.81 m/s^2).

2. Infrared telescope: Monitors the engine heat signature using an infrared telescope to estimate specific impulse and energy consumption. This information would help assess the efficiency of the microwave beam energy absorption and

conversion into thrust. Infrared telescope is capable to retrieve the temperature data from the engine plume [14], which allows to estimate the Specific Impulse:

$$I_{sp} = V_e g, \tag{20.2}$$

where

$$v_e = \sqrt{\left(\frac{2k}{k-1}\right)RT_c\left(1 - \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}\right)} \tag{20.3}$$

where

- V_e is the exhaust velocity
- k is the specific heat ratio (adiabatic index) of the exhaust gas
- R is the specific gas constant of the exhaust gas
- T_c is the temperature of propellant in the heat exchanger
- P_2 is the pressure at nozzle exit
- P_1 is the pressure of propellant in the heat exchanger

3. Satellite relay communication system: A relay satellite is needed to establish a communication link with the launch vehicle and provide actual telemetry data to the ground command station. This system should be designed to handle the high-speed transmission of large data volumes and provide as low as possible latency communication between the launch vehicle and the ground command station.

The actual telemetry data, despite being delivered with latency, can still be helpful to provide information on the engine thrust, propellant mass flow rate (which helps to estimate vehicle mass), and heat exchanger pressure, which are needed to make final estimations of Delta-v. The telemetry data also will provide data to adjust analytic estimations.

$$\Delta v = I_{sp} \cdot g_0 \cdot \ln\left(\frac{m_0}{m_f}\right) \tag{20.4}$$

where

- Δv : Delta-v, the change in velocity (m/s)
- I_{sp} : Specific impulse, a measure of how effectively a rocket uses propellant (seconds)
- g_0 : Standard acceleration due to gravity (approximately 9.81 m/s²)
- m_0 : Initial mass of the rocket, including propellant (kg)
- m_f : Final mass of the rocket after expelling the propellant (kg)

4. Launch control computer: The telemetry data from both the indirect monitoring system and the satellite relay data link should be combined to evaluate the launch vehicle's performance and adjust the microwave beam tracking and

power density. The indirect monitoring system can serve as a baseline and provide the initial estimates for the launch vehicle's performance, while the satellite relay data link system can provide the real-time telemetry data to refine and adjust these estimates.

5. Beam adjustment: based on the data analysis, the microwave beam tracking and power density adjusted to maintain the desired trajectory, thrust to weight ratio, and energy absorption efficiency.

In the event of a failure or anomaly detected by the indirect monitoring system or transmitted via satellite relay data link, the ground station should be able to abort the mission and initiate contingency plans. The ground station should have the necessary control mechanisms in place to safely and effectively abort the launch, including the ability to adjust the microwave beam energy transfer, control the launch vehicle's attitude, and execute emergency procedures.

By combining indirect monitoring with a satellite relay data link system, it is possible to establish a robust and reliable communication and control system for the microwave beam launch technology. The indirect monitoring system can serve as the primary method for performance monitoring, while the satellite relay data link system can provide real-time data for refining and adjusting the analytical assumptions made by the indirect monitoring system. Additionally, the satellite relay communication system can provide a direct link to the launch vehicle for critical control commands and emergency procedures, enhancing the overall safety and reliability of the launch process.

The logic of the control loop for the combined indirect monitoring and satellite relay communication system can be outlined in the following steps

1. Initialization: Before the launch, the ground-based radar, infrared telescopes, and the satellite relay satellite must be set up and calibrated to ensure accurate data collection and transmission. The communication link between the launch vehicle and the ground station via the relay satellite must be established.
2. Launch phase monitoring: During the launch, the critical parameters must be continuously monitored using both the indirect monitoring system (ground-based radar and infrared telescope) and the satellite relay communication system. Data collected on the launch vehicle's velocity, altitude, attitude, engine heat signature, microwave beam alignment, main microwave power consumption.
3. Data integration and analysis: Data from the indirect monitoring system and the relay satellite data link must be merged at the ground command station. The combined data must be processed and analyzed to assess the launch vehicle's performance, trajectory, and microwave beam energy absorption.
4. Decision-making: Based on the integrated data analysis, it is determined whether any adjustments are needed to the microwave beam parameters, launch vehicle attitude, or propulsion system to maintain the desired trajectory, thrust to weight ratio, and energy absorption efficiency.

