A Stable Sub-Orbital Permanent Structure Based on Readily Attainable Technological Advancements

Philip Swan

Brian Baker

Sean Conner

Gunnar Clovis

Chris Fornof

Alexander Halaszyn

Alba Misciagna

C. Prado Nickel

2017

A Tethered Ring is a dynamic structure that can cost-effectively support space launch facilities, transportation infrastructure, and a sizable human settlement at high altitudes. An altitude of 32km and a population of 250,000 is shown to be technologically and economically feasible using 2017 science and technology.

A minimally viable implementation of The Tethered Ring is described. It has a diameter like that of the Pacific Ocean. It stays aloft by generating and properly combining inertial forces with tensile forces to offset the pull of gravity. The inertial forces are produced by the circular motion of magnetically levitated rings within the pipelines, and the tensile forces are generated by appropriately tethering the pipeline bundle to the side of the planet that protrudes through the ring, using tethers made of strong, light-weight, industrial fiber.

The entire structure can be fabricated on Earth and neither its construction nor its deployment depends on a pre-existing space infrastructure or space-based industry. The deployed structure is resilient to catastrophic failure because its precision-guided fast-moving components are: a) not exposed to seismic or climatic battering, and b) safely above and thus out of range of tacit civilizational threats, such attacks involving torpedoes or commandeered aircraft.

The tethered ring is an optimal stepping-stone infrastructure for furnishing humanity with a safe, affordable, and sustainable means to escape Earth's gravity, expand its civilization into space, and ultimately evolve into a multi-planetary species.

Contents

Introduction

Sea travel and air travel have evolved in recent history from perilous enterprises into ubiquitous services. Associated with this evolution is an increase in the amount of capital-intensive transportation infrastructure. For example, many notable high traffic water routes have been supplanted by very expensive and ambitious bridge and tunnel projects. Magnetically levitated (MAGLEV) transportation infrastructure is being funded to supplant high-traffic routes that are currently served by airlines. The trend demonstrates that infrastructure planners value the long-term benefits of high capital cost infrastructure projects.

Space travel is anticipated to similarly evolve in response to growth in demand and improvements in transportation technology. However, as there are currently few habitable destinations in space to visit, demand for space access transportation services is comparatively low.

Rockets represent the incumbent technology for accessing space. The Space Transportation System (STS), commonly known as the Space Shuttle Program, while technically not a fixed infrastructure like a bridge or a tunnel, was represented by its proponents as having a characteristics of fixed infrastructure project. The program's paradigm was to build a fleet of orbiters and boosters at a high capital cost but to make them reusable to reduce the per-use costs.

Figure 1 shows the economics of the Space Transportation System (STS). Cost-per-kg for the STS is shown to be strongly affected by capital costs if, over its lifetime, the system is used to deliver between 10 and 10,000 metric tons to LEO (Hsu, 2011). If the system is used to deliver over 10,000 metric tons, then cost-per-kg becomes dominated by the per-use costs. The Space Shuttle System was arguably retired while capital costs were still the dominant component of the cost-per-kg equation. However, in the Space Shuttle's case it should be noted that for many missions the orbiter and its crew *were* the payload that needed to go to space and this affects the overall payload tally.

New launch systems face a challenging set of technical and economic constraints. The STS set a high bar technically. The Orbiter and Solid Fuel Boosters were reusable, and reusability is an advanced technique for reducing operational costs. When the Space Shuttle System was retired in 2011, the main engines were still considered to

Figure 1: The chart shows how Cost Per Kg is reduced as the total amount of payload launched increases. The dotted line projects the costs had the STS program continued.

be the most advanced in the world – in fact, they were removed from the shuttles so that they could be reused in NASA's new Space Launch System (SLS).

Rockets are a mature technology as their development was well-funded during the cold war. It is now relatively difficult to develop significant technological breakthroughs in rocket based propulsion. While rocket research may potentially yield substantial advancements that enable a new launch system to capture market share and hold it long enough to recoup the R&D costs, the odds of this happening are low when compared to less mature technological arenas. It is more likely that rocket technology will continuously improve at a steady rate through small incremental improvements.

Competition in the commercial launch services arena remains high. In 2016, nineteen different launch systems shared the market for launching payloads into space (Krebs G. D., 2017). Demand for launch capability has been steady since the 1980's at approximately 330 metric tons launched per year worldwide (see Figure 6). As the Total Available Market (TAM) for launching mass into space is steady, new entrants must find ways to eke business away from the incumbents. From an investor's perspective, a market with exponential growth would present a more attractive opportunity.

Due to these constraints, it is presently difficult for new rocket-based system proposals to justify high R&D and/or capital costs. This appears to be supported by the estimated capital cost of NASA's SLS – which is only $7 Billion from Feb 2014 through to Nov 2018 (Harwood, 2014). While seemingly high, it is considerably lower than the approximately $150 Billion capital cost of the STS (Hsu, 2011). Neil deGrasse Tyson captured the problem succinctly during a recent interview when he said, "Corporations need business models, and they need to satisfy shareholders, public or private." (O'Kane, 2015)

There are several ideas in the literature that can be categorized as high capital-cost fixed-infrastructure projects for making the operational cost of accessing space more affordable. Among the better known of these are The Orbital Ring, The Space Elevator, and The Launch Loop. Their proponents assert that these structures can greatly lower the cost-per-kg of delivering payloads into useful orbits. The lowered costs are expected to create great demand, and the increase in demand is expected to offset the capital costs of these projects. So far, investors have yet to wholeheartedly embraced these concepts and their business models.

A Tethered Ring is a differentiated architecture because it achieves the goal of being attractive from an investment perspective. It supports three primary business models for generating revenue: 1) Terrestrial Transportation Services, 2) Real Estate, and 3) Low-Cost Space Launch. It avoids the need for significant advances in the material sciences or space based manufacturing capabilities of the human civilization. Therefore, it achieves both technical and economic feasibility much earlier than other architectures.
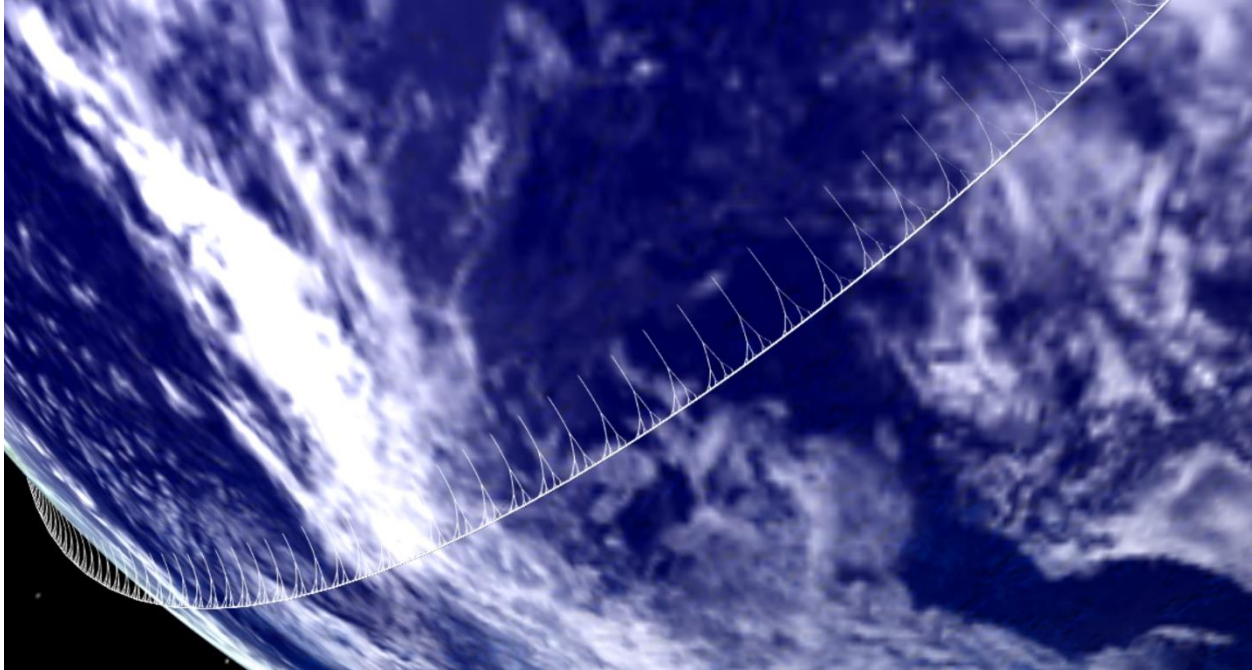
Figure 2: The Tethered Ring seen from Low Earth Orbit. Thicknesses have been increased to improve visibility.

A Tethered Ring (see Figure 2) is a thin stationary ring constructed with a diameter large enough to encircle a portion of the planet. It can be built on the planet's surface, and then is pulled away from the surface towards space by attaching numerous forked cables, called "Tethers", between: a) The stationary ring, and b) Anchor points positioned on the protruding side to the planet. The stationary ring generates an outward radial inertial force which prevents it from collapsing under the tension of the tethers. This is accomplished by magnetically guiding the path of a second internal moving ring within the stationary ring.

