Two-Stage-to-Orbit Transporting System Combining Microwave Rocket and Microwave Thermal Rocket for Small Satellite Launch

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Abstract: This paper proposes a two-stage-to-orbit launch system comprised of a Microwave Rocket 1st stage and a Microwave Thermal Rocket 2nd stage. The air-breathing 1st stage improves payload fraction relative to a single-stage-to-orbit system and carries the 2nd stage above the atmosphere and into range of its beam director. For the 1st stage task, a Microwave Rocket is superior to an unmanned aerial vehicle because it is simpler, faster, and reaches higher altitude at higher speed. In addition, we present a new trajectory that eliminates power beaming at low elevation angles and improves system performance. This combination of factors reduces the propellant needed in the 2nd stage, which in turn increases payload fraction by a remarkable factor of 3 times.

Nomenclature

A	=	cross sectional area
C_D	=	drag coefficient
D	=	drag
m	=	rocket mass
p	=	pressure
r	=	geocentric radius
T	=	thrust
t	=	time
V	=	velocity
β	=	longitude

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θ = height
ρ = air density

Subscripts

a = ambient
ple = plenum
W = thrust wall

I. Introduction

WHEN we transport something to space, the way still remains the same since Sputnik was launched for the first time in the world by chemical rockets. Even though many problems of this way have been pointed out, the most critical one is the cost. The launch cost remains around $ 10,000 per kilogram of payload, and an omen of further cost reduction cannot be detected at present. Various ways of space transportation have been researched to break the deadlock, and Beamed Energy Propulsion (BEP) is one of the most promising future launch systems because it is expected to realize high-rate low-cost space access. High payload fraction, small environmental burden, and semi-permanent repetitive utilization of the launch system can be achieved because its propulsive energy is supplied externally by an electromagnetic beam radiated from a ground facility.

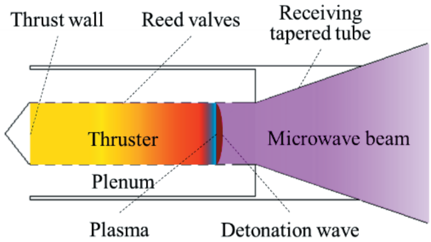

Figure 1. Schematic of Microwave Rocket.

At the University of Tokyo, Microwave Rocket (MR), which is one of several BEP approaches, has been researched and developed for practical use. MR is a kind of pulsed detonation engine (PDE) with an exceedingly simple configuration shown in Fig. 1. The concept was invented in 2003 and the experiment of the thrust generation succeeded for the first time in the world[1-3]. The thrust is generated by high pressure due to the detonation wave that is supported by the plasma absorbing the microwave beam energy supplied from the ground, using ambient air as propellant. The energy source, the propellant and the complex structure such as turbo-pump are unnecessary on board. The specific impulse is equivalent to infinity when propelling itself in the atmosphere. Meanwhile at NASA, Microwave Thermal Rocket (MTR),[4-6] which is also one of BEP and an analogy of the nuclear thermal rocket, using microwave beam rather than neutron as an energy source, is studied and planned for 1st orbital launch of 50 kg vehicle by 2020[7]. In that conception, MTR is carried into the beam range by an unmanned aerial vehicle (UAV), then launched in the air and propelled within the beam range.

This paper proposes a two-stage-to-orbit (TSTO) launch system whose 1st stage is MR as alternative to the UAV. The UAV cannot reach altitude much above 25 km and takes an hour or more to reach that height. Such a long flight costs more than the unit cost of the 1st stage MR for the fuel, and furthermore for an LH_2 2nd stage, means complex equipment is needed for the prevention of LH_2 boiling off and oxygen ice build-up on the outside of the tank. In comparison, MR can reach more than 30 km with at least 1 km/sec in a few minutes, and costs considerably less than the development cost for the UAV, even including the beam director construction cost. To compare with the UAV case, the TSTO ascent trajectory was calculated, and the scale of ground facilities and costs were estimated.

