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An Overview of Advanced Concepts for Near-Space Systems

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Abstract

A brief review of both near-term and far-term platforms proposed for near-space operations is given. The primary focus of the paper is, however, a review of potential advanced propulsion systems for such long-duration near-space platforms. The basic requirements for near-space propulsion systems are defined. Low Reynolds number propellers, the current workhorse, are used as a baseline for comparison. Two broad classifications are identified as potential sources of force in near space: rarefied gas and electric propulsion. Radiometric force propulsion systems, the only candidate propulsion systems found in the open literature, suffer from both significant uncertainty in their underlying physics and from significant operational difficulties. Thermal transpiration propulsion systems were shown fundamentally incapable of providing the required performance. Air-breathing electric propulsion systems for long-duration near-space missions will be significantly different than their in-space counterparts with specific impulses likely under 100s. Electrohydrodynamics propulsion systems show some promise, but have thus far shown limited thrust efficiency at sea level operation, and the efficiency is only predicted to get lower at higher altitudes. The potential effects of systems based on breakthrough physics are also qualitatively discussed. All of the identified potential advanced propulsion concepts for long-duration near-space operations suffer from major technological challenges with significant advancements required for any of them to be viable.

Nomenclature

A	= Cross-Sectional Area (m^2)
C	= Transpiration Membrane Conductance (m^3/s)
c_p	= Gas Specific Heat at Constant Pressure (J/kgK)
D	= Collection Diameter (m)
d	= Electrode Gap Distance (m)
d_{fp}	= Footprint Diameter (m)
F_b	= Net Buoyancy Force (N)
g	= Local Gravitational Acceleration (m/s^2)
g_o	= Gravitational Acceleration at Sea Level (9.8062 m/s^2)
h	= Altitude (m)
I	= Current (A)
I_{sp}	= Specific Impulse (s)
k	= Ion Mobility Coefficient (m^2/Vs)
k_b	= Boltzmann Constant ($1.381\text{x}10^{-23}$ J/K)
k_{th}	= Thermal Conductivity (W/mK)
L	= Arc Length Between Horizons (m)
L_x	= Membrane Thickness (m)
l_{max}	= Effective Horizon (m)

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$\dot{M}$ = Mass Flow Rate (kg/s)
m = Molecular Mass (kg)
m_{pr} = Propulsion Device Mass (kg)
m_{ps} = Power Supply Mass (kg)
m_t = Total System Mass (kg)
P = Period (s)
P_{in} = Stage Input Power (W)
P_{out} = Power Leaving Stage (W)
P_e = Electrical Power (W)
P_{avg} = Average Transpiration Membrane Pressure (Pa)
p = Pressure (Pa)
Q_t = Thermal Transpiration Flow Coefficient
Q_p = Poiseuille Flow Coefficient
R_E = Earth Radius (6.371×10^6 m)
T = Thrust (N)
T_{avg} = Average Transpiration Membrane Temperature (K)
$T_{t,max}$ = Maximum Total Time in View (s)
V = Envelope Volume (m^3)
v_e = Exhaust Velocity (m/s)

α = Mass Per Unit Power (kg/W)
β = Mass Per Unit Area (kg/m^2)
Δp = Pressure Difference (Pa)
ΔT = Temperature Difference (K)
Δx = Ground Resolution (m)
ϕ = Access Angle (radians)
γ = Ratio of Specific Heats
η = Thrust Efficiency
η_c = Ideal Cycle Efficiency
κ = Realized Fraction of Maximum Pressure Difference
λ = Wavelength (m)
ρ_{atm} = Ambient Atmospheric Density (kg/m^3)
ρ_{fill} = Envelope Gas Density (kg/m^3)

I. Introduction

Near space is qualitatively defined as the range of Earth altitudes above where commercial aircraft can produce sufficient lift for steady flight and below where the atmosphere is rarefied enough for satellites to orbit with meaningful lifetimes. Near space is often, but not always, quantitatively defined as the range of Earth altitudes from 20km to the "edge of space", the Kármán line, at 100km. This review will use this definition of near space. There has been recent interest in long-duration near-space vehicles motivated by the possibility of operating with the relative benefits of both high-altitude aircraft and low-altitude satellites.[1] The common assumption is that operating in this range of altitudes will lead to certain advantages: persistent intelligence, surveillance, and reconnaissance (ISR), long endurance, beyond line of sight communication, and low cost access to space-like performance. There has been a wealth of recent reviews published on near-space systems and their potential performance levels.[2,3,4] The reviews have found a rough consensus on the field so the information will only be briefly summarized in this work. There hasn't been a review of propulsion systems for near-space systems, however. This review is primarily focused on propulsion systems applicable to low-speed, long-duration near-space systems. The two primary focuses of the present work are: to identify the basic characteristics and performance that near-space propulsion systems must have, and to evaluate potential near-space propulsion systems against these requirements to determine if any of them are currently viable and, if not, then what challenges remain to be overcome.

The attractiveness of operating in near space lies primarily in the potential of achieving optimum performance per unit cost for ISR systems and beyond line-of-sight communication. Both atmosphere-based and space-based ISR systems encounter a fundamental trade-off between ground resolution and instantaneous area of access (total surface area available for a sensor) or footprint area (total surface area that a sensor observes at one time).[5] As the altitude increases both the instantaneous area of access and footprint area increase to include a larger fraction of the Earth's surface. The ground resolution, however, decreases with increasing altitude. The ground resolution for a diffraction limited optical system is given by[5]

$$\Delta x = \frac{2.44h\lambda}{D} \tag{1}$$

The maximum arc length along the earth's surface (the distance between the horizons) that a craft can view is given by

$$L = 2R_E \cdot \cos^{-1}\left(\frac{R_E}{R_E + h}\right) \tag{2}$$

More complicated, sensor-dependent expressions can be derived for specific systems that take into account limitations in the operation of sensors and communication systems near the horizon. Most sensor systems cannot view the entire instantaneous area of access and are limited to a certain angle, ϕ, taken from the vehicle altitude. If ϕ is small then the dependence of the footprint diameter on altitude is given by

$$d_{fp} = 4R_E ATAN\left(\frac{h}{R_E} Tan\left(\frac{\phi}{2}\right)\right) \tag{3}$$

Figure 1 shows a plot of the ground resolution, instantaneous access arc length, and footprint diameter as a function of altitude. The resolution was calculated assuming a wavelength of 500nm and a collection diameter of 1m. The instantaneous access area was calculated assuming that the sensor could operate to within 3 degrees of the horizon. A sensor acceptance angle of 10 degrees was assumed to calculate the footprint diameter. The Figure illustrates that centimeter-scale optical ground resolutions are associated with near-space platforms. The footprint diameter for a sensor with a 10 degree acceptance angle would be approximately 10 km. The horizon to horizon arc length is on the order of 500km. This simple representative example illustrates the optimal trade-offs of near-space systems: resolution allowing the identification of vehicles and questionable activities, footprint diameters allowing city-scale areas to be monitored continuously, and instantaneous access areas allowing country-scale areas to be monitored by one platform in one location.

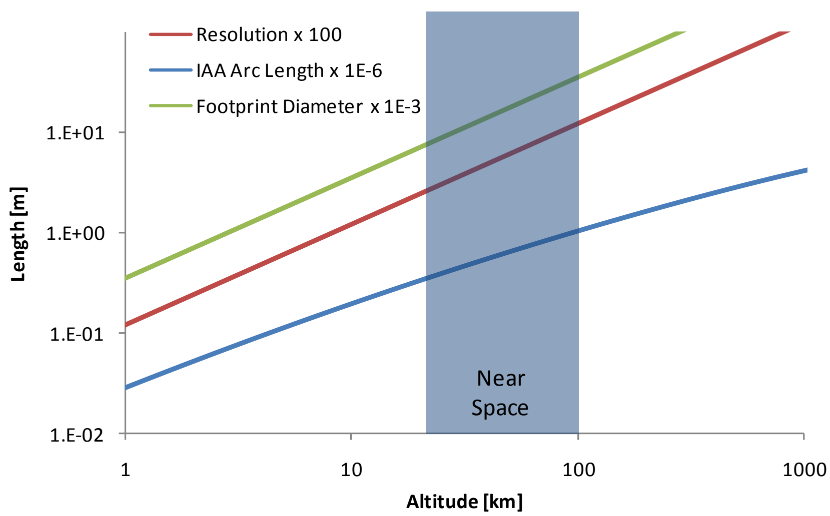

Figure 1. Ground Resolution and Maximum Arc Length for Near-Space Systems

There are a wide variety of other metrics that must also be considered when analyzing near-space systems. Only several of the more important metrics will be discussed in this work. One such metric is the actual observing time that a craft would have of a target, total time in view (T_t). For aircraft and near-space vehicles this can effectively be their useful endurance. For LEO satellites, however, the total time in view can be a major limitation. The maximum total time in view for a LEO satellite is achieved when the satellite crosses directly overhead and is given by

$$T_{t,MAX} = P\left(\frac{l_{max}}{180°}\right) \tag{4}$$

The ground speed of the vehicle is also important for most applications. High ground speeds can be particularly problematic for ISR applications. Ground speed for geosynchronous orbits and some near-space vehicles can be effectively zero. The ground speed for satellites orbiting in low earth orbit, however, can be very high and produce time over targets on the order of minutes.