5. Control command generation: If adjustments are required, appropriate control commands are generated to modify the microwave beam parameters (e.g., intensity, phase, or focus) or to instruct the launch vehicle to adjust its attitude or propulsion system.
6. Command transmission: The control commands are transmitted to the launch vehicle using the established communication link through the relay satellite, with latency in the communication process accounted for.
7. Command execution: The launch vehicle receives the control commands and executes the necessary adjustments to its attitude or propulsion system, as well as providing feedback on the success of the executed commands.
8. Loop iteration: The control loop is continuously iterated throughout the launch process, with the ground station constantly monitoring the launch vehicle's performance, generating control commands, and adjusting the microwave beam parameters as needed to ensure optimal propulsion performance, trajectory control, and thrust to weight ratio.

Implementing this control loop logic, presumed to maintain a seamless flow of information between the ground station, the indirect monitoring system, and the launch vehicle. This enables real-time adjustments and ensures the success of the microwave beam launch while taking advantage of the benefits offered by the combined indirect monitoring and relay satellite communication approach.

Radar System requirements

For tracking the launch vehicle's altitude, velocity, and attitude, a high-resolution tracking radar system capable of providing precise and accurate measurements over long distances is needed. Some key features to look for in a suitable radar system include:

- High-frequency operation (e.g., X-band or higher) for improved resolution and accuracy.
- Phased-array or electronically steered antenna for rapid and precise target tracking.
- Adaptive beamforming and signal processing capabilities to minimize interference and noise.
- Weather-resistant design to ensure reliable operation under various environmental conditions.

Infrared Telescope requirements

For monitoring the engine heat signature, a high-performance infrared telescope system with adequate sensitivity, resolution, and range is required. Some essential features to consider in a suitable infrared telescope system include

- Mid-wave or long-wave infrared (MWIR or LWIR) detection capability for better sensitivity to the engine's heat signature.
- High-resolution sensor to accurately detect and track the launch vehicle's thermal emissions.

- Adequate cooling system (e.g., Stirling or pulse-tube cryocoolers) to ensure optimal sensor performance and sensitivity.
- Robust tracking system that can maintain a lock on the launch vehicle throughout its ascent.

Integration with advanced image processing and analysis software to extract relevant information from the collected data.

20.3.3 Economic Problems of Microwave Thermal Launch Systems

The application of hydrogen as a reaction mass causes technical complexity, consequently leading to cost growth. First of all, hydrogen has a low density (71 kg/m³) which forces to include bulk tanks and use more heat shielding in the case of reusable vehicles. Even extra specific impulse and thus less mass of needed hydrogen does not allow avoiding the application of bulk tanks. Hydrogen requires a more expensive storage and distribution system with higher handling standards. Another problem with hydrogen is that microwaves cannot directly heat it, which causes certain limitations on the variety of propulsion system options.

The requirement for using two beam directors significantly limits the launch inclinations available for the launch system, as the vehicle must follow the line between two beam directors. Another problem is the two separate facilities' high capital expenditures for construction and maintenance costs.

Studies suggest using Gyrotrons as a ground-based microwave generator [10]. A Gyrotron is a maser capable of producing sub-terahertz electromagnetic waves at continuous wave power of up to 2.5 MW with a typical plug-to-beam efficiency of 50%. For the launch application, it is suggested to use 140 or 170 GHz class gyrotrons. However, to power a one metric-ton payload lifting launch vehicle, it is required to simultaneously use under 1000 gyrotrons at each ground station [1]. The economic problem is that gyrotrons have a significant market price of around 1–2 million USD, which means only gyrotrons would cost 2–4 billion USD for the 1-ton class launch vehicle powering.

At given conditions, the economic state of suggested configurations of the microwave launch systems is not competitive with conventional launch systems, which we will see in the «The outcome» section.