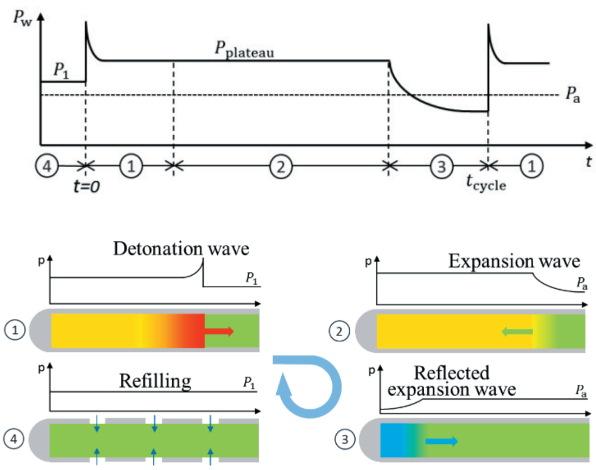

Figure 2. Schematic of pressure history at the thrust wall (Top), and of PDE cycle (Bottom). Note that the process of refilling is assumed to be conducted instantaneously so its time duration is neglected in the top.

II. Microwave Rocket Thrust Model

The thrust generation model of the MR is explained as a PDE cycle,[8] and there are four steps in a cycle (Fig.2).

The 1st step is the propagation of the detonation wave and the pressure increment, the 2nd step is the propagation of the expansion wave and the high pressure maintenance, the 3rd step is the reflection of the expansion wave and the pressure decrement, and the 4th step is the refilling and the pressure recovery. Generally, the thrust is generated by the pressure difference between thruster and ambient atmosphere. The average thrust of a cycle $\overline{T}$ can be written as follows.

$$\overline{T} = \frac{1}{t_{cycle}} \int_0^{t_{cycle}} \left[(p_w - p_a) A_w + (p_a - p_{ple}) A_{ple} \right] dt \qquad (1)$$

The plenum is the space for the thruster refilling and assumed to be in stagnation condition. The refilling is assumed to be conducted instantaneously at the point of the negative pressure in the thruster, and to obey the adiabatic gas mixing law. Figure 3 draws a comparison between computation and experimental data of the pressure history at the thrust wall, which indicates good agreement.

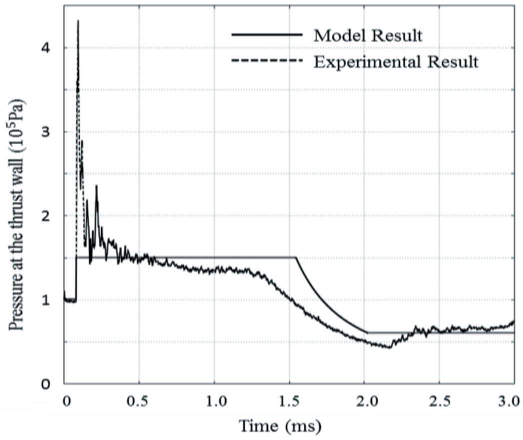

Figure 3. Pressure history at the thrust wall.

III. Trajectory Analysis

In this analysis, the 2-dimentional and 2-degree-of-freedom EOM of mass point is solved in the polar coordinate (Fig.4), using Runge-Kutta 4th order method. The earth is treated as rotating sphere, therefore the gravity follows the inverse-square law. The atmospheric state is calculated from 1976 U.S. standard atmosphere[9)]. The thrust and body axis are on the same line, neglecting the deflection angle of the thrust. The external forces applied to the body are the thrust, the gravity, and the drag, neglecting the lift. The wind is assumed to be much smaller than the speed, so the influence of the wind is neglected. The equations of motion are as follows.

$$\frac{d^2r}{dt^2} = r\left(\frac{d\theta}{dt}\right)^2 - \frac{\mu}{r^2} + \frac{(T-D)\sin\beta}{m} \qquad (2)$$

$$\frac{d^2\theta}{dt^2} = -\frac{2}{r}\frac{dr}{dt}\frac{d\theta}{dt} + \frac{(T-D)\cos\beta}{mr} \qquad (3)$$

Drag is calculated as follows.

$$D = \frac{1}{2}\rho V^2 A C_D \qquad (4)$$

The frontal area is assumed to be the maximum cross sectional area of the vehicle, or the cross sectional area of the receiving tapered tube. The drag coefficient is roughly evaluated using simplified analytical equations,[8)] which consider the skin friction drag and the base drag.