Near-space systems may also represent the optimal point in the trade-off between time on station and accessibility. Most of the proposed near-space vehicles can be landed, serviced, repaired, and upgraded, and then launched again. Near-space vehicles may, therefore, have the lifetime of a satellite (>10yrs), but the accessibility of an aircraft. Near-space vehicles are also likely to have a responsiveness closer to that of an aircraft (hours instead of years). Without any existing near-space systems it is impossible to make accurate cost comparisons between the different platforms. By many metrics near-space platforms represent an optimum trade-off between aircraft and satellite operations. If the proposed near-space vehicles that are briefly described later can be demonstrate they will greatly improve performance because of their optimal operation. Alternative propulsion systems that may enable alternative near-space platforms must also be evaluated to determine the long-term potential of near-space platforms in the entire range of near-space altitudes.

II. Near-Space Environment

The potential of near-space systems is difficult to achieve partially because of the unique operating environment at near-space altitudes. The environment differs significantly from both the lower altitude atmospheric environment and the space environment. The atmospheric pressure and temperature taken from standard atmosphere tables[6] is shown in Figure 2. The atmospheric pressure at an altitude of 20km has decreased to approximately 40 Torr. At the upper boundary of near space, 100km, the atmospheric pressure has fallen to roughly 0.24 Torr. The atmospheric pressure at near-space altitudes is significantly below that at the surface, but the chemical makeup of the atmosphere in near space is very similar to that at lower altitudes.

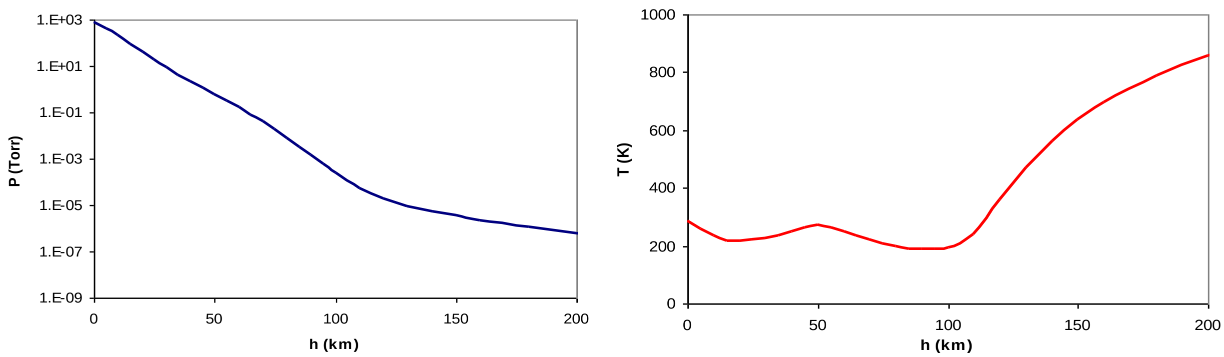

Figure 2. Atmospheric Pressure and Temperature In and Around Near-Space Altitudes[6]

Aircraft can generate enough lift for steady flight at the lower boundary of near space by either flying very fast or by having very large wing spans, but it is impossible with current or near-term systems to operate much higher than the lower near-space boundary. Lift achieved through buoyancy, such as with dirigibles and free-floating balloons, can achieve higher altitudes, but their useful payload mass trends to zero at about 50km altitude for existing and near-term systems. It is simply impossible for spacecraft to orbit at near-space altitudes for long durations. Ambient temperatures in near space range from approximately 190K to 270K. Components, including the propulsion system, must be either designed to operate in this temperature range or must be placed in a controlled environment. Propulsion systems viable for application on near-space craft with lifetimes significantly greater than approximately one week must use the ambient gas for propulsion as is discussed later. The propulsion systems must, therefore, be able to operate in these gas pressure and temperature conditions or pretreat the incoming air to conditions in which they can operate. It would be beneficial if a propulsion system could operate over a range of conditions, preferably the entire range of pressures and temperatures experienced from the Earth's surface to the operating near-space altitudes.

Wind speeds are a major design driver for near-space systems. Stratospheric wind speeds vary with time, geographic location, and altitude. Figure 3 shows the average wind speed as a function of altitude over the four seasons above Cape Kennedy, FL. There is typically a minimum in the wind speed at an altitude of about 20km, which is the motivation for many proposed concepts to operate at this altitude. Most near-space vehicles, however, are required to have > 95% station availability, so they must be able to fly at close to the maximum wind speeds which can be significantly higher than the mean.

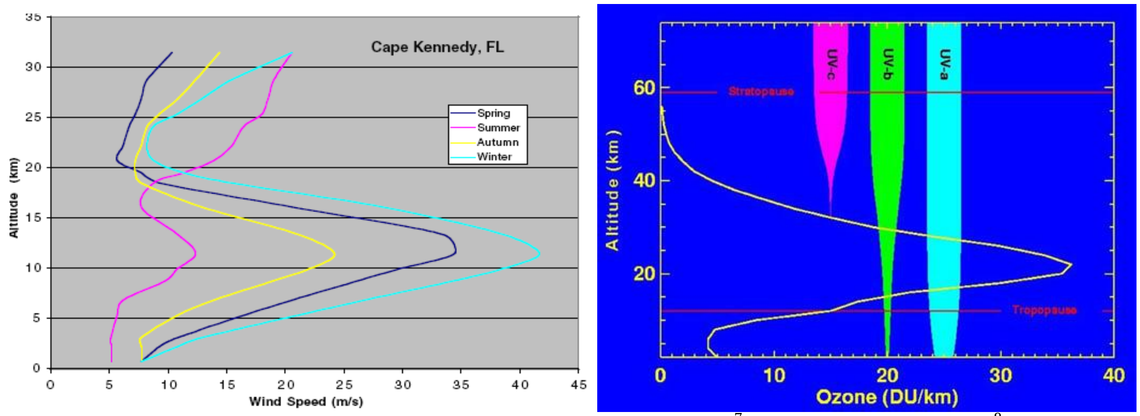

Figure 3. Seasonal Averaged Wind Speeds at Cape Kennedy[7] and Ozone Concentration[8]

The lower boundary of near space, altitude of 20km, also corresponds to the maximum density of the ozone layer. Figure 3 also shows the concentration of ozone as a function of altitude along with the relative intensity of the different bands of ultraviolet radiation. All altitudes will experience a significant flux of UV-a radiation, while altitudes above 40km will also experience a significant flux of UV-b radiation, and altitudes above 60km will also experience a significant flux of UV-c radiation. The upper near-space altitude limit (100km) also happens to correspond with the maximum atomic oxygen density in the atmosphere. These factors will place severe materials constraints on systems that plan on operating continuously for multiple years in the near-space environment.

III. Near-Space Systems

A. Existing Near-Space Systems

What might be called "near-space craft," or "nearcraft," have actually existed since the 1930's. From the Soviet manned high-altitude balloon Osoaviakhim-1[9], which flew (and crashed) in 1934, reaching an altitude of 22 km, to the record-setting flight of Scaled Composite's SpaceShipOne[10], which reached an altitude of 112 km in 2004, near-space flight has been achieved for over seventy years. However, the majority of the proposed near-term systems meant to endure in the near-space realm are designed to fly only in the lowest ten percent: 20-25 km above the Earth's surface. Given the long history of expeditions into the near-space territory, it is understandable that there are already several existing systems that routinely fly in those altitudes. For the purpose of this review, existing near-space systems are defined as those that exist and have demonstrated flight and useful performance at near-space altitudes. The proposed near-space systems must, therefore, outperform the existing systems in some critical metric to be of any practical value. For that reason, it is worthwhile summarizing relevant details for several existing systems that operate in near space.

There are three general classifications for existing and near-term near-space systems: free-floating balloons, dirigibles, and fixed-wing craft. Each has its own unique challenges and limitations, especially in the realm of power generation. The simplest of these are the free-floating balloons, but they also have the lowest performance and are also the least controllable, as they are at the mercy of the winds in the stratosphere. Dirigibles and fixed-wing craft are significantly more complex, but there are several examples of fixed-wing craft that regularly operate within near-space altitudes. Stratospheric dirigible flight has been demonstrated, but for very short time periods (hours) and without the required performance and capabilities required for real applications.[11] What follows is a discussion of select examples of free-floating and fixed-wing craft that have demonstrated relevant performance and capabilities at near-space altitudes.