Proposed solution

As a solution to the hydrogen problem, methane can be a better alternative. Methane provides the closest to hydrogen specific impulse and, at the same time, has a significantly higher density (422 kg/m³). In the case of reusable vehicles, because smaller tanks require less heat shielding, the methane-based launch vehicle wins in the payload mass ratio [1]. Another advantage is directly heating the methane reaction mass in the microwave transparent cavity. With advanced cooling solutions, this

method promises much higher energies to be delivered than other methods. Methane also requires less demanding equipment standards.

The air launch method can be applied to overcome the requirement for two beam directors, thus reducing the ground-based beam director cost twice the initial assumption. The launch vehicle has to (1) take off from a runway, on the carrier aircraft or using an onboard jet engine, (2) raise an altitude of around 15 km, (3) approach the beam acquisition point at a distance of around 120 km from the beam director (Fig. 20.3). With this approach, the orbit inclination problem is also naturally solved.

Gyrotrons can be more economically efficient if we use 95 Ghz class gyrotrons because, in this case, it is possible to use cheaper non-cryo magnets, one of the significant cost drivers, and cheaper equipment, including less precision antennas.

Another step up is to build larger power supply units that can power up to 4 gyrotrons, as we found an effect economy of scale, which another drastic cost-reducing factor. A gyrotron cost might drop to \$100 k.

The outcome

The following equation is determined to define the launch cost:

$$L_{cp} = \frac{L_{ec}}{P_c} + \frac{\left(\frac{L_{vc}}{L_{vf}}\right) + \left(\frac{E_{cq} * C_{aw}}{A_{lr}}\right) + \left(\frac{G_{bd} * A_{im}}{A_{lr}}\right)}{P_c} \tag{20.5}$$

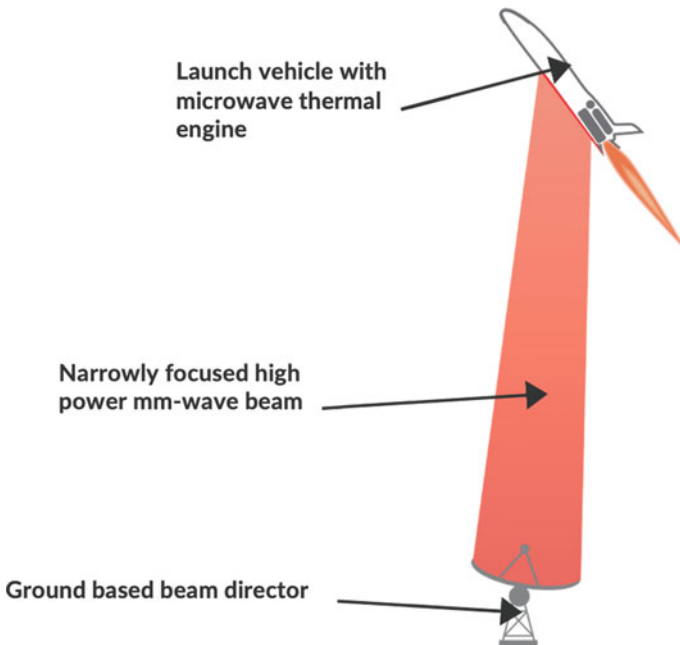


Fig. 20.3 Microwave beam launch conceptual illustration

where,

$$Lec = \frac{\left(\frac{Pc}{0.25}\right) * 300 * 1000}{3600} * 0.0726 \quad (20.6)$$

And,

$$Los = \left(\frac{Lvc}{Lvf}\right) + \left(\frac{Ecq * Caw}{Alr}\right) + \left(\frac{Gbd * Aim}{Alr}\right) \quad (20.7)$$

$\frac{Pc}{0.25}$ is the power required from wall plug at launch in MW, assumed that each kg of payload required one MW of power.

0.25 is the energy conversion efficiency of 25% from wall plug to microwave beam.

300 is the assumed launch time of 300 s.

1000 is for conversion from MW to KW.B

36,000 is for conversion from KJ to KW/h.

0.0726 is the cost of KW/h for industrial consumers in USD in the US for 23 Jan, 2023.