At any given position on the ring, there are three forces at play:
    1) The force of gravity pulling the ring (and whatever it is designed to support) towards the planet,
    2) The inertial force caused by magnetically guiding the path of the moving internal ring, and
    3) The tensile force contributed by the tethers.

The ring is constructed and operated so that these three forces remain in balance. In other words, the tensile and inertial forces combine to counter the downward pull of gravity (see Figure 3, below).
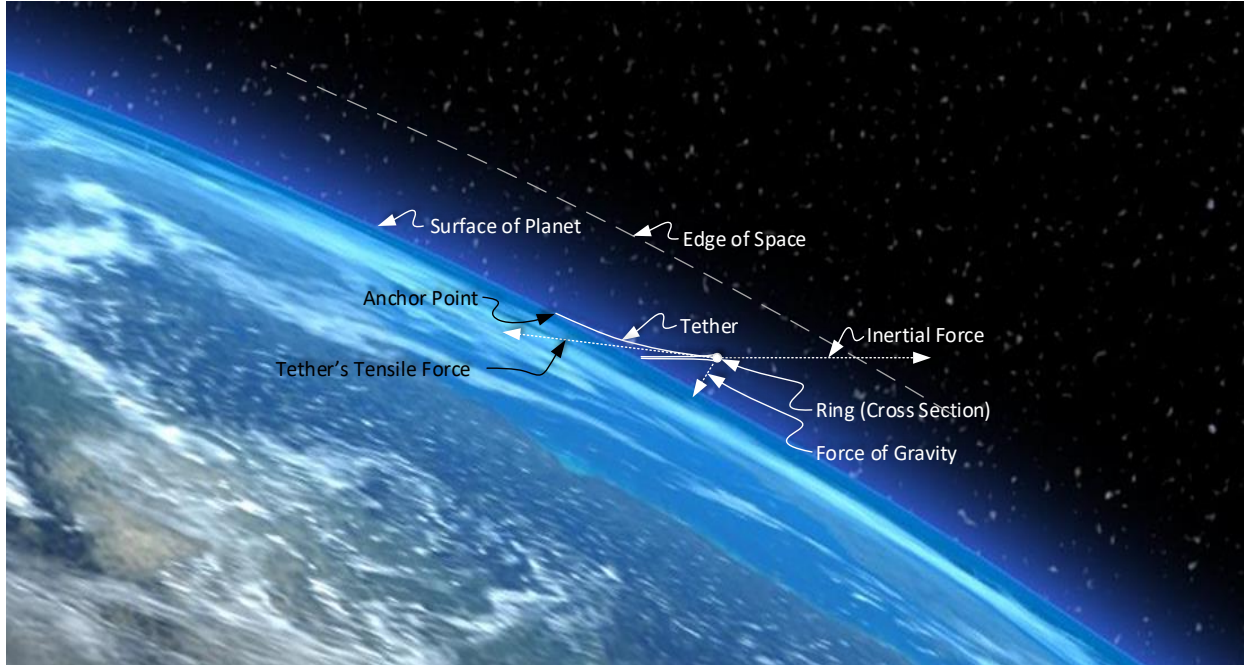
Figure 3: Cross-section of the Tethered Ring showing the gravitational, tensile and inertial forces.

Later it will be shown mathematically that a Tethered Ring can be constructed at altitudes of 30-50km, when constructed using materials, such as carbon fiber, that our civilization already mass-produces in large quantities.

Note that in practice, a Tethered Ring will comprise several moving rings. This provides redundancy and makes it possible to take an individual moving ring off-line for maintenance or refurbishment.

For succinctness, herein this paper will describe and analyze a single reference implementation for the Tethered Ring. The reference implementation is not the only possible implementation nor is it necessarily the most optimal. Future articles will explore some of the possible variants in more detail.

Business Models

As with a bridge, tunnel, or mag-lev transit system, a fixed infrastructure for accessing space will incur a high capital cost; therefore, it is vital that the infrastructure be architected to support a viable and robust business model. A business model based solely on providing low operational cost space launch services is presently insufficiently attractive to the broader investment community.

An infrastructure that delivers significant value in addition to launch services is more attractive from an investment standpoint. The Tethered Ring architecture is thus designed to provide high-speed transportation services and leasable floorspace in addition to supplying low-cost launch services. These services enable recuperation of the capital cost of the project within a reasonable amount of time, making profitability relatively certain.

Transportation Services

The Tethered Ring is designed to support a stratospheric maglev transit system. This transit system is well-positioned to compete with and win market share from the airline industry. A trip by a stratospheric maglev involves a 15-minute elevator ride up to the ring, a 60-minute to 240-minute journey around the ring in a transit vehicle, and a 15-minute return journey to the surface by elevator.

While there are many places on the planet where one could construct a Tethered Ring, to illustrate potential business models, we will examine a case where the ring is located proximate to population centers around the Pacific Rim.

Currently the market for long-distance transportation services between Pacific Rim population centers is satisfied primarily by the airline industry. The revenue of commercial airlines worldwide between 2012 and 2016 has been between 700B and 750B USD per year (Statista, 2017). The capital cost of the hundreds of airplanes that service these routes is close to $100B. Past airport projects in Asia (e.g. in Hong Kong and Japan) have cost as much as $20B per airport. A proposal to expand Hong Kong International Airport is projected to be around $141.5 billion HKD or 43.8B USD (Hon Regina Ip, 2015). New airplane development efforts, such as the carbon composite Boeing 787 which cost $32B (The Seattle Times, 2011) and double decker Airbus's A380 which cost $25B (Ausic, 2014) also represent large bets on long-distance transportation infrastructure.

It should also be noted that in addition to making sizable investments into air travel infrastructure and technology, projects such as the Tokyo-Nagoya stretch of Japan's Maglev High-Speed Rail, which is projected to cost nearly $100B USD (McCurry, 2015) and the California's High-Speed Rail estimated at $64B (Snibbe, 2017) demonstrate that planners and investors also believe in the promise of high-speed rail-based transportation infrastructure. The transportation services industry clearly attracts mega-investment and nurtures new technologies.

Stratospheric maglev transport provides a premium level of service. The system is designed to deliver passengers to their destinations up to four times quicker than a conventional airliner can. Individual maglev vehicles are small and can depart frequently, enabling passengers to leave when they want as opposed to planning their trip around airline flight schedules. During a trip, due to the vehicle's magnetic propulsion, there is minimal ambient noise within the maglev vehicle. This improves the passengers' inflight entertainment experiences.

Operational costs per passenger of a stratospheric maglev will be lower than airliner operational costs. The rarified atmosphere outside will cause minimal air friction thereby reducing energy consumption. Vehicles can be controlled and routed using computers instead of human pilots. They will depreciate more slowly because they will not endure the metal fatigue of constant pressurization and depressurization. They will cost less to maintain because they will not be subject to the jarring and shaking of take-offs, turbulence, and landings. Their electromagnetic propulsion systems will be less complex and easier to maintain than the jet engines used by commercial jet airliners.

The proposed reference design has intangible benefits as well. Passengers will receive smaller doses of ionizing radiation during their trips (see the section on "Space Radiation" below). As the vehicles are computer controlled and run on tracks, they will require fewer people (that is, pilots and cabin crew, both of which are classified as radiation workers) per passenger to operate. Energy to propel the elevators and vehicles can be provided by clean energy technologies that do not consume fossil fuels, create hazardous waste, or cause harm to local environments; this will provide price and revenue stability in the event of fossil-fuel shortages.

Figure 4: Air traffic around the Pacific Rim (Pinkfroot Ltd, 2017)

A stratospheric maglev system supported by the Tethered Ring could supply the Pacific Rim market that is currently serviced by airline industry (see Figure 4, above). It would foster international trade, provide a nexus for cultivating international cooperation, and generate wealth for the global economy.

Real Estate

The Tethered Ring supports millions of square meters of habitable floorspace. Individual habitats are interconnected by a high-speed maglev transit system. The inclusion of real estate into the value proposition improves the economics of the Tethered Ring because there are large numbers of small to mid-sized investors who are willing to invest in preconstruction real estate.

In general, real estate value is driven by many factors including: proximity to transportation infrastructure, proximity to population centers, tranquility, views, safety, community, attractions, scarcity, expenses, and anticipated future value. Real estate on the tethered ring compares favorably to terrestrial real estate on all metrics, as shown in Table 1.