Existing high-altitude balloons have no propulsive or steering capability. Once deployed, they are free to drift with the high-altitude winds. This makes them a very simple solution for near-space applications, and though it is possible to recover a balloon's payload, it must be considered expendable. However, balloons are considerably less expensive than other near-space craft, which makes up for their expendability, as long as their payloads do not carry sensitive equipment. The small price tag, combined with the potential for quick deployment on demand, makes them a good solution for communications relays and some reconnaissance. The major drawback, however, is that they cannot be directed at will to observe a particular target, as a fixed-wing aircraft or dirigible could.

An example of near-space balloons in use today is Space Data Corporation's SkySite® Platform and its military equivalent, the StarFighter™.[12] The SkySite® Network is a constellation of balloons used to provide wireless data and communications coverage where there is none, or where existing coverage is cost prohibitive. Each balloon covers a range of more than 640 km, and carries a payload of less than 5.4kg, at an altitude of 20-30.5km, for 12-24 hours. One balloon can be launched by a single person in about 20-30 minutes, and, with two launches a day per given area, continuous coverage can be achieved. Currently, a commercial network using these balloons exists over the south-central region of the United States, geared for the oil and natural gas industry. These balloons can also be used for communication applications in the transportation and utilities industries, border control, or isolated events for emergency response. They have already demonstrated an increase in the range of military radios from sixteen kilometers to nearly eight hundred.

Fixed-wing craft offer many more options for long-term near-space travel, although they carry a considerably higher price tag, and require more resources and support. A classic and well known example of an existing aircraft that flies in near space is the Lockheed U-2.[13] It is specialized for day-and-night, all-weather surveillance from very high altitudes. The U-2 was first introduced in 1957 and is still in service over 50 years later. The service ceiling for the U-2 is almost 26 km and its maximum speed is 800 km/h. It has a range of 10,300 km, and is able to stay aloft for approximately 12 hours. With several U-2s it is conceivable to achieve continuous coverage over a given area. However, for the purpose of continuous coverage over an extended period of time, the U-2 is not the best choice. Although many applications would benefit from an essentially zero ground speed, the U-2 is one of the most difficult aircraft to fly; its stall speed is only ten knots below its maximum speed at an altitude of 21 km (very often, it is flown only five knots above stall speed), so there is little margin for error. The structure of the airplane also makes it very sensitive to crosswinds, and it is extremely difficult to land because of a tendency to float over the runway.

The aircraft meant for the replacement of the U-2 is the Northrop Grumman RQ-4 Global Hawk, an unmanned aerial vehicle.[14] Its role is also surveillance, and it is capable of flying at an altitude of 20 km, with a speed of 650 km/h and an endurance of 36 hours. It is able to carry a payload of about 1,400kg. Theoretically, the Global Hawk could provide persistent ISR with several aircraft in constant rotation, launched one and a half days apart.

An example of a different type of high-altitude aircraft is AeroVironment's Helios Prototype, developed under NASA's Environmental Research Aircraft and Sensor Technology (ERAST) program.[15] It was a solar electric-powered flying wing, specifically designed for long duration flights at high altitudes. Powered by fourteen electric motors driving 2 meter, two-blade, laminar-flow propellers, the Helios reached an altitude of almost 29.5 km in 2001, with typical endurance missions envisioned at15-21 km. It was capable of flying at an airspeed of 30-43 km/h at low altitudes, and up to 274km/h, ground speed, at high altitudes. With solar power, Helios was able to fly during daylight hours, running an extra five hours after dark on lithium batteries. A second version of Helios was to be powered with fuel cells to enable it to fly around the clock, and eventually extend its endurance to anywhere from several days to several months. Unfortunately, during one of its flights, this version broke apart and crashed due to turbulence.

B. Near-Term Near-Space Systems (<15 years)

For the purpose of this study, near-term near-space systems are those designs that are relatively mature and could be fully operational in roughly the next 15 years. Balloons are currently capable of operating in near space for several weeks. Super pressure balloons such as NASA's Ultra Long Duration Balloon (ULDB) are being developed that could have lifetimes of up to 100 days.[16] Another technology being developed for near-space balloons is Global Aerospace Corporation's StratoSail® balloon guidance system.[17] The system doesn't provide propulsive force, but instead uses a tethered aerodynamic body to provide a steering force. A small amount of steering control may yield the capability of maintaining continual coverage at all points on the earth at very low cost.

A variety of dirigibles have been proposed and are being developed for near-space operation. As of early 2009, however, only two powered stratospheric airships have ever flown with a combined powered flight time of less than 4 hours. Aerostar International's HiSentinel airship represents the current state of the art of stratospheric airships that have actually achieved powered stratospheric flight.[18] In 2005 HiSentinel achieved 1.5 hours of powered flight at an altitude of 22.6km with a payload of 27 kg. Another airship under development for near term applications is the Lockheed Martin High Altitude Airship (HAA™).[19] The HAA™ is being developed with the capability of providing satellite-like performance at 1-2 orders of magnitude reduction in cost. The goals for the current generation of demonstration prototype, the High Altitude Long Endurance-Demonstrator (HALE-D), is to have sustained operations (> 2 weeks) at an altitude of 18.3km and a payload of 23kg. A flight demonstration of the HALE-D airship is scheduled for 2009. A higher performance airship under development with a longer time horizon is the DARPA Integrated Sensor is Structure (ISIS) airship.[20] By using next generation multifunctional materials, ISIS is thought capable of having a payload mass fraction of 30-40% vs. 1.7% for the HAA™. ISIS will have 99% station availability for more than one year at a time and operate at an altitude of 21.3km. The first flight was originally scheduled for early FY11.

Near-space aircraft have two possible solutions to the problem of providing sufficient lift for steady flight at near-space altitudes: high speeds or large wing spans. Both solar-powered and liquid hydrogen-powered, large wing span aircraft have been proposed and tested. An example of the next generation solar powered aircraft is the recently initiated DARPA Vulture project.[21] The long-term goal of the project is to demonstrate a high-altitude aircraft with a flight endurance of 5 years, 454 kg payload, 5kW of available power, and 99% on station capability. The project is still in phase I so the designs haven't been finalized, but it is estimated that the Vulture stratospheric aircraft might be flyable by 2020. An example of a liquid hydrogen-fueled near-space aircraft is AeroVironment's Global Observer. It has been designed to operate at an altitude of 20km for several days with the ability to carry a 400-1000-lb payload.[22] It uses propellers and a liquid hydrogen-powered propulsion system to sustain flight as a communications relay and remote sensing system. Currently, a prototype has successfully flown, but it has yet to be fielded as a complete system. These near-term platforms are representative of the types of platforms that advanced concept near-space propulsion systems could propel.

C. Advanced Concepts in Near Space (> 15 years)

All of the near-space vehicles described above are designed to fly in the lowest 10% of near space. Operating nearcraft at altitudes above approximately 25-30 km in near space requires either conventional vehicles with extreme properties, or entirely new vehicles with entirely new propulsion systems. Propellers for many proposed high-altitude airships already have a diameter of roughly 5m at an altitude of 20km, and will scale larger with increased altitude.[23] Fixed-wing aircraft already have large wingspans at the low near-space limit; Helios had a wingspan of 75 meters.[15] New technologies and materials will have to be developed to allow conventional vehicles to operate at these altitudes.

Another potential solution, however, is to develop entirely new types of vehicles with entirely new types of propulsion systems. There was very little published information on entirely new types of platforms for near-space loitering missions. One platform that was identified was a thin membrane supported by continuous beaming of microwave energy. The concept is described in detail in section 4.c.1. Far-term near-space platforms may use air-breathing electric propulsion systems. The general performance requirements for such a device, along with a potential example, electrohydrodynamics propulsion, is reviewed in section 4.b.1.

IV. Near-Space Propulsion Systems

Propulsion systems can be used for many different near-space applications including: drag compensation, repositioning, and providing lift. The near-space vehicles described in section III provide some idea of the future near-space vehicles requiring propulsion, but it is impossible to define the exact properties required from a near-space propulsion system. Typical properties of existing near-space propulsion systems along with existing and near-term platforms will be used as a guide when evaluating the potential of advanced concepts for near-space propulsion systems. Near-space dirigibles use buoyancy forces to generate the required lift, and propellers driven by electric motors to provide thrust. Both techniques will be discussed briefly to allow comparisons with advanced concepts for near-space propulsion systems.