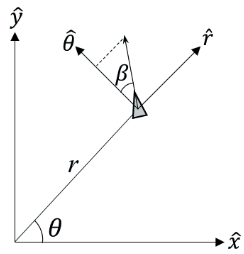

Figure 4. Parameters in the polar coordinate.

A. Problem setting

A TSTO vehicle takes off vertically and delivers payload into a 300 km circular LEO. The 2nd stage is MTR whose specification is shown in table 1, which is in case of using an UAV. After the cutoff of the 1st stage, the 2nd stage thrusts horizontally and propels itself within the beam range. The beam range for MTR is set to 150 km to compare cases evenly. Using the values in table 1 and the rocket equation, the equivalent delta V of the 2nd stage is 9.5 km/s.

Table 1. Specification of MTR shown in 2).

Wet mass	50 kg
Structural mass	11 kg
Propellant mass	37 kg
Payload mass	2 kg
Payload fraction	4 %
Vacuum specific impulse	721 sec
Propellant mass flow	0.37 kg/sec of H_2
Absorbed power	10 MW

B. Trajectory design and performance evaluation

First of all, the simple replacement case was investigated (Fig. 5), and the results indicate only double the payload fraction (table 2). This is because MR is able to propel only vertically, which leads to shorter range for propulsion of the 2nd stage MTR.

Table 2. Comparison of the simple replacement case

1st stage	UAV	MR
Propellant mass	37 kg	35 kg
Payload mass	2 kg	4 kg
Payload fraction	4 %	7 %

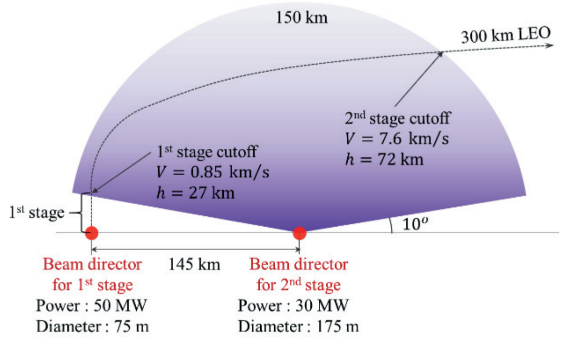

Figure 5. Simple replacement of the UAV by MR.

A new trajectory design is proposed to solve this problem and show the ability of MR. As shown in Fig. 6, the length of the intervals between beam directors is increased and the 1st beam director is shared by both 1st and 2nd stage. The power output of 50 MW and the beam range of 34 km for the 1st stage has capacity equivalent to the beam range of 105 km for 2nd stage. After the 2nd stage thrust halt at the edge of the 1st beam director beam range, it has a sub-orbital flight until the entrance into the beam range of the 2nd beam director, and propels itself again within the beam range to get the rest of ΔV. This trajectory design brings out the potential of MR and improve the performance of the whole launch system. The payload fraction is about 3 times larger than the UAV case (Table 3). Furthermore, this trajectory design has a practical merit, which is a small beam emitting angle. A larger beam emitting angle leads to larger attenuation of the microwave beam in the atmosphere and a larger number of difficulties in constructing ground facilities. This remarkable performance improvement results from small velocity losses of 2nd stage MTR. Delta-V budget breakdown is shown in Table 4, which indicates that the role of 1st stage MR is to compensate velocity losses because of its only vertical acceleration. The total delta-V is 7.20 km/sec, which is almost equal to the orbital velocity at 300 km LEO.