Table 1: Metrics Used to Assess the Value of Real Estate

Metric	Narrative
Proximity to Transportation Infrastructure	Residents will be able to quickly and conveniently travel to where they need to go without having to endure traffic jams, parking, motor vehicle accidents, or lines at gas stations. Computer controlled maglev vehicles will be able to stop at individual habitats (e.g. homes, shops, restaurants, recreational facilities, etc.) to take on or off-load passengers. These vehicles will accelerate along a collector track, and then merge into a traffic stream travelling along an express track. Because very high speeds are possible, travel time between habitats will be short. Because of the computer controlled nature of the system, almost everyone, including children, the elderly, and people who would not normally qualify for a driver's license, will be able to travel around the ring easily.
Proximity to Population Centers	Due to the speed of the transportation system, the residents of the habitats will be close, in time, to all population centers on Earth that are near the ring. An owner or lessor of real-estate on the ring will be able to travel to many adjacent terrestrial destinations for business or pleasure very conveniently – perhaps more conveniently and certainly more affordably than if they owned a private jet. This will make this real-estate attractive to someone who's work involves a lot of travel, such as an executive.
Tranquility	Terrestrial real estate near airports, train tracks, or highways is generally devalued because of noise. A noisy neighbor can also be an irritation. Habitats on the ring, high in the stratosphere, will be blissfully quiet. Neighboring habitats will be

	spaces such that no one will be disturbed by noisy neighbors. Furthermore, the rarified air of the stratosphere will not conduct sound well and the high-speed maglev vehicles will travel silently within evacuated tubes.
Views	Habitats will sport breathtaking views of Earth and its weather from near-space. Some habitats will be located where they will be able to see Aurora Borealis and Arora Australis at night. It is likely that many residents of the ring will also own cottages and ski chalets as well, and these cottages will be in isolated paradises, with beautiful views, that are close to the ring but removed from major population centers.
Safety	Safety is condition of being protected from harm. The most causes of harm are motor vehicle accidents, drowning, homicides, firearm accidents, poisonings, unintentional falls, and natural and anthropogenic disasters. A society on the Tethered Ring inherently reduces or eliminates some risk because: a) The habitats are distributed, and b) Because the transportation system is computer controlled. It is unlikely that a population of street criminals will flourish on the ring, nor will drunk or distracted drivers cause traffic accidents. For medical emergencies, the transportation system minimizes first response times. The location of the Tethered Ring introduces new sources of harm, including exposure to space radiation. This is covered in the section entitled "Space Radiation". Some buyers may question whether a dynamic mega-structure offers as much safety as, for example, a skyscraper. Others may have safety concerns about the integrity of the habitats themselves, as these habitats will be pressurized, like airplanes, as the atmosphere outside is too thin to breath. Despite these kinds of concerns, after all factors that affect safety are aggregated, it is quite possible that the ring could establish itself as being among the safest places on Earth to live. As the airline industry had to do with airplanes, it will be important to develop reliable pressurized habitats, maglev vehicles, and emergency backup systems. Using the latest computer aided engineering and testing technologies, it should be possible to quickly build public trust in the ring's engineering.
Community	The ring will be able to support a population of approximately 250,000. It is anticipated that it will be a popular tourist destination because will offer spectacular views and because people will be using the ring to travel between other destinations. Therefore, it is likely to attract shops, restaurants, and other kinds of businesses to serve travelers, tourists, as tourist workers. It is likely that the ring's residents will also include people whose work demands a lot of international travel, and scientists and engineers who work on the ring's facilities or in space-related professions. These people will need schools and parks for their children, sports facilities, shopping centers, places of worship, theaters, etc.
Attractions	The ring will host attractions to increase its appeal as a tourist destination and to make life more enjoyable for its residents. For example, vehicle launchers will allow tourists to orbit the Earth and experience weightlessness. They could even provide affordable trips to the moon and beyond. It will not be possible for the ring to support massive point loads such as football stadiums or Olympic-sized swimming pools. However, any venue that is designed so that it generates a uniform and widely distributed load can be supported by the ring. For example, it could support museums, art galleries, casinos, clubs, botanical gardens, and even theme parks. Any attraction that is naturally linear in nature, such as a jogging path, bicycle trail, or a ski trail, is amenable to being supported by the ring.
Cost of Living	A resident on the Tethered Ring may experience a lower cost of living than a resident on Earth. When living on the ring it will not be necessary to own and maintain one or more personal vehicles. Medical insurance costs may be lower if it can be established that the ring is a relatively safe place to live. Solar panels, which will stay clean and never contend with a cloudy day, will help to keep energy costs low. Access to numerous population centers on Earth can help to keep the prices of goods low. Some necessities will cost more than they do on Earth. Fresh air will need to be supplied via compressors, which may require more energy to run than traditional HVAC systems. Water will be more expensive as it will need to be pumped up from the planet below or recycled. Furniture will need to be of light-weight construction which might make it costlier.
Anticipated Future Value	Real estate value is strongly affected by its anticipated future value. Investors are likely to predict that: a) Acceptance of the ring as a safe place to live will increase over time, b) The ring will grow in popularity as a tourist destination, c) That low-cost access to space will nurture the growth of space based businesses, such as asteroid mining, and d) That the ring will become a supplier of goods and services to these off-planet enterprises. If indicators and analyses suggest that the value of floorspace on the ring will appreciate over time, it will attract investor interest.

Low Cost Space Launch

Payloads, such as satellites or spacecraft, will be launched into space using a maglev launch facility. The launch facility's weight will be supported by the ring; however, transient forces, such those associated with the acceleration of the payload, will be isolated from the ring and dampened by aeronautic means rather than dissipated into the structure of the ring itself. The maglev accelerator will insert spacecraft into high elliptical insertion orbits. In most cases, these orbits will be altered (for example, to circularize them) using small efficient engines, such as ion thrusters.

There are several advantages to using a stratospheric maglev launcher. With a maglev launcher, acceleration can be gradual, and vibration and shake can be minimized. This can lead to the payloads themselves being lighter, cheaper to construct, and less time-consuming to test. Whereas, with a rocket-based launch system, a vehicle incorporates large engines that are capable of very high power output. This makes them large, expensive, and dangerous to operate.

A maglev launcher experiences minimal wear and tear and can be reused immediately. Rocket based systems typically use either: a) Disposable components, or b) Reusable components that need to be recovered, inspected, refurbished, and refueled. In the case of the reusable components, the vehicle's payload is typically reduced to make room for the recovery systems, such as landing struts, fuel, or parachutes. A rocket must carry its reaction mass (aka propellant) with it. With a maglev launcher, the "reaction mass" is the Earth itself. Therefore, the total energy expenditure per kg launched is much lower for a maglev system than for a rocket.

Economic Analysis

As discussed above, there are three primary ways that the Tethered Ring generates economic value: Terrestrial Transport, Real Estate, and Space Launch.

For Terrestrial Transport, let's assume that in 2020 an investor assesses the stratospheric maglev project, and this investor assumes that the project will capture 2% of the airlines industry's revenue in 2025, 4% in 2026, and 5% every year after that until 2038. The investor wants to know what the present value of this revenue in in 2020 dollars. Historical data between 2003 and 2016 (Statista, 2017) shows steady growth, so the investor predicts that it will continue to grow. Starting in 2025, some of the of the projected revenue will begin to be captured by the stratospheric maglev service (see Figure 5, below).
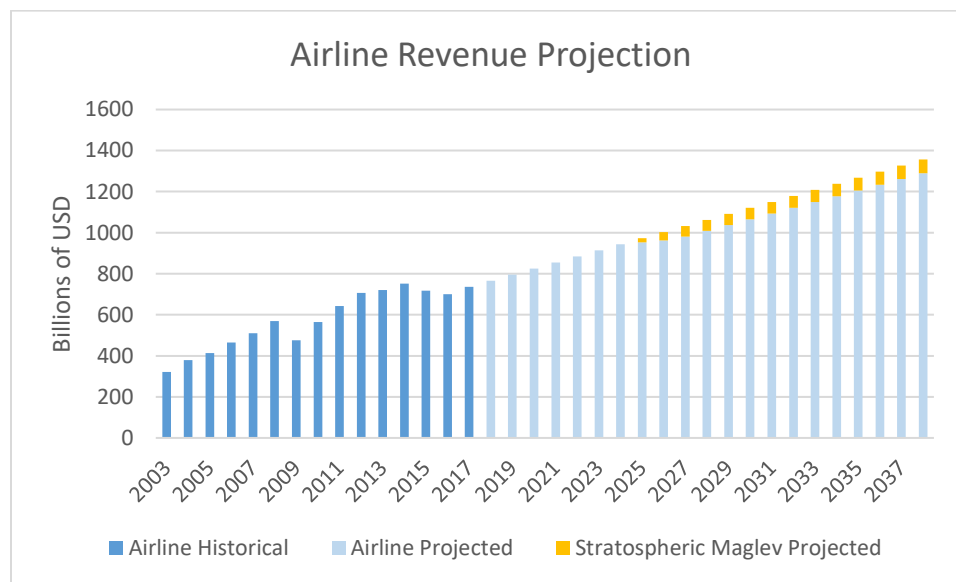
Figure 5: Past Global Airline Revenue and Projections of Future Revenue

The orange portions of the bars represent the revenue that is captured from the airline industry. The value of the orange portions, in 2020 dollars, assuming an interest rate of 3%, is 544 Billion Dollars. In other words, if the project could deliver this anticipated level of service with $544 Billion of investment made in 2020, the project would break even by 2038.

The analysis is conservative, however, because it assumes that stratospheric maglev profit margins are the same as the those of the airlines. Because of the premium value of faster transport, lower operating costs, and non-dependence on fossil fuels, profit margins for the stratospheric maglev are likely to be significantly higher. A stratospheric maglev could potentially earn additional profit through carbon credits, by offsetting some of the airline industry's emissions.