Nomenclature

Lcp	Launch cost per kg [\$]
Los	Launch operations cost [\$]
Lec	Launch electricity cost [\$]
Lvc	Launch vehicle cost [\$]
Lvf	Launch vehicle lifetime missions quantity
Ecq	Engaged crew quantity
Caw	Crew average wage [\$]
Alr	Annual launch rate
Aim	Annual infrastructure maintenance cost [\$]
Gbd	Ground beam director capital expenditures [\$]
Pc	Payload capacity [kg]

Assumptions

- Annual infrastructure maintenance cost is assumed to be 5% of beam director capital expenditures.
- Launch vehicle manufacturing cost is set at \$10 M in all scenarios because the calculation of actual cost is too out of the scope of this paper. The vehicle is set to have 300 missions lifetime.
- Each ground beam director is operated by a crew of 50 persons with a \$130 k yearly wage.
- The annual launch rate is set to be 100 missions.

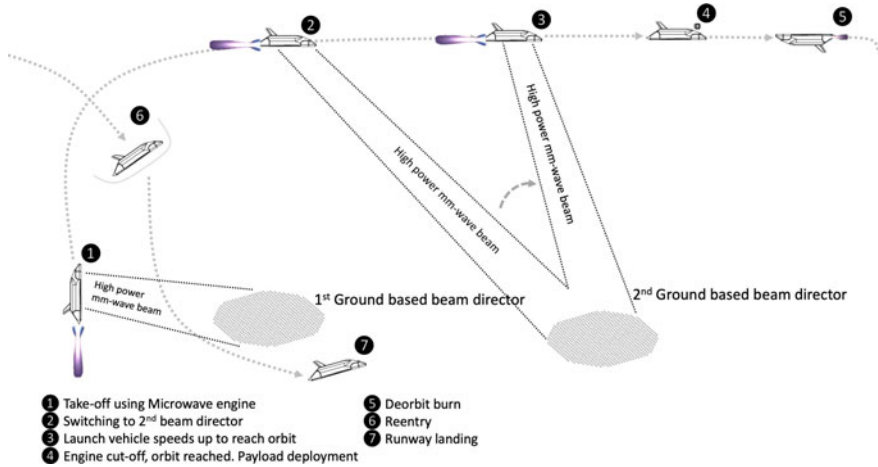


Fig. 20.4 Double beam director launch method

- Each ground station is set to have 1000 gyrotrons, antennas, aiming platforms, and 500 pcs of power supply units for suggested approach and 250 for improved approach.
- Energy is assumed to be taken from existing generating infrastructure.

Initially suggested approach costs for components of beam director

1. Gyrotrons \$1 M/pc.
2. Gyrotron power supply \$1.1 M per gyrotron.
3. The antenna and aiming platform cost \$130 k.

Offered optimization costs for components of beam director

1. Gyrotrons \$100 k/pc.
2. Gyrotron power supply unit \$275 k per gyrotron.
3. The antenna and aiming platform cost \$130 k.

During the research the authors consulted with manufacturers and confirmed the cost numbers for the initial approach. The numbers for the optimized version were set via consulting with developers, suppliers, and manufacturers.

The graph on Fig. 20.5 shows that the suggested technical and economical solutions lead to an order of magnitude improvement in the beamed energy launch cost. They are opening the opportunity to overcome conventional launchers on the free market. A launch system capable of lifting one metric ton might offer \$353/kg, whereas initial system design offers \$2331/kg. For comparison conventional launchers offer the lowest theoretical price of \$2350/kg (SpaceX 2023).