A. Required Propulsive Forces in Near Space

The net buoyancy force produced by a volume of gas is given by

$$F_b = (\rho_{atm} - \rho_{fill})gV \tag{5}$$

The net buoyancy force for near-space dirigibles which have envelope volumes on the order of one million cubic feet (28,000m^3)[19] of helium is thus about 20kN. Much of the buoyancy force must be used to lift the envelope, structure, power system, propulsion system, and other non-payload mass. Typical payload mass fractions for proposed near-space dirigibles are several percent. A payload mass fraction of two percent would yield a net payload lifting force of 400N, allowing a payload of roughly 40kg to operate at altitudes of up to 20km. Near-space dirigibles must also have a propulsive force to overcome drag due to high-altitude winds and to move the dirigible between positions. Proposed near-space dirigibles commonly have diameters of greater than 20m.[19] If a near-space dirigible with a 20m diameter flew at an altitude of 20km, had a drag coefficient of 0.03, and operated in winds of 35m/s, then the thrust required would be approximately 500N. Advanced concepts for near-space propulsion systems must be able to produce force levels of 100N to 100kN to be of use on near-term near-space dirigibles. If a

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near-space propulsion system could enable an entirely new (much smaller) near-space vehicle then the required forces could be reduced.

Near-space aircraft, in contrast, will require similar thrust forces, but significantly lower lift forces. Large aspect ratio aircraft can have lift to drag ratios of 20-40 or more. With masses as low as 900kg, lifts of only 9kN are required. With lift to drag ratios of 30, this would correspond to a thrust of approximately 300N.

In general, therefore, to be useful on predicted near-term near-space platforms, an alternative propulsion system should capable of producing force levels ranging from 100N to 100kN with the higher force range corresponding more to large-scale lift applications. Several additional considerations must be kept in mind when evaluating potential near-space propulsion systems. They must be very lightweight, very reliable, and work at temperatures down to 217K. An additional complicating factor is that the near-space platform must be capable of reaching near space, so it would be advantageous if the propulsion system could work over a large range of altitudes. Two classes of force generation mechanisms were identified and will be reviewed below: low ionization degree electric propulsion and rarefied gas propulsion.

B. Propellers for Near-Space Propulsion

Most craft intended for true continuous, long-term use (i.e. several days or longer) are driven by propellers. While balloons are capable of staying aloft for long periods of time, propellers allow much more control over the craft and changes in mission goals. To make any worthwhile progress in solutions for near-space propulsion, proposed technologies must increase performance over propellers. Therefore, it would be beneficial to discuss characteristics of high-altitude propellers that must be overcome by other technologies.

However, propellers are far from being a cut-and-dry technology themselves.[24] Although, in general, propeller size must increase with altitude in order to provide usable thrust in a thinning atmosphere, this rule can be modified with the use of higher numbers of propellers, as well as tailoring the propeller shape to specific operating conditions and mission needs. High-altitude, or low Reynolds number, propellers are very much a developing technology, and their characteristics are yet to be fully understood. There is no comprehensive "catalog" for these propellers – around the same time that near-space ideas started taking off, the older design methods of referencing a catalog faded away. They are now developed and built on a case-by-case basis to fit the specific mission and craft. It is not even a simple matter to describe general characteristics, since there are strong, non-linear effects with airflow over the blades, which cause unusual behavior. This currently makes it impossible to generate a complete or accurate model with which to compare other propulsion technologies.

In spite of this, however, it is possible to evaluate other proposed propulsion technologies based on a more complete picture of the craft that they are envisioned to propel. Factors such as payload, loiter time, range, altitude, cost (including the cost of operation and maintenance), and number of vehicles needed for continuous coverage are all things that must be considered. Assuming all vehicles would be capable of flying the desired distance, perhaps the most useful metric would be cost per hour of coverage. Factored into this would be loiter time, the complete costs associated with running and maintaining the vehicle, and number of vehicles needed for continuous coverage during a given time period. Payload and altitude would be considered separately, with choices made depending on mission goals.

C. Electric Propulsion in Near Space

Most of the proposed near-space platforms are powered using photovoltaic energy conversion with batteries or fuel cells used for energy storage. These types of vehicles would require a propulsion system that converts electrical energy into the mechanical energy of the flowing gas in the propulsion system. Propellers are the current method of choice, but it is worthwhile evaluating other electric propulsion devices that have no mechanical parts. A large variety of electric propulsion devices have been developed for in-space applications with specific impulses ranging from several hundred seconds for resistojets to over 10,000s for field emission electric propulsion (FEEP) thrusters. Before evaluating electric propulsion devices for near-space loitering applications, the desired specific impulse must be determined. The term specific impulse is used here to refer to the thrust per unit mass flow of ambient gas through the device because stored propellants are not feasible for long-duration near-space applications.

The optimum specific impulse for electric propulsion systems for in-space applications is typically estimated by determining the specific impulse which yields the minimum total mass (propellant and power supply) for a specified mission. The propellant mass decreases with specific impulse while the power supply mass increases with specific impulse typically yielding an optimum specific impulse in the range of 1000s to 3000s for earth orbiting satellites.[25] This type of analysis can't be directly used for near-space electric propulsion systems that use ambient gas as propellant. Air-breathing electric propulsion systems have a stored propellant mass of zero, but the mass of the thruster itself can be significant and strongly dependent on the specific impulse. It is expected that near-space electric propulsion devices will scale to larger sizes at lower specific impulses. The method for estimating the optimum specific impulse for near-space systems will be to determine the specific impulse that yields the minimum total system mass which includes the power system mass and propulsion system mass. It is assumed that the air-breathing electric propulsion systems are large, lightweight structures with masses that scale with the cross-sectional area used for propulsion. The total mass of the system is then given by

$$m_t = m_{ps} + m_{pr} = \alpha P_e + \beta A = \frac{\alpha g_o T I_{sp}}{2\eta} + \frac{\beta g_o^2 T}{\rho_{atm} I_{sp}^2} \tag{6}$$

The total mass per unit thrust as a function of specific impulse for a wide variety of the system parameters at an altitude of 20km is shown in Figure 4.