From a real estate perspective, assume that the Tethered Ring is designed to support 8 million m^2 of saleable floor space. The value of that floorspace will vary depending on where it is located, but if we assume that on average it could sell it for $10,000/$m^2$ (or $1550/$ft^2$) then it would be worth $80B USD. To put these prices in perspective, the best high-rise floorspace in Hong Kong currently *leases* for $3000/$m^2$/year (Frank, 2017).

The value proposition around launch services is much more difficult to gauge as there are both tangible and intangible aspects to it. In a tangible sense, humanity launches mass into space at a steady rate. The mass that is still in space is tracked, and reasonably complete records of past launches are available on-line (Krebs G. , 2017).
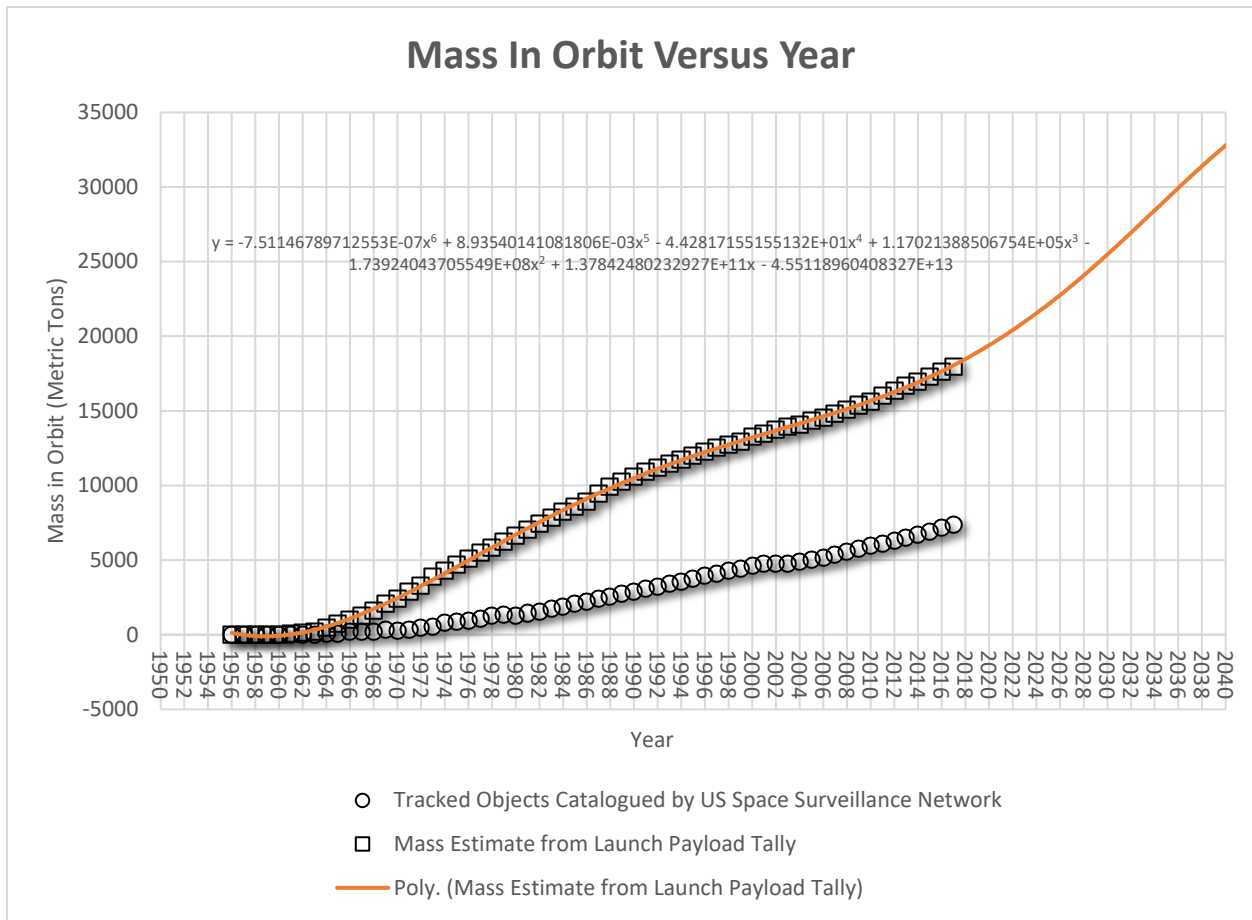
Figure 6: Mass in Earth Orbit

A computer-generated tally of payloads listed on (Krebs G. , 2017) calculated that the total amount of payload mass launched into space as of Nov 9th, 2014 was 13,368 metric tons. (Note: Guidance on writing a python script that can perform the tally is posted on StackExchange (dotancohen, 2017).) For each year, the following tallies were accumulated:

n - Number of Launches
$n_{unknown\ mass}$ - Number of Launches with Unknown Mass
$m_{known\ mass}$ - Total Mass of Launches with Known Mass

As payload mass information was not available for all launches, an estimate, $m_{estimate}$, was made using:

$$m_{estimate} = m_{known\ mass} * \frac{n}{n - n_{unknown\ mass}}$$

These data points are plotted as squares in Figure 6. If we assume a growth trend (using a sixth order polynomial approximation) then from that trend it could be projected that possibly, between 2025 and 2038, 9269 metric tons will be launched into space. At the current prices of roughly $10,000 per kg, this represent about $92.7B USD worth of launch services.

It should be noted that launching people into space costs significantly more. In April 2013, NASA signed a deal with Russia for six additional seats to carry NASA astronauts to the International Space Station (ISS) during 2016 through June 2017 (Martin, 2013). The price per seat was $71 million. If the mass per seat is estimated to be 100kg, the cost per kg for human payloads works out to be $70,000 per kg. This suggests that launch services with proven reliability command a significant premium.

Since a maglev system can launch payloads at a tiny fraction of the current cost, it would certainly capture a significant portion, if not all, of the launch services market.

Already, some launch services companies are taking steps to reduce launch costs. This suggests that some believe that lower price will enable new business models and unleash new demand, and that that demand will be sufficient to justify the effort to develop lower cost launch systems. For example, asteroid mining has the potential to disrupt the metals markets by bringing down the cost of certain precious metals. Some investors may believe that by reducing the cost of launch, you can create a larger market, more demand, and ultimately generate higher profits. Although this may perhaps seem counterintuitive, there are certainly lots of precedents including: cost of electricity, cost of lighting, cost of communications, cost of computing power, and cost of transportation. These industries have, year over year, cut costs per unit of service and yet businesses serving these markets have flourished nevertheless.

The intangible benefits of furnishing humanity with an affordable means of accessing space is likely to resonate with some investors. Investment opportunities are not evaluated solely on their ability to generate a monetary return on investment. If they serve the social good, serve our species in some way, or serve to protect and preserve our planet and its climate, then they may be attractive to people who wish to use their accumulated wealth to make a positive impact. However, before discussing these intangible aspects, let us recap the tangible economics.

The terrestrial transportation capabilities of the stratospheric maglev supported by the Tethered Ring could justify as much as $500B of investment. Preconstruction sale of real estate may raise around $80B. The promise of reliable and low-cost launch services might attract an additional $93B. Is it possible to build a Tethered Ring that can meet the needs of these businesses with these levels (that is, 500+80+93 = $673B) of investment? Before we can answer this question, we need technical specifications.

Technical Specifications

There are a variety of different ways that a Tethered Ring can be built. To illustrate the concept, let us consider a design that is customized to provide transportation services between population centers around the Pacific Rim. The technical specifications of this reference design, calculated using an engineering calculation program, are…

Ring		
Radius of Ring	5,182,853	M
Circumference of Ring	32,564,825	M
Equivalent Latitude	36.1	degrees
Altitude	32	km
RUnit* Mass of Ring and its Supported Payload	100	Kg/m
RUnit* Weight of Ring and its Payload	972	N/m
Total Mass	3,256,482,488	Kg
Total Floor Space	8,792,503	m^2
Total People	293,083	
Meters of Ring Per Person	111	m
Floor Space Per Person	30	m^2
Acceleration of Gravity at Ring	9.724	m/s^2
Orbital Velocity at Ring's Altitude	7,891	m/s
Escape Velocity	11,159	m/s
Potential Energy Per kg at Ring's Altitude	312,738	J
Cost of Power	0.10	USD/kWh
Potential Energy Cost Per kg	0.008687	USD

Stationary Ring Speed Due to Earth's Rotation	377	m/s
Delta-V to Orbit from Ring	7,514	m/s
Delta-V to Orbit Kinetic Energy Per kg	28,229,068	J
Delta-V to Orbit Kinetic Energy Cost Per kg	0.78	USD
Delta-V to Escape Velocity	10,782.33	m/s
Delta-V to Escape Velocity Kinetic Energy Per kg	58,129,289	J
Delta-V to Escape Kinetic Energy Cost Per kg	1.61	USD
Air Pressure at Sea Level	101,325	Pa
Air Pressure at Ring	0.0012	Atmospheres

Anchor

Altitude	0	m
Inter Tether Spacing at Anchor End	45,228.92	m
Diameter of Tether at Anchor	0.16	m

Tethers

RUnit* Radius	0.000385	m
Density	1,800	kg/m^3
Yield Tensile Strength	6,370,000,000	Pa
RUnit* TUnit** Mass	0.000837	kg
RUnit* TUnit** Weight	0.008139	N
RUnit* Horizontal Tension	1,487	N
RUnit* Vertical Tension	915	N
RUnit* Tension at Ring	1,496	N
Total Tensile Stress	3,217,171,717	Pa
Tether Length	111,628	m
Volume of Tether Material	1,690,247	m^3
Mass of Tether Material	3,042,443,842	kg
Cost of Tether Material	66,933,764,515	USD
Tether Cost Per Person	228,378	USD
Global Manufacturing Capacity In 2016	106,654,600	kg/year
Years to Manufacture Tether Material	28.53	years

* RUnit means "per one-meter section of the Ring"
** TUnit means "per one-meter length of the Tether".