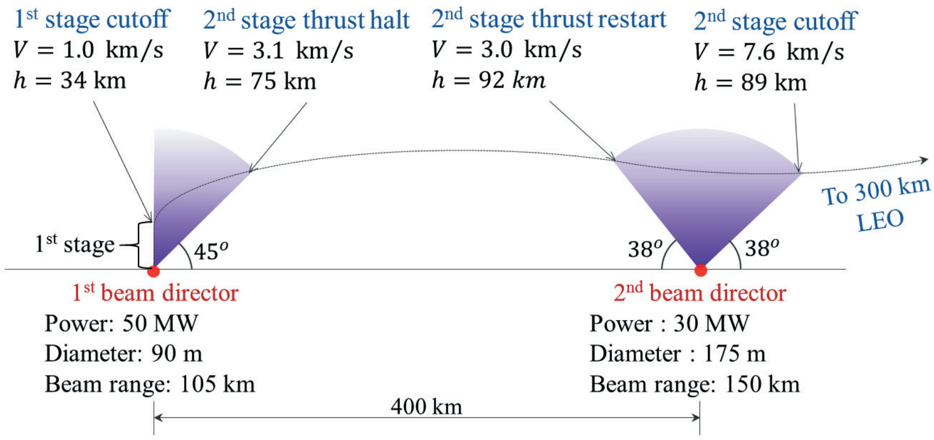

Figure 6. Newly proposed trajectory sharing 1st beam director.

Table 3. Comparison of the newly proposed trajectory case

1st stage	UAV	MR
Propellant mass	37 kg	37 kg
Payload mass	2 kg	8 kg
Payload fraction	4 %	13 %

Table 4. Delta-V budget (km/sec)

	1st stage	2nd stage	Total
Thrust	+ 6.38	+ 6.97	+ 13.35
Drag	- 4.59	- 0.17	- 4.76
Gravity	- 0.79	- 0.60	- 1.39
Total	1.00	6.20	7.20

IV. Beam Facility

The most different from conventional launch system is the microwave beam facility on the ground. Generally, the construction cost of the beam facility accounts for a large percentage of the whole cost relating to BEP launch system. However, it can be amortized in the future scale of launch system because vehicle itself is not expensive and expected to be launched repetitively and frequently.

The beam facility roughly consists of power storage, beam production and beam transmission system.[6] Flywheel batteries are suitable for power storage to supply large electrical power over a few minutes to the vehicle, which charge in between launches and discharge rapidly during flight. The microwave beam is produced by a network of MW-class gyrotron, which has already been used to heat plasma in nuclear fusion research. For the beam transmission, phased array antenna is supposed to be selected because no mechanical movement is needed, and high power and large aperture can be achieved (Fig.7).

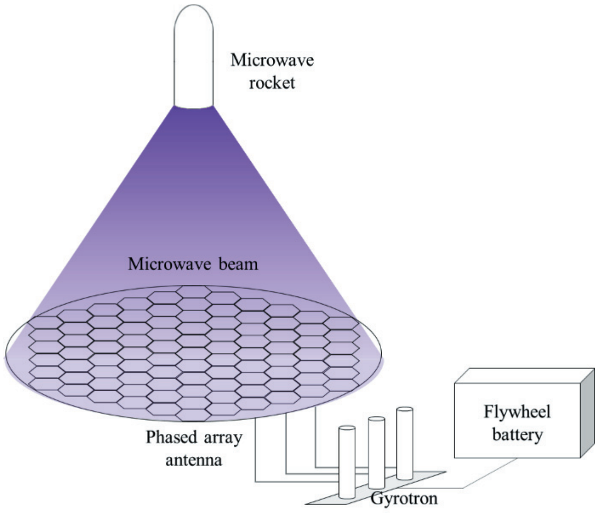

Figure 7. Schematic of the beam facility.