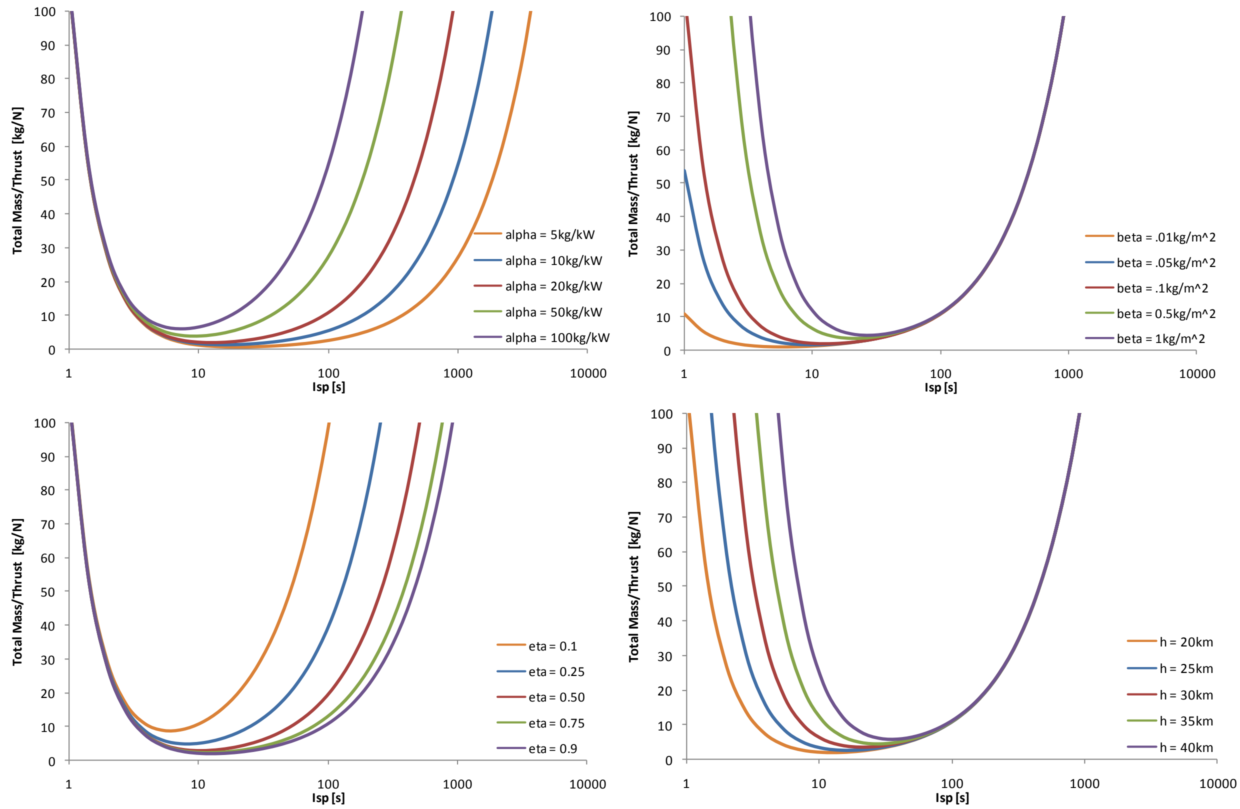

Figure 4. Total Mass/Thrust for Various Near-Space Propulsion Configurations

It is impossible to accurately determine the optimum specific impulse for air-breathing electric propulsion systems in near space without a specified platform and mission. It is quite clear from the figures, however, that specific impulses significantly lower than for in-space applications will be optimum. It is reasonable to assume that specific impulses in the range of 5-50s will be useful for long-duration near-space systems. The required electric propulsion system would then be a very lightweight system that operated at very low specific impulses and had a very low ionization cost. A specific impulse of 50 seconds typically corresponds to a cold gas thruster and not to an electric propulsion device. Electromagnetic and electrostatic propulsion systems require significant ionization fractions and, correspondingly, have large ionization costs. They are simply not applicable for these near-space missions. Electrohydrodynamic (EHD) propulsion systems that use very low ionization fractions and produce gas flows of tens to hundreds of m/s could potentially achieve the required performance, and are evaluated in more detail in the following section.

1. Electrohydrodynamics in Near Space

Electric propulsion systems that require significant ionization to operate efficiently (most air-breathing variants of electromagnetic and electrostatic systems) operate at specific impulses that are orders of magnitude too high for near-space loitering applications. Electrothermal propulsion systems aren't capable of providing the required performance because they would require compression to operate on ambient gases and would be prohibitively inefficient because nozzle acceleration is fundamentally inefficient at the low pressure ratios corresponding to the low required specific impulses. One possible solution, however, is to ionize only a small fraction of the propellant and produce a low-speed, predominantly neutral flow using electrohydrodynamics (EHD). EHD was first investigated as a source of pressure difference by Chattock in 1899.[26] Since then there has been slow, but continuous progress in the development of EHD pumps for both air and liquids. EHD is currently employed in devices such as air purifiers and has been proposed as a low-altitude propulsion system, but it has traditionally suffered from low energy conversion efficiencies (typically < 1%).[27] More recent efforts have demonstrated improved performance with efficiencies approaching 7.5%.[28] The conclusion reached in the literature assembled from sources ranging from analytical models[28] to a transient, three-dimensional EHD model capable of solving coupled charge transport and Navier-Stokes equations,[29] along with the supporting experimental data is that significant improvements in efficiency are possible.

A simple schematic of an EHD propulsion system is shown in Figure 5a, along with an example of a simple EHD propulsion system built by Blaze Labs in Figure 5b.[30] The typical EHD propulsion system, like that shown, uses a corona discharge as an ion source. A high voltage (tens of kV) is maintained between the thin corona wire and a parallel collecting electrode, which provides the acceleration of the ions and, through collisional coupling, the ambient neutral gas. Energy is lost predominantly as heat during the acceleration process[27] with only ~1-4% of the input energy being lost in the corona.[30] Two methods have been identified to increase the efficiency of EHD propulsion systems: decrease the ion mobility in the acceleration region[27], and increase the incoming flow velocity.[28,29]

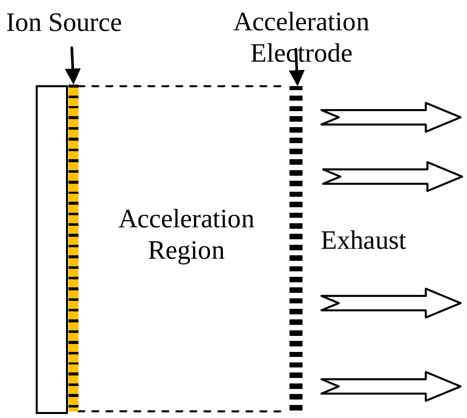

Figure 5a. Simple EHD Schematic

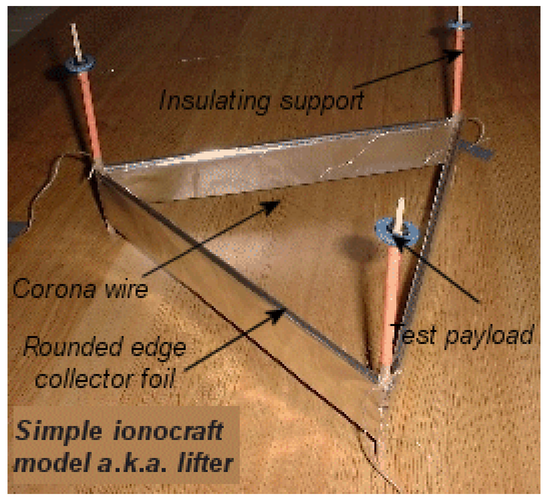

Figure 5b. Simple EHD Propulsion System

In the limit of very high ion mobility there is effectively no coupling between the ion flow and the neutral flow. In this case the propulsion system would operate more like a traditional ion thruster, but operated with a noninteracting background gas. Decreasing the ion mobility increases the efficiency of the coupling between the ion flow and the neutral flow, which will increase the produced thrust and energy efficiency of the device. A typical ion mobility for EHD thrusters operating at standard temperature and pressure conditions in air is about 2×10^{-4} m^2/Vs.[31] In general, ion mobility is dependent on the molecular weight of the charged species, the pressure of the neutral gas, the temperature of the gas, and the ratio of the electric field to the gas pressure. The gas pressure in near space ranges from a fraction of 5×10^{-2} to a fraction of 3×10^{-4} of the pressure at the surface of the Earth. The lower pressure will increase the ion mobility and lower the thrust efficiency of the device unless the electric field strength can be lowered as well. The lower gas temperature will slightly improve the thrust efficiency of the EHD propulsion system. High typical wind speeds may also partially counteract the reduction in performance at lower pressures.

It has been shown that the incoming gas flow velocity has a strong effect on the overall thrust efficiency of EHD propulsion devices.[28,29] Increasing the incoming flow velocity can dramatically improve the thrust efficiency in EHD propulsion systems. As the incoming flow speed increases, the current due to charge convection increases, which increases the ratio of the convection current to the total current. Convection current is more efficient at producing thrust and increasing it will increase the overall thrust efficiency. Bonder and Bastien demonstrated a thrust efficiency improvement from a value of 2.6% to 7.5% was achieved at a velocity of 50m/s.[28] Singhal and Garimella predict that the trend will continue at higher velocities.[29] Average wind speeds of greater than 10m/s can be encountered even at the altitude with the lowest winds as shown in Figure 3. Vehicles with nonzero ground speed would also benefit from increased efficiency.

EHD propulsion systems are possible candidates for near-space loitering applications in the lower altitude range of near space. They can be made very lightweight, can operate over a wide range of pressures (altitudes), and are relatively simple devices. Reductions in thrust efficiency are expected at the lower operating pressures of near space, but the reductions may be counteracted by operating at lower ambient temperatures and with a significant incoming gas velocity. A method to significantly reduce the ion mobility in the acceleration region of the device is the primary technological hurdle limiting application. There are, however, several other concerns with the devices that must be addressed. The most obvious concern is the potential for Paschen breakdown: the thin corona wire can be charged to potentials of tens of kV, but a charged conductor at 20kV in air at 40Torr (h=20km) would breakdown for electron distances between 13μm and 13cm.

D. Rarefied Gas Based Near-Space Propulsion

At near-space altitudes the atmospheric number density drops to between 2×10^{24} m^{-3} at an altitude of 20km and to 1×10^{19} m^{-3} at an altitude of 100km. The corresponding mean free path as a function of altitude is shown in Figure 6. The mean free path in near space varies from roughly 1μm at an altitude of 20km to roughly 10cm at an altitude of 100km. Rarefied gas effects must be considered when analyzing the behavior of platforms operating in the upper near-space altitudes, but it is also worth determining if any rarefied gas dynamics mechanisms for force generation are applicable for near-space propulsions systems. Such systems may enable flight in the higher range of near-space altitudes where no near-term near-space platforms would operate. Two such mechanisms are discussed in this section: radiometric forces and thermal transpiration.