Moving Rings

Moving Ring Percent Mass	0.36	
Moving Ring Speed	17,674	m/s
Moving Ring Speed RPM	0.0326	Rev Per Min (RPM)
Moving Ring Speed Time Per Turn	30.7	Minutes/Revolution
Moving Ring Inertial Acceleration	60.27	m/s^2
Cost of Kinetic Energy in Moving Ring (at 10 cents per kWh)	5.721	Billion USD

Table 2: Cost breakdown of major components

Item	Units	Unit Cost (Billion USD)	Total Cost (Billion USD)
Technology R&D	1	5	5
Maglev Vehicles	1000	.001	1
Maglev Track	32564	.001 / km	32.564
Habitats	36635	.001 / habitat	36.635
Elevators	200	.01 / elevator	2
Launch Facilities	2	.1	0.2
Inertial Force Generation	32564	.001	32
Tethers	720	.1	72
Anchors	720	.01	7.2
Total			**188.599**

It was estimated earlier that if investors invested $673B into the project around 2020, that they would break even by 2038. The ballpark estimate of $188.6 in costs (Table 2, above), suggests that a $673B investment would amply fund the project. Therefore, a likely outcome of a more thorough economic analysis is that project is economically feasible.

Architecture

A fundamental question that needs to be addressed by the architecture is whether the Tethered Ring is technically feasible. To most efficiently communicate the level of progress that the investigators have made in this direction, we chosen to address some of the most obvious questions first and address more insightful questions later. For example, an obvious question concerns the fundamental mechanism by which the ring maintains its elevation.

Mechanism for Maintaining Extreme Elevation

Earlier it was revealed that for any given section along the ring there are three forces at play:

1) The force of gravity pulling the ring (and whatever it is designed to support) towards the planet,
2) The inertial force caused by magnetically guiding the path of the moving internal ring, and
3) The tensile force contributed by the tethers.

The ring is constructed and operated so that these three forces are always in balance. In other words, the tensile and inertial forces will combine to counter the downward pull of gravity (see Figure 3, above). Let's examine this more closely now.

The force of gravity is calculated at the altitude of the ring using Newton's law of universal gravitation:

$$F = G \frac{m_1 m_2}{r^2}$$

where m_1 represents the mass of Earth and m_2 is the mass of a discrete segment of the ring plus its supported payload. This is a force that points directly towards the center of the planet.

Consider a cylindrical coordinate system $\{\rho, \theta, z\}$ defined such that:

1) The center of the ring is at $\{0, 0, 0\}$,
2) The z-axis points away from the center of the planet,
3) All points on the ring have a "z" coordinate of zero, and
4) All points share the same "ρ" value.
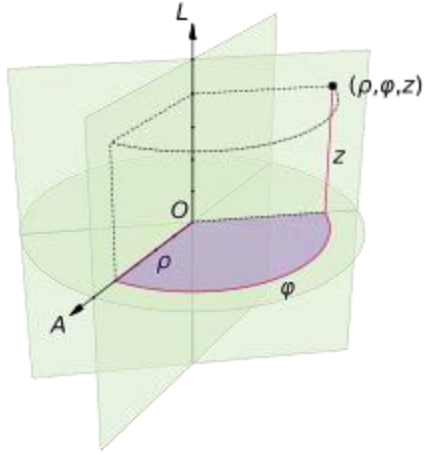
Figure 7: Depiction of the cylindrical coordinate system.

In this coordinate system, a vector, **G**, that represents the force of gravity acting on a small segment of the ring will have both a radial 'ρ' component and a 'z' component, because the force points towards the center of the planet and is not parallel with the 'z' axis of the coordinate system.

Let's define a term called "Equivalent Latitude", which can be any value between 0 and 90 degrees, to define where the ring is in relation to the planet. The ring's radius, $radius_{ring}$, will be…

$$radius_{ring} = (radius_{Earth} + altitude_{ring})\cos(Equivalent\ Latitude)$$

The goal is to offset the Gravitational Force Vector, **G**, using a combination of tensile forces and inertial forces. The inertial forces generated by the moving ring will be purely radial and will thus have a 'z' component of zero. Therefore, the 'z' component of the tensile force must be entirely responsible for offsetting the 'z' component of the gravitation force.

Another way to view this is to consider the vectors for the three forces acting on a discrete segment of the ring…

1) The Gravity Force Vector, $\mathbf{G} = \{G_\rho, G_\theta, G_z\}$,
2) The Inertial Force Vector, $\mathbf{I} = \{I_\rho, I_\theta, I_z\}$, and
3) The Tensile Force Vector, $\mathbf{T} = \{T, T_\theta, T_z\}$.

The direction of **G** is toward the center of the planet. Its exact direction depends of the "Equivalent Latitude" of the ring - defined as the latitude that the ring would be at if our chosen cylindrical coordinate system were aligned with the planet's axis of rotation. The components of the **G** vector are…

$G_\rho = -|\mathbf{G}|\cos(Equivalent\ Latitude)$,
$G_\theta = 0$, and
$G_z = -|\mathbf{G}|\sin(Equivalent\ Latitude)$.

The magnitude of the Gravity force can be calculated using:

$$|\mathbf{G}| = G\frac{M_{Planet}M_{RingSegment}}{r^2}$$

Where the 'G' is the Gravitational constant, $G = 6.67 \times 10^{-11}$, 'M_{Planet}' is the Mass of the planet, '$M_{RingSegment}$' is the mass of an arbitrarily small discrete segment of the ring and its payload, and 'r' is the distance from the ring

segment to the center of the planet. A discrete segment is simply a section of the ring that is small enough to allow us to assume that the θ components of the acting forces are all zero.

If we engineer the three forces, **G**, **I**, and **T**, to be in balance, then there will be no net force. With no net force, the ring segment will tend to remain "at rest", per Newton's First Law, above the surface of the planet. To have no net force, we need...

$$\mathbf{G} + \mathbf{I} + \mathbf{T} = 0 \qquad (1)$$

... or ...

$$G_\rho + I_\rho + T_\rho = 0 \qquad (2)$$
$$G_\theta + I_\theta + T_\theta = 0 \qquad (3)$$
$$G_z + I_z + T_z = 0 \qquad (4)$$

Equation #3 is easily satisfied because none of the forces has a 'θ' component.

Equation #4 is also easily satisfied because the Inertial Force Vector, **I**, is purely radial and thus doesn't have a 'z' component. Therefore, $I_z = 0$. From Eq#4 we can see that...

$$G_z + 0 + T_z = 0 \qquad (5)$$
$$T_z = -G_z \qquad (6)$$

Therefore, using Eq#6, we can easily calculate T_z from G_z.

To determine T_ρ, we need to know the direction of the Tensile Force Vector. To determine the direction, we need to know the curvature of a tether that is strung between the section of the ring and an anchor point optimally positioned on surface of the planet.
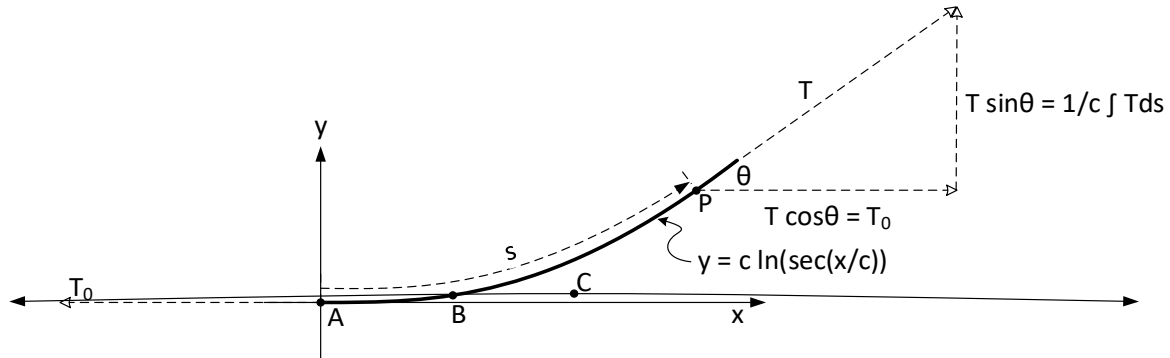
Figure 8: The curve formed by the tether.