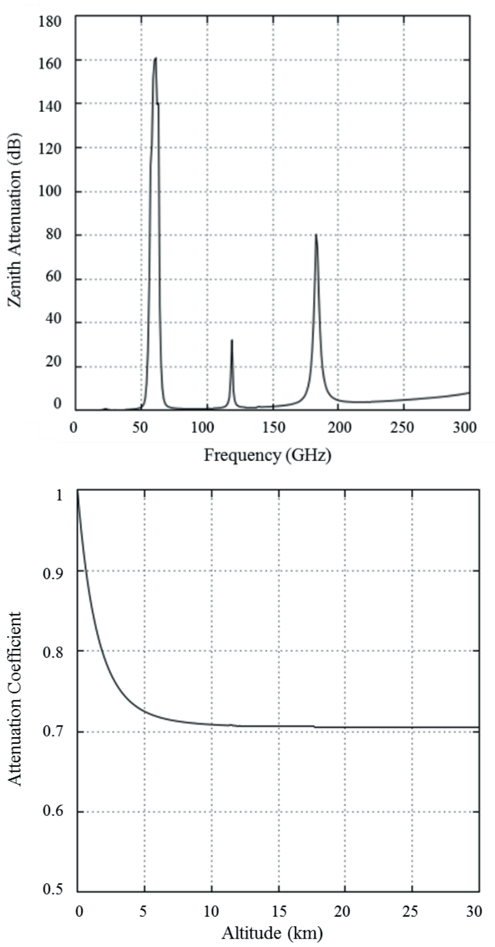

Figure 8. Zenith attenuation calculated by the Line-by-Line method (Top), and the attenuation coefficient as function of altitude (Beam frequency 140 GHz) (Bottom)

When considering the beam transmission, the attenuation of the microwave beam has to be taken into account. The atmospheric attenuation of the microwave beam is calculated by the Line-by-Line method[10)]. Only zenith attenuation is considered and the computed result focused on milli-wave zone is shown in Fig. 8. In this analysis, the beam frequency of 140 GHz is selected because of its relatively low attenuation. According to Fig. 8, about 30 % of the microwave beam attenuates in the atmosphere.

V. Cost Estimate

The cost estimate of the UAV case is shown in table 5. This includes only the fuel cost and other costs relating to the UAV such as developing cost, production cost and maintenance cost are excluded. In the same way described in Ref.7, the cost of the vehicle and the beam facilities in the latter case of replacement by MR is estimated. Table 6 shows the vehicle launch cost, and table 7 shows the beam facility cost.

Table 5. Cost estimate of the UAV case

Vehicle launch cost	$ 40,428
Beam facility cost	$ 280 M

Table 6. Vehicle launch cost estimate breakdown

Component	Mass (kg)	Cost ($)	Cost justification
MR	6.7	8,040	Complex short run aircraft rule of thumb: $ 1,200/kg
MTR	46.688	15,062	Based on Ref.7
		23,102	
Integration		23,102	Assumed equal to component cost
Electricity		148	1st stage: 50 MW (81 sec, duty ratio = 0.24), 2nd stage: 50 MW (54 sec), 30 MW (46 sec). Based on industrial rate of $ 0.1055/kWh for California on May 1, 2013
Total	53.388	**46,352**	Exclude operational personnel cost and initial R&D + beam facility cost

Table 7. Beam facility cost estimate breakdown

Component	Scale	Cost ($)	Cost justification
Gyrotron	80 MW	8 M	Assuming $ 0.1M/MW
Flywheel	1403 kWh	14 M	Assuming $ 0.01 M/kWh
1st Antenna	90 m dia.	173 M	Based on Ref.7
2nd antenna	175 m dia.	293 M	Based on Ref.7
Total		**488 M**	

VI. Conclusion

This paper proposed a TSTO launch system whose 1st stage is MR (instead of UAV) and 2nd stage is MTR. The comparison of the whole launch system is shown in table 8. By adopting MR as 1st stage and the trajectory shown in Fig. 6, the whole launch system has remarkable performance of 3 times larger payload fraction, and the launch cost per unit mass of payload is only one quarter as much, compared with the case in which a UAV carries MTR. These differences are expected to be much more marked in a larger scale launch system.

To demonstrate an 8 kg satellite launch, the beam facility construction costs $ 490 M, the vehicle costs $ 46 k, and the electricity costs $ 150.

Table 8. Comparison of whole launch system

1st stage	UAV	MR	Ratio
Payload mass	2.0 kg	8.0 kg	4
Payload mass fraction	4.0 %	13 %	3.25
Launch cost	$ 40 k	$ 46 k	1.15
Lunch cost per unit mass of payload	20 k$/kg	5.8 k$/kg	0.29
Beam facility construction cost	$ 280 M	$ 490 M	1.75

Acknowledgments

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