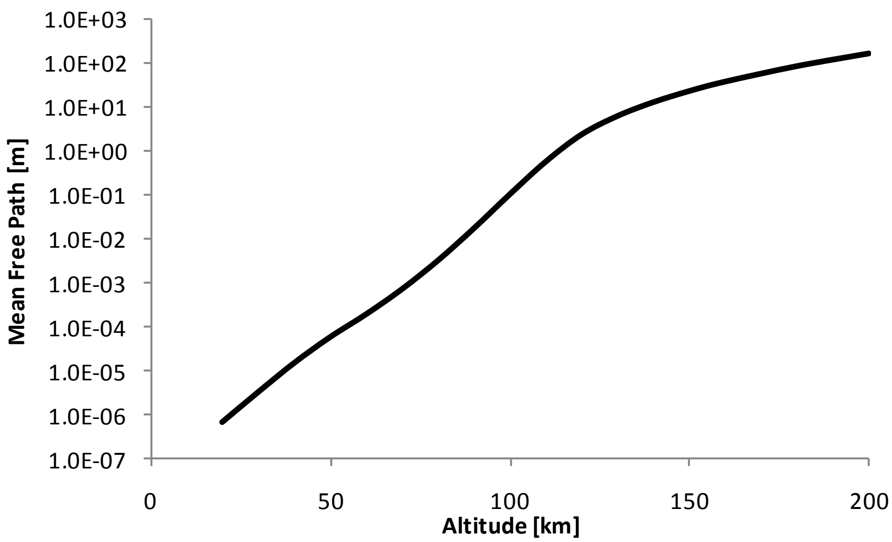

Figure 6. Mean Free Path for Near-Space Atmosphere

1. Radiometric Forces

The radiometric force occurs when a temperature difference is created between a hot and cold side of a plate or vane that is in a rarefied gas. The classic example of a device employing this effect is Crooke's radiometer.[32,33] Crooke's radiometer contains rotary vanes, each with one black side and one white side. The vanes are mounted on a pivot in a partially evacuated glass bulb. When exposed to light, the black side of the vanes heats to a temperature greater than the white side, causing the vanes to spin due to the radiometric force.

While the radiometric force was identified as early as the late 1700s[34] it is still not fully understood. Since its discovery, two main driving mechanisms have been identified to explain the force mechanism. One explanation is that the force acts on the entire area of the vane in the collisionless or free-molecule limit. This area force is based on kinetic theory, in which molecules undergoing fully accommodated collisions will leave a surface with higher normal velocities when the surface temperature is higher. The surface temperature of the black side of the vane is higher than the white side, indicating that a force will be generated on the vane towards the white side. If the gas pressure were to be increased the relative importance of particle-particle interactions would increase, which would decrease the area force. Another mechanism proposed to explain the radiometric force under these conditions scales with the total edge length of the device, and appropriately referred to as an edge force. This mechanism is conceptually more complicated and is often described by two separate effects: thermal creep,[35] which drives the gas from colder side to the hotter one, and Einstein's effect based on thermal transpiration[36]. Figure 7 shows the streamlines and gas temperature for a vane place in a vacuum chamber filled with a rarefied gas. It is clear from the figure that the edge force is much more complex than the simple area force. There has been a large debate over which mechanism dominates at different pressures. Force levels predicted for the different mechanisms can vary drastically, with the edge force being potentially much larger than the area force for geometries such as slotted plates where the edge length has been greatly enhanced. In recent work it has been shown that, at gas pressures corresponding to the peak in radiometric force, the effect is dominated by an area dependence[37].

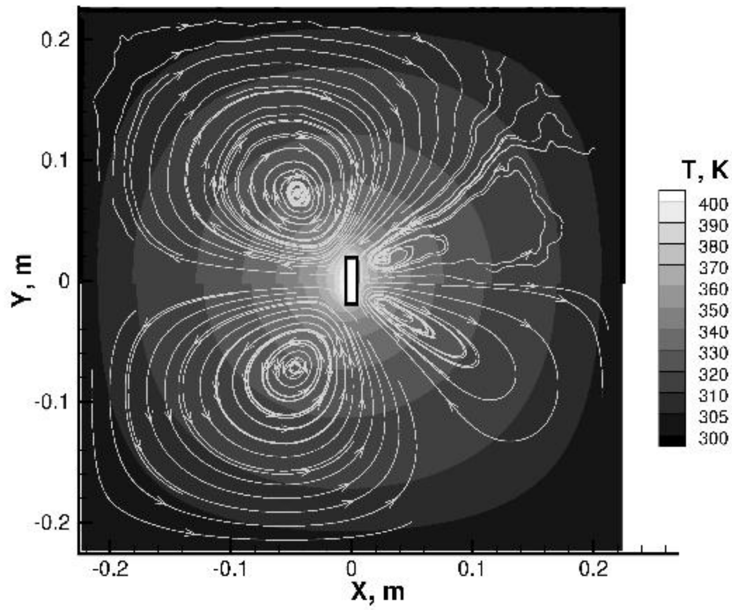

Figure 7. Streamlines for a Radiometric Gas Flow Around a Plate in Transitional Conditions

Newly proposed applications, in conjunction with recent experimental techniques and advances in computer simulations, have led to a resurgence in radiometric research. It has been shown that radiometric forces produce a maximum force at a Knudsen number of approximately 0.1. This Knudsen number can readily occur at near-space altitudes, indicating that the radiometric force can occur. However, because the exact driving mechanism as a function of pressure is unknown, it is difficult to make accurate estimates concerning the viability for use in near-space propulsion systems.

There are multiple theories suggesting that by drastically increasing the vane edge length, relatively large forces per unit area can be produced. Predictions indicate that enough force to perhaps support a high altitude near-space craft may be possible. Benford[38] proposed a lifter concept utilizing a light carbon fiber material to create a sail that optimizes both area and perimeter effects. His craft is designed to operate at a near-space altitude of 73km, where the optimal Knudsen number is achieved. The temperature gradient used to drive the radiometric force would be formed from a ground based microwave beam being absorbed by one side of the lifter. The published design employed a 20m diameter sail that would weigh 10kg. The physical design of the sail appeared possible using current carbon-carbon microtruss technology with a density of 10g/m^2. Analysis predicted a payload capability of 90kg. At a predicted lifting power of 0.01g/W, which appears experimentally possible[39], it would take 10MW of continuous power to provide the necessary lift. Microwave sources capable of providing 5MW currently exist in fusion laboratories. The predicted performance seems convincing, but these estimates are based on the optimistic radiometric force models and use optimistic parameter estimates. The physical understanding of the radiometric force mechanism must be improved before the true potential of radiometric forces in near space can be determined.

There are several operational considerations, in addition to the technical considerations, for such a concept. The first is that the radiometric force will become insignificant at altitudes significantly above and below the design altitude. Rocket launch or some alternative delivery technique must be used to position the lightweight microtruss structure in its operational near-space altitude. After delivery the sail must be quickly released (at the right speed) and deployed. A rocket might be used to deliver the system to the required altitude, but the deployment would be difficult, and, it may counteract the potential cost savings of not launching to space. A craft like SpaceShipTwo might be used to deliver it to the required altitude, but the deployment problems would be similar.

Another important systems consideration is that long-duration systems requiring constant beamed power to generate lift are fundamentally expensive to operate. Stratospheric airships are very large, but once on station, the buoyancy force keeps them at the required altitude. Orbiting satellites are costly to launch, but only require propulsion energy to overcome the atmospheric drag force acting on the craft. The radiometric propulsion system described earlier used 10MW of continuous power to maintain the altitude of the sail. Using a minimum energy cost of 0.011$/MJ (off-peak rates) the cost of operating the proposed system would be $0.11/second or approximately $35 million for a 10 year lifetime. When factoring in the higher true cost of electricity, all losses between the input electric energy and the output thrust energy, and the additional cost to construct, maintain and operate the beam station, the real costs would certainly be significantly higher. It is often suggested that near-space craft would yield spacecraft performance for aircraft costs, but constantly beaming power to generate lift appears to contradict that suggestion. For example, if SpaceX's Falcon 1 program is successful, the launch vehicle will be capable of delivering a 420kg payload to LEO (185km) for a total cost of around $7 million.[40]

The evidence supports the fact that radiometric forces can be generated in the upper altitudes of near space. Radiometric force based propulsion systems were the only propulsion technique reviewed that could potentially provide forces at that range of altitudes. The physical model and assumed properties must be verified to demonstrate that force levels relevant for near-space vehicles are possible. Systems considerations such as the fundamentally high cost of maintaining lift through constant beamed power are likely to limit the viability of such a system. Once the understanding of the driving mechanism is improved, the concept should be analyzed for other potential force applications such as thrust and steering.