Let us assume a constant gravity field, and that the cross-sectional area of the cable is proportional to the tension within the cable. If wds is the weight of cable element ds, then $T = cw$, where c is the constant of proportionality, and T is the tension at Point P. It then follows that:

$$T\cos\theta = T_0, \qquad T\sin\theta = \frac{1}{c}\int T ds \qquad (7)$$

Substituting into the second equation the value of T from the first, we get:

$$c\tan\theta = \int \sec\theta \, ds \qquad (8)$$

Differentiating, we get:

$$c\sec^2\theta = \sec\theta \frac{ds}{d\theta} \qquad (9)$$

Solutions to this equation are:

$$y = c \ln\left(sec\left(\frac{x}{c}\right)\right) \quad (10)$$

$$x = c\theta \quad (11)$$

$$s = \ln\left(tan\left(\frac{\pi + 2\theta}{4}\right)\right) \quad (12)$$

These equations describe the shape of the tether if it is being acted on by a uniform gravity field, which is an engineering approximation that we will make in this case. Referring to Figure 8, above, we will anchor the cable at Point B and attach it to the ring at Point P. A gentle arc, representing the curve of the planet's surface, passes through Points B and C. Point C placed on the arc directly above the center of the arc's circle. The x coordinate of the center of the circle is midway between the x-coordinates of Points B and P.

The constant, $c = \frac{T_0}{w}$ can be determined from the density and tensile strength of the tether material and the desired engineering margin. Commercially available carbon fiber has a Tensile strength of up to 6370MPa and a density of 1800 kg/m^3 (TorayCA, 2017). If we choose carbon fiber for our tether material, use the acceleration of gravity at the surface of the planet, ignore buoyancy, and apply an engineering margin of 2X, then 'c' is calculated to be 180555. A graph of the tether's curve made using Equation 10 is shown in Figure 9, below.
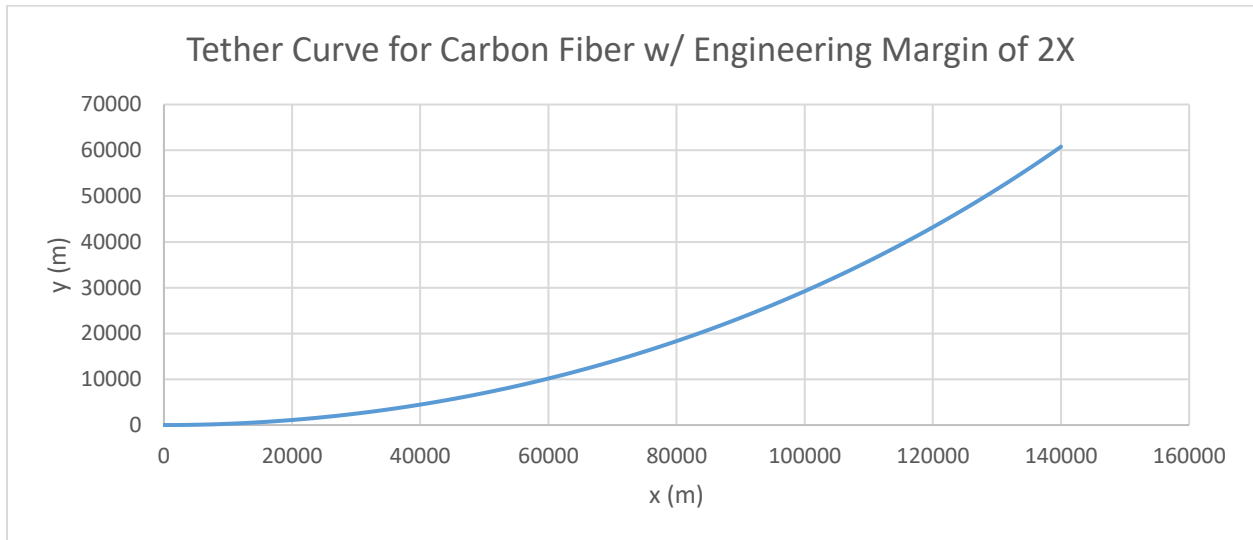
Figure 9: Plot of tether curvature for carbon fiber assuming a 2X engineering margin.

This curve closely approximates the curvature of a tether. Placing the tether's anchor point, Point B, closer to {0, 0} will improve the angle at the point where it connects to the ring, Point P, and this in turn will reduce the tether's thickness. However, anchoring the tether away from the curve's origin, for example at {60000, 10000} can reduce the tether's length. An analytical derivation of the optimal location for the anchor point is not provided here; however, if given the desired altitude of the ring, it is possible to determine the optimal anchor point iteratively.

We can rearrange equation 10 to solve for 'x' if given 'y':

$$x = c \; acos\left(e^{-\frac{y}{c}}\right) \quad (13)$$

Substituting x into equation 11, and solving for θ, we can determine the angle at Point P:

$$\theta = acos\left(e^{-\frac{y}{c}}\right) \quad (13)$$

Given y coordinates for Points B and P, we can calculate the x coordinates as well as the angle of the tether at these points.

These slopes are still in the 2D "ground" coordinate system of the planet. We need to perform calculations in the cylindrical coordinate system that we defined earlier for the ring; therefore, we need to rotate the vector by angle 'ϕ' using.

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

Let us define a unit tensile force vector, [x, y], at Point P. Since the cable, where it is attached at Point P, is pulling down and to the left in Figure 8 (above) we assign 'x' to '-$\cos\theta$', and 'y' to '-$\sin\theta$'.
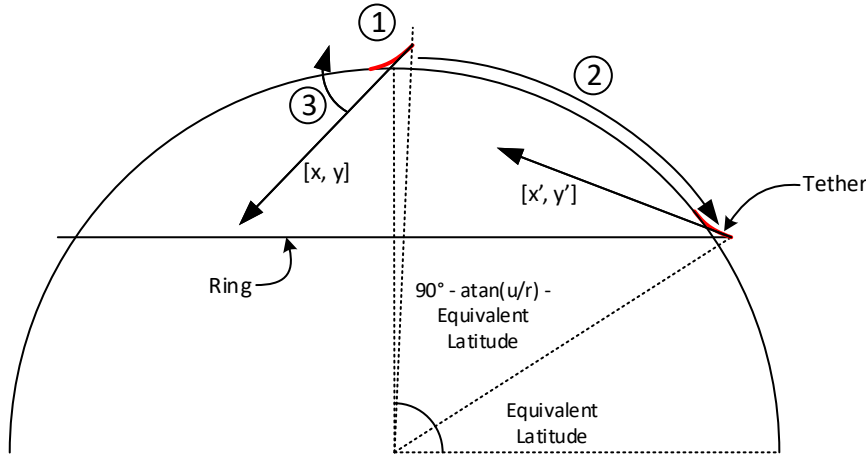
Figure 10: Rotation of the Tensile Force Vector Derived from the Catenary

To determine the correct angle of rotation, 'ϕ' for our rotation formula, refer to the Figure 10, above, where we placed our catenary of equal strength curve (shown at the top in red), representing our tether, such that Point C is on the north pole of our "Equivalent Planet" (1). We then move the tether down the right side of the planet to the ring, as shown by the large curving arrow (2) in Figure 10, above. In so doing, we will clockwise rotate (3) the original tensile force vector [x, y] by '90° - atan(u/r) - Equivalent Latitude', where 'u' is the distance along the x-axis in Figure 8 (above) from Point C to Point P, and 'r' is the radius of the planet. Therefore, we can assign 'ϕ' to *minus* '90° - atan(u/r) - Equivalent Latitude' (because the rotation is clockwise), and then calculate the rotated vector $[x', y']$ which is now a useful vector in our cylindrical coordinate system.

Since we already know 'T_z', we can use this new vector, $[x', y']$, to calculate T_ρ with:

$$\frac{x'}{y'} = \frac{T_\rho}{T_z}$$

Now we can return to equation (2) to solve for 'I_ρ':

$$G_\rho + I_\rho + T_\rho = 0$$
$$I_\rho = -G_\rho - T_\rho$$

From the required forces, it becomes possible to calculate: 1) The thickness of the tethers per ring segment, the total amount of tether material needed, and ultimately estimate the total cost of the tethers, and 2) The mass and speed of the moving ring that will generate the inertial force, **I**.

As stated earlier, the moving ring is a magnetically coupled to the stationary ring by a magnetic levitation system. The system resembles a permanent magnet biased active magnetic bearing (Maslen, 2009) except that the levitated shaft (that is, the moving ring) moves through the bearing longitudinally as opposed to rotating on its axis within the bearing. It is, in essence, an Active Magnetic *Linear* Bearing (AMLB). The system is engineered so that magnetic fields are homopolar in the axial direction (that is, the direction of motion of the moving ring) and heteropolar in the radial direction. This minimizes operational costs and heat generation because the longitudinally travelling moving ring will experience steady magnetic fields, and steady fields do not induce currents within conductive components. Use of laminates and non-conductive materials where appropriate also helps to prevent induced currents from being generated. Minimization of induced currents, such as eddy currents (aka Foucault currents), leads to:

1) Less drag on the moving ring,
2) Lower energy requirements for maintaining the ring's rotational speed,
3) Less waste heat generation, and
4) Reduced thermal dissipation requirements.