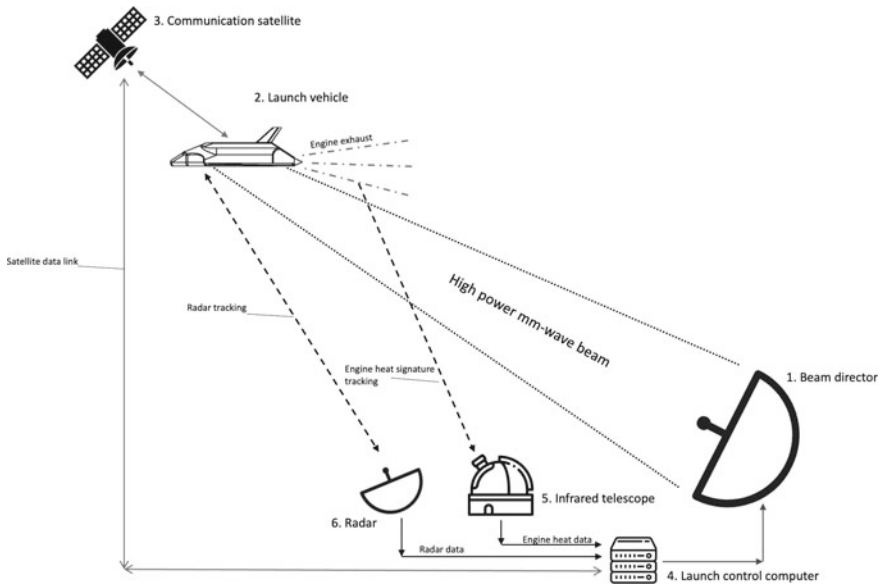


Fig. 20.5 Microwave beam launch control and monitoring system

20.4 Conclusions and Recommendations

The paper reviews the concept of beamed energy propulsion and focuses on microwave continuous wave-based propulsion solutions. Outlined the significant benefits of the technology, that could benefit the field of orbital transportation and thus benefit the whole space industry ecosystem. Eventually, the advancements in the space industry are presumed to deliver significant socio-economic benefits on Earth (Figs. 20.6 and 20.7).

The main restricting technical and economic problems of the concept were considered. The authors describe solutions that might bring significant optimization. The evaluation illustrates that these solutions might solve the command-and-control problem at launch process via establishing a robust and reliable communication system that consists of indirect monitoring methods and additional relay satellite communication. The proposed economic solutions provide significant cost reduction and open the way for realization in the near future. The authors suggest further studies of microwave thermal propulsion for launch application and testing the proposed methods.

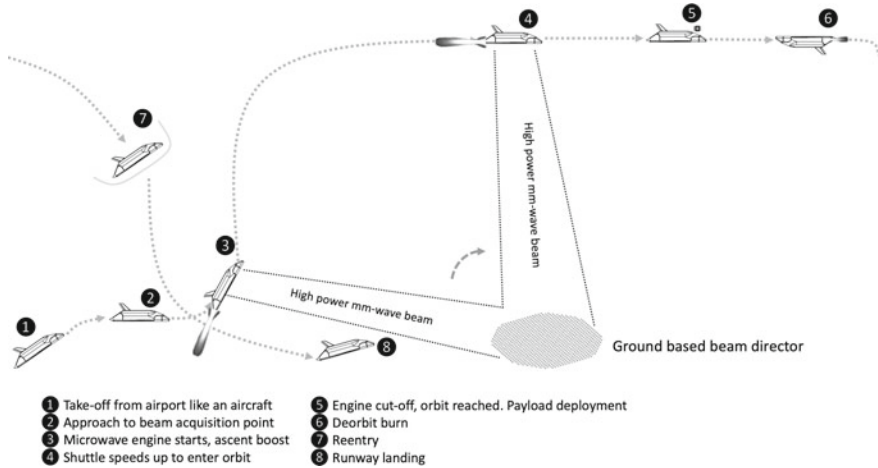


Fig. 20.6 Single beam director air-launch method

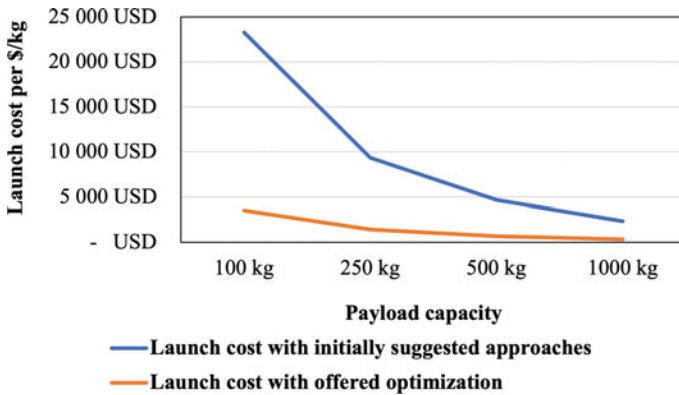


Fig. 20.7 The launch cost \$/kg comparison of discussed approaches

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