2. Thermal Transpiration

Thermal transpiration is a physical mechanism which produces a gas flow simply by maintaining an axial temperature gradient across a tube containing a rarefied gas. Thermal transpiration has been investigated as a driving mechanism for gas pumps/compressors that can operate in the pressure range of roughly 100mTorr to 5,000Torr.[41] The gas flow travels from the cold side of the tube to the hot side, which yields a pressurized high-temperature gas with a net flow, the basic requirements for a near-space electrothermal propulsion system. The energy efficiency of thermal transpiration devices is their primary limitation and a significant effort has been focused on increasing their energy efficiency to practical values over a wide range of pressures.[41,42] The thermal transpiration mechanism would suffer from the same practical limitations generating lift as the radiometric propulsion system, but it could potentially be used for thrusting or steering applications. Thermal transpiration is, therefore, evaluated to determine the potential of the mechanism to provide thrust in place of propellers on a near-space dirigible. One potential benefit would be that the device may be directly solar powered. Instead of first converting the solar energy to electrical energy and then to propulsive force, the system could use solar energy to directly heat the transpiration membrane and then the flowing gas to provide propulsive force.

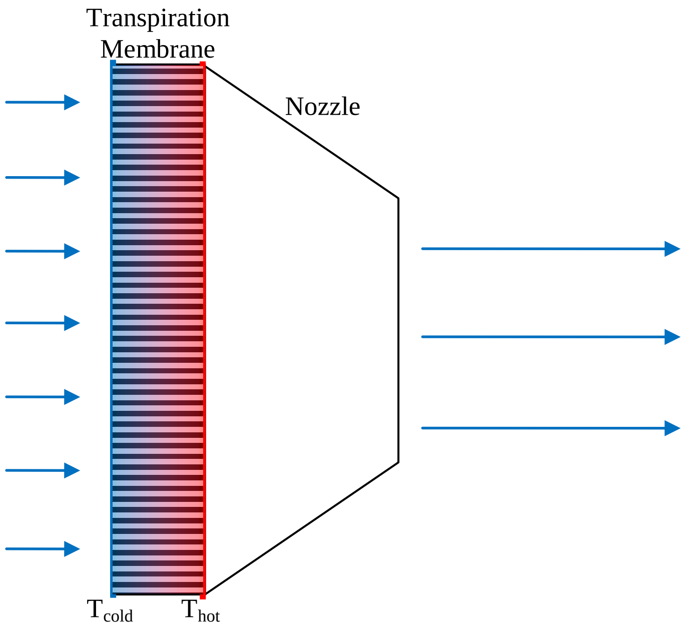

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Figure 8. Thermal Transpiration-Driven Near-Space Thruster

For a thermal transpiration-driven propulsion system to be viable as a near-space dirigible propulsion system, it must produce the required thrust under the physical dimension, mass, and power constraints consistent with near-space vehicles. For the following analysis, the High Altitude Airship was used as an example. The analysis attempts to determine what a thermal transpiration based propulsion system would look like that can provide 450N at an altitude of 20km. A single stage thermal transpiration propulsion system would consist of two components: a transpiration membrane and a nozzle as shown in Figure 8. The figure shows the foundation for the performance model and the basic components for such a device. It is not meant to represent how an actual system would look. The actual system would require that the membrane stay oriented relative to the sun, with the exhaust of the nozzle oriented in the direction necessary for thrust production.

A meaningful performance model of a thermal transpiration based propulsion system can be assembled from just a few validated analytical expressions.[41] The pressure difference achieved across a single thermal transpiration membrane is given by

$$\Delta p = p_{avg}\frac{\Delta T}{T_{avg}}\frac{Q_t}{Q_p}\kappa \tag{7}$$

Where Qt and Qp are flow coefficients for thermally-driven and pressure-driven flows. Their ratio (Qt/Qp) varies from 0 for continuum flows to 0.5 for free molecular conditions. The mass flow through the membrane is similarly given by

$$\dot{M} = \frac{m}{k_b T_{avg}} C\left[p_{avg}\frac{\Delta T}{T_{avg}}\frac{Q_t}{Q_p}\right](1-\kappa) \tag{8}$$

The power consumption in the device can be divided into three categories: thermal conduction through the transpiration membrane, energy radiated or convected outward from the hot membrane surface, and thermal energy used to increase the temperature of the pumped gas. For the analysis, it is assumed that the convection/radiation thermal fluxes from the hot side of the membrane can be reduced to negligible levels. It is also assumed that the cold side of the membrane is connected to a perfect heat sink and that the incoming radiant flux is absorbed essentially at the hot surface. The power balance for the system is then given by

$$P_{in} = P_{out} = k_{th}\frac{\Delta T}{L_x}A + c_p\dot{M}\Delta T \tag{9}$$

The output of the transpiration membrane is then fed directly to the nozzle section of the device to convert the gas thermal energy into thrust. Subsonic isentropic flow conditions are assumed in the nozzle section, and the nozzle properties are calculated using the standard isentropic flow relationships. Ideally, the Knudsen compressor based propulsion system would operate at a critically expanded condition so there wouldn't be any pressure difference across the device. The thrust produced by the device would then only be due to the mass flow rate produced by it, and is given by

$$T = \dot{M}v_e \tag{10}$$

With this model, it is possible to make estimates of the performance of such a system with a single stage Knudsen compressor based on optimized stages from previous work.[41] Figure 9 shows the thrust as a function of maximum pressure difference for a solar-illuminated carbon-doped aerogel membrane stage with a thickness of 1cm, a cross-sectional area of 100m^2, a membrane mass of 100kg, and a thermal conductivity of 10mW/mK. The thrust level produced by such a large device is still three orders of magnitude too low for the proposed application.

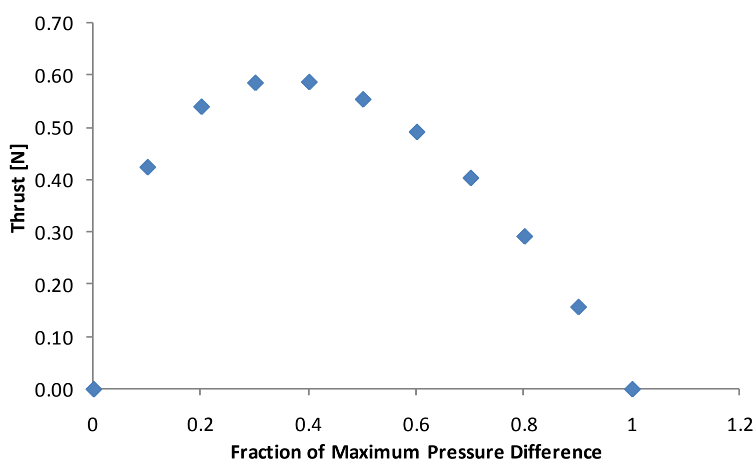

Figure 9. Thermal Transpiration Thruster Performance Based on Existing Technology

The same model was used with highly optimistic numbers to determine the limit of potential performance gains of the technology. The highly optimistic stage had an area of 400m^2, a thickness of 5mm, a total mass of 100kg, and a thermal conductivity of 4mW/mK. The thrust as a function of the realized fraction of the maximum pressure difference is shown in Figure 10.

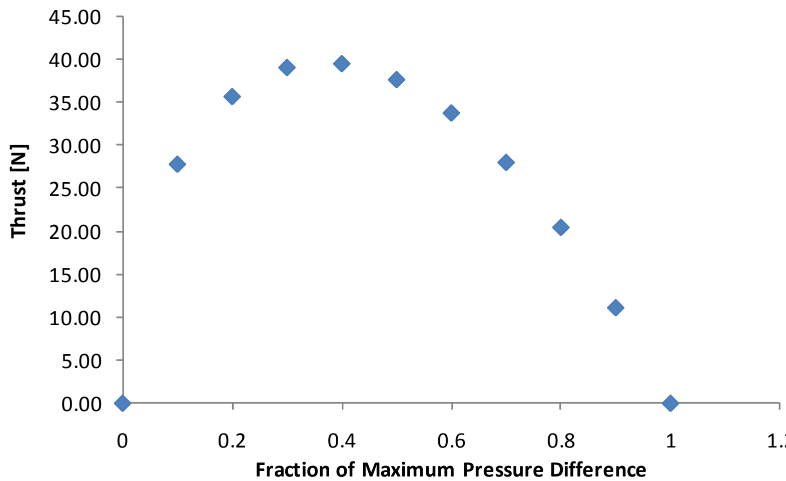

Figure 10. Thermal Transpiration Thruster Performance Based on Highly Optimistic Technology

Even with the highly optimistic assumptions, the thrust produced is one order of magnitude too low. The limitation of thermal transpiration-based propulsion systems is a fundamental one. The ideal cycle efficiency for isentropic flow between two pressures is given by

$$\eta_c = 1 - \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \tag{11}$$

Figure 11 shows the isentropic cycle efficiency for a nozzle as a function of pressure ratio, along with the temperature difference that would be required for an ideal thermal transpiration device to yield that pressure ratio. It is clear from the figure that thermal transpiration devices are able to produce a maximum pressure ratios of perhaps 1.5 for reasonable hot side temperatures (<2000K). The maximum cycle efficiency at that condition is only 10%, illustrating the fundamental difficulty in using thermal transpiration in propulsion devices.