While the steady magnetic fields will produce the forces needed to curve the path of the moving ring, Earnshaw's theorem explains that these permanent magnet fields are insufficient for *stable* levitation. The use of active electronics to precisely measure and maintain the specified separation of moving and stationary components is favored within the magnetic bearing industry (Larsonneur, 2009). When biased with permanent magnets, the electromagnets consume energy primarily when disturbances perturb the system; therefore, the ring will be mechanically isolated from external disturbances to reduce the energy consumption of the active magnetic bearing components.

The space within the stationary ring that the moving ring travels through is evacuated using turbo molecular pumps to further minimize air friction and the associated generation of waste heat. Note that the outside atmospheric pressure is only 0.1% that of sea level air pressure. It is therefore much easier to keep air from leaking into the evacuated environment at the ring's operational altitude than it is at sea level.

How is it Constructed?

The ring is constructed in the ocean at a depth that will permit ships and most icebergs to pass over it.

Ring constructed underwater
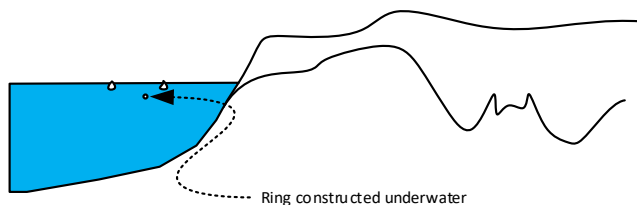
Figure 11: The bearing constructed underwater in the ocean.

Although the ring has its own casing, it is constructed within a second "construction casing". The ring is connected to the construction casing's interior via actuators. These actuators are responsible for actively mechanically isolating the ring from the undulating currents of the undersea environment. In addition, the construction ring will use omnidirectional thruster nacelles to maintain the ring's circularity and geographical position precisely when the moving ring is in operation. Mooring lines, tensioned by the construction casing's buoyancy, may be used to reduce the nacelles' workload.
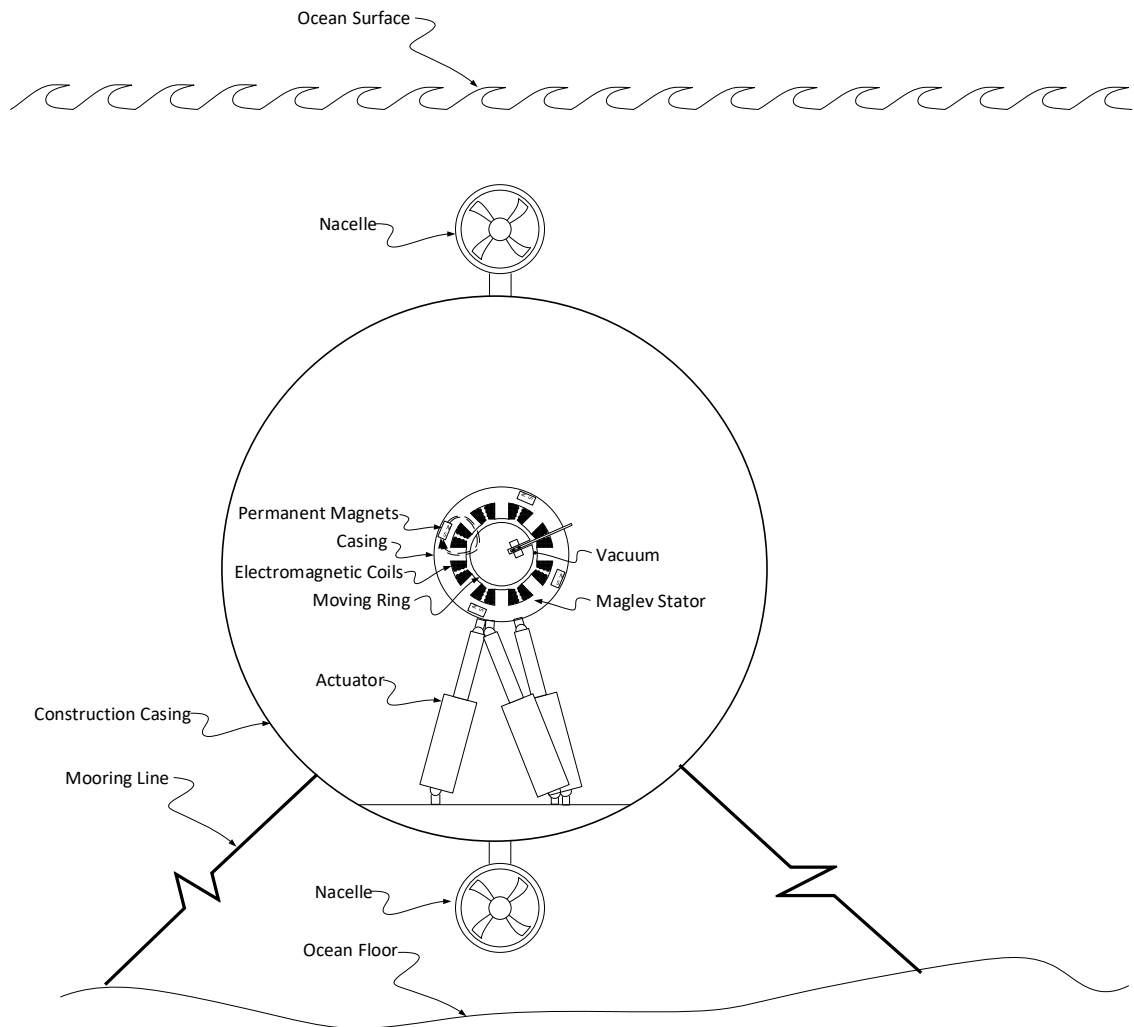
Figure 12: A conceptual illustration (not to scale) of a cross section of the ring within its construction casing.
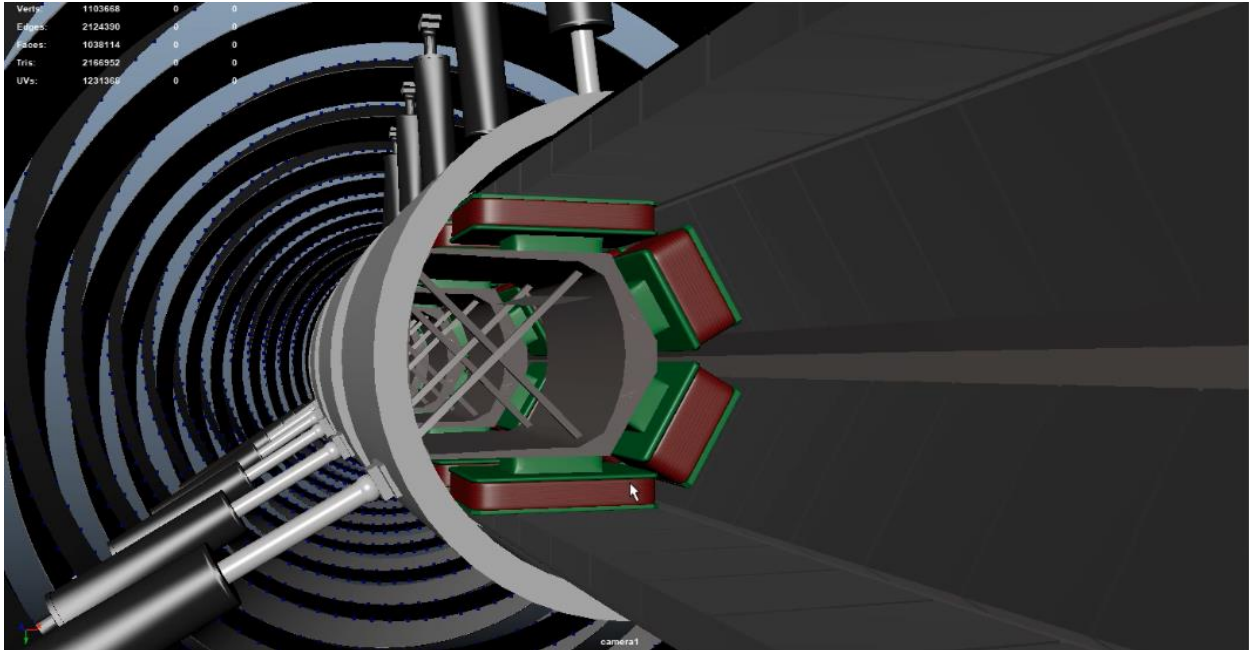
Figure 13: Conceptual Rendering of The Ring Within its Construction Casing

During this phase of construction, the ring would be human and robot accessible for inspection. While safely underwater, the ring will be tested by rotating it at gradually greater and greater speeds until sufficient a margin of safety at operational speeds is established. The partial vacuum of near space will be created within the construction casing so that testing conditions will be as realistic as possible. The ring could even be shot at with projectiles from a high-energy cannon to test and establish the design's resilience to micro-meter impacts.

Air friction losses will be eliminated by evacuating the air between the stationary and moving parts of the ring. The containment system, instrumentation, and emergency backup systems, etc. will all be thoroughly verified during this phase of construction.

To prevent the centripetal forces from stretching the bearing during testing, numerous low-tech temporary stays would be attached between the stationary ring and anchor points on the sea floor to the inner side of the ring, and on the protruding side of the planet. The tension of these stays would serve to counter the centripetal forces generated by the moving ring during testing.

Tethers are strung between the ring and anchor points positioned on the protruding side of the planet hundreds of kilometers away from the ring. The tethers fork repeatedly so that there are fewer anchor points on the planet than attachment points at the ring. Many attachment points at the ring distributes tensile forces more evenly. Fewer anchor points near planet makes it easier for air traffic and ships to navigate around the tethers and reduces the tether's aggregate cross-section at lower altitudes where the atmosphere is thicker. Tethers are overlapped to provide redundancy in case of tether failure.

Interesting Fact

The symbolism of a large immense structure emerging majestically from the ocean led the investigating team to name their project "The Atlantis Project".

After underwater testing is complete, the process of raising the ring into the stratosphere can begin. During this process, the diameter of the ring does not need to change. Ships with the tethers wrapped up on large spools are brought into position on the inner side of the ring. The ends of the tethers are connected to the ring, and the ships begin

to travel along the surface of the ocean away from the ring. Unspooling mechanisms on the ships ensure that all tethers on all ships are equally tensioned by the right amount as they are unwound from their spools. At the ocean surface, the construction casing is left behind as the ring emerges from it through hatches. The ring is gradually pulled away from the planet's surface, and ultimately up into the stratosphere. Simultaneously, the moving ring is accelerated to keep the tensile, inertial, and gravitational forces properly balanced. From the perspective of a ship, raising the ring resembles the process of launching a kite - except that the force that lifts the ring is not the wind but rather the inertial force of the moving ring. When the ring is fully raised, the tethers can be detached from the ships and attached instead to permanent anchor platforms.

Compared to other space infrastructure concepts, the Tethered Ring is easier to construct and deploy. Other proposed forms of permanent space infrastructure, such as orbital rings and space elevators, depend on a pre-existing space infrastructure to either lift their components into space, or to manufacture them in space. Launch loops and space cables require maglev system designs that can tolerate being flexed during their deployment. The Tethered Ring has no dependency on a pre-existing space infrastructure. The Tethered Ring's circular shape is precisely maintained throughout its deployment; therefore, its maglev system needs to tolerate relatively minor distortions during its deployment.

Are Gyroscopic Forces an Operational Concern?
The moving ring is magnetically levitated, and it completes one rotation every 0.5 hours. While there are gyroscopic forces, the rate of Earth rotation is $1/48^{th}$ the rate of ring rotation; therefore, they add only a small additional load on the magnetic levitation system that links the moving rings to the stationary ring.

How is a Moving Ring Magnetically Levitated?
A moving ring is coupled via a coupling mechanism that uses electromagnetism to generate forces of attraction and/or repulsion between a moving ring and its stationary track. The forces are applied and adjusted to maintain the positions of a moving ring with respect to its track within the tolerances supported by the coupling mechanism. The coupling mechanism is designed to impart minimal friction and generate minimal waste heat. This insures that the operational cost of maintaining the moving ring's speed is manageable and the cost and complexity of thermal dissipation systems for managing waste heat is likewise reasonable.
One technique that can be utilized to minimize magnetically induced friction, is to minimize time-varying magnetic fields within the magnet levitation system. This can be achieved by making the magnetic levitation system as uniform as possible along the direction of travel of the moving ring. Examples of non-uniformities to be avoided include, for example: a) periodic expansion joints in a ring, b) a coupling system comprised of many discrete elements that are not manufactured to be sufficiently equivalent, or c) discrete elements that are not designed to integrate seamlessly.
A magnetic field non-uniformity on the moving ring will appear to travel rapidly from the perspective of the track, and a magnetic field non-uniformity on the track will appear to travel rapidly from the perspective of the moving ring. In either case, a magnetic field difference that passes by rapidly will be perceived as a time-varying magnetic field, and it will generate loops of electrical current know as Eddy currents of Foucault currents within any conductive materials of the magnetic levitation system. These currents would dissipate energy through ohmic losses as heat, or by emitting electromagnetic radiation. Therefore, the moving ring magnetic levitation system must be designed to minimize such losses through sufficiently strict adherence to the uniformity criteria described above. Additionally, such losses can be avoided through techniques such as using magnetic core materials that have low conductivity and by creating laminates of insulating materials and the core magnetic material to prevent Eddy currents flowing.

How is the Moving Ring Accelerated/Decelerated?
To accelerate the ring, electricity will be supplied to linear motors which will accelerate the moving ring. To decelerate the ring, the linear motors can be reversed such that they will generate electrical energy while the moving ring is decelerated. Thus, the kinetic energy of the ring can be converted to electricity and sold when the ring is decommissioned.
The linear motors must be designed to minimize the kinds of magnetic non-uniformities which would generate rapidly oscillating time-varying magnetic fields and thus magnetic friction. However, unlike the linear motors used for trains on Earth, they do not need to be capable of high rates of acceleration as the moving ring can be accelerated over several weeks of time. Thus, the linear motor may be engineered with a low frequency non-

uniformity to provide it with the means to magnetically engage with the moving ring. For example, if the linear motor generated a sinusoidal oscillating magnetic field that was designed to travel along with and magnetically propel the moving ring, then specifying a long oscillation wavelength would reduce the field's frequency from the perspective of a stationary observer. This technique could be used to minimize the parasitic magnetic friction of the linear motor.

How are the Tethers Designed?

Key Points: Forking nature. Climate versus altitude graph. Use of buoyancy. Tether strand breakage monitoring and replacement. Break-away mechanisms in case of over stress.

Each tether in the tether system is designed with a branching structure so that the branches fan-out the tensile forces and distribute them more evenly along a supported section of the ring. The tethers' trunks reach down to the planet's surface and attach to anchoring platforms. At altitudes occupied by commercial aircraft, the tether trunks and anchors are spaced kilometers apart so that there is ample space for ships and aircraft to navigate between them. The branches from each tether overlap with those of neighboring tethers to provide redundancy should a tether break or become detached from its anchor.

The tethers are instrumented so that breakage of individual tether strands can be pinpointed, and appropriate repairs initiated. Inspection and maintenance is performed by fleets of maintenance robots.

The tethers' positions are maintained by active aeronautic stabilizers - essentially specialized robots that are equipped with precision GPS and electrically powered thruster nacelles. These active aeronautic stabilizers serve to prevent the wind from distorting the optimal shape of the tethers and creating additional stresses on the tether system.

What Material(s) are the Tethers Constructed From?

Key Points: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4639556/, may be more than one material.
Examine Ashby Charts to see if we're using the best materials for the job.
Survey all the synthetic fibers such as Aramid, Kevlar, Technora, Twaron, Dyneema, Vectran, Zylon, etc. M-5, Sulfron, Teijinconex, Endumax.

How are the Anchors Designed?

Key Points: Anchors can move and are moored to the ocean floor. Storms, Rogue Waves, Tidal Waves, Tides. 100 Year Wave from Wikipedia. Anchor separation to allow for aircraft to safely fly between them. Rogue wave video link: https://www.youtube.com/watch?v=WffR6HrEqTA

Wind Shear Compensation

The force that wind exerts on the ring, its tethers, and its elevator cables must be minimized through streamlining and actively countered using aeronautic stabilizers.

Streamlining involves shaping the cables and tethers so that their cross-section resembles an airfoil to minimize the coefficient of drag, and providing a means to orient the airfoil with the direction of airflow when wind direction shifts.

Aeronautic stabilizers are lightweight autonomous machines equipped with electrically and/or chemically powered thruster nacelles. These units are distributed around the ring, and along the lengths of tethers and elevator cables. Collectively they are responsible for maintaining the absolute position of the ring, its tethers, and its elevator cables. They are designed to handle extreme weather conditions. They can load share and they can adapt and rebalance the load when unit failures occur.

Stabilizers use augmented GPS (Yiming Chen, 2016) to precisely determine the difference between their actual position and their assigned position. An onboard computer actively controls the amount and direction of thrust to minimize this difference.

The weight of each stabilizer is supported by the tether, cable, or ring that it attaches to; therefore, stabilizers must be light in weight in comparison to the mass of the ring, tether, or cable section that they are assigned to shepherd through the winds. Stabilizers are designed to be able to detach, fly away under their own power like (e.g. like a

quadcopters), fly back, and reattach. This allows them to get out of the way of cable climbers (see "How are People and Cargo Brought up to The Ring?", facilitates redistributing them, and rotating some of them out for servicing.

Most of the time, winds will track seasonal averages and the stabilizers will be lightly loaded. Infrequently, but occasionally, the stabilizers will need to perform in extreme winds. (Note: The fastest wind gust ever officially recorded was a 113m/s, but slightly faster winds are believed to have occurred within