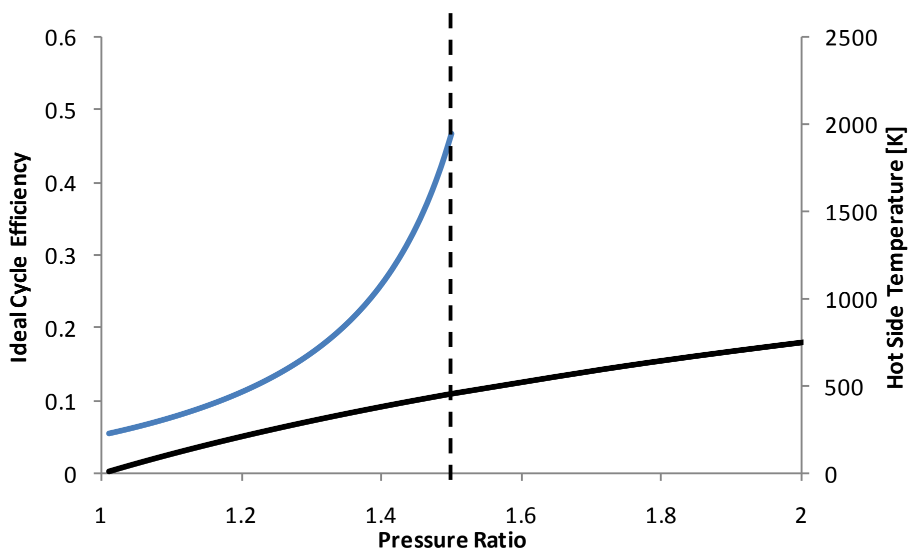

Figure 11. Isentropic Cycle Efficiency for Isentropic Flow Compared to Required Temperature Differences

E. Breakthrough Physics

No breakthrough physics-based near-space propulsion systems were located in the published literature. It is, however, worthwhile evaluating the impact that some breakthrough physics may have on near-space propulsion systems if the physics was shown viable, and devices employing the physics could be constructed. The exciting nature of breakthrough physics leads one to believe that such a breakthrough can automatically provide significant performance benefits over classical systems. However, previous work has shown that some breakthrough physics-based in-space propulsion systems would not lead to revolutionary advancements in performance.[43] Some breakthrough physics concepts such as the Casimir force[44] can't produce relevant force levels in meaningful configurations and won't be discussed.

There have been many advanced concepts for launch that involve the modification or complete removal of gravity as a means for accessing space.[45,46,47] The physics behind these concepts is unproven and obviously none of them exist, but it is worthwhile postulating what performance advantages these types of devices could yield for near-space systems if they were possible. The near-space platforms under consideration in this report travel at low velocities making inertial mass modifications unnecessary. Gravitational shielding technologies, if properly applied, could modify the altitude of the geosynchronous orbit for a near-space craft. Figure 12 shows the fraction of nominal standard gravitational parameter (GM) for Earth required to produce a geosynchronous orbit as a function of altitude. The curve crosses 1 at the nominal altitude of 42,164km. Above that altitude, additional gravitation would be necessary in order to yield a geosynchronous orbit. Below the nominal GEO altitude, the required gravitation rapidly decreases, but the decrease rate slows at an altitude of about 1000km. The required gravity at 100km is only 0.36% of the nominal gravity. By 20km in altitude is has reached 0.35% of gravity. Only 0.01% change in gravity reduction separates yielding a geosynchronous orbit at the lower limit of near space from the upper. If the physics for such a gravitational shielding device was valid and a device could be built, it would have to shield greater than 99% of the gravitational force, and would have to be very precise to be of use. If constant power was required, it would probably experience the same operational limitations as technologies that use beamed power to generate lift.

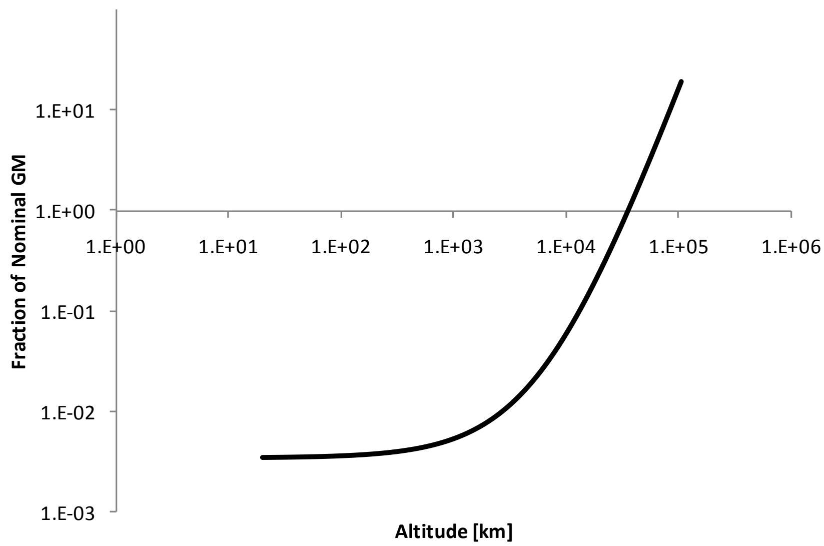

Figure 12. Degree of Gravitational Shielding Required to Produce Geosynchronous Conditions

Antimatter is one breakthrough physics concept that actually exists, and antimatter propulsion has been suggested.[48] Antimatter annihilation has the highest energy density ($9\text{x}10^{16}$J/kg or ~10^{17}* lithium ion batteries) of any known material. It is worthwhile examining if there are any potential uses of antimatter in near-space propulsion systems in the next 50 years. A subscale near-space dirigible demonstrator being developed by Lockheed Martin, HALE-D, uses a thin film solar cell/battery/electric motor driven propeller for propulsion.[19] Each motor is rated at 2kW. With an energy density of $9\text{x}10^{16}$ J/kg antimatter annihilation would require a minimum of 80ng/hour to operate each motor making it appear to be a promising concept. The current rate of antimatter production, however, is 1-10 ng/year with rates as high as 30ng/year expected by 2020.[49] The current and near term production rates are insufficient to provide one hour of propulsion from 1 propeller on one subscale near-space vehicle demonstrator. Additionally, the energy efficiency of the current production process is in the range of 10^{-8}, indicating that significant power is required to produce a relatively small amount of contained antimatter. This factor must be significantly improved for antimatter to become a useful fuel. Antimatter based propulsion is also naturally high in specific impulse (>1000s), so new propulsion systems must be envisioned for near space. Antimatter is also the most expensive material on the planet.[50] At the current cost of production at CERN (~$10 billion/ng), it would cost $800 billion per hour to run a single motor. Antimatter storage is another technological challenge that must be overcome. Significant improvements in antimatter production are expected, but the number and level of improvements required for near-space propulsion applications employing antimatter to be viable indicates that antimatter probably has no application for use in near-space propulsion systems for the foreseeable future. None of the identified breakthrough physics concepts (whether proven or not) would yield fundamental improvements in near-space propulsion systems.

V. Conclusions

Near space shows clear potential for providing several optimum conditions for ISR missions. A large number of long-duration near-space vehicles have been proposed and some of them are under development. The vast majority of them, however, operate at the lowest near-space altitudes where several current vehicles that are not commonly identified as near-space vehicles can already operate. The proposed near-space vehicles all use propellers for propulsion. New propulsion systems are required to enable new types of vehicles at these lower near-space altitudes and to allow operation at the higher near-space altitudes. Electric propulsion systems operating in near space will be fundamentally different than in-space electric propulsion systems. Near-space electric propulsion systems must be lightweight, have a long lifetime, have specific impulses in the range of 5-50s, and be capable of producing thrusts of hundreds of newtons to hundreds of kilonewtons. Only one candidate electric propulsion system was identified that could potentially meet the requirements, EHD-based propulsion systems. EHD propulsion systems have been demonstrated and are lightweight, but currently operate at low energy efficiencies. A comprehensive optimization effort would be required to improve the efficiency of less than 10% at the Earth's surface to greater than 50% at near-space conditions. The reduced density at near-space altitudes also indicates that thrust mechanisms based on rarefied gas dynamics may also be possible. A propulsion system using radiometric forces was shown to be a candidate propulsion system, but the physics underlying the performance predictions has a great deal of uncertainty and must be proven. Radiometric propulsion systems also have numerous practical and operational hurdles that must be overcome before the systems could be viable. The first step in developing radiometric force propulsion systems is to improve the understanding of the operating mechanism. Thermal transpiration-based propulsion systems were shown to have fundamental limitations keeping them from being viable as near-space propulsion systems. Breakthrough systems concepts, if proven, seem to yield limited performance advancements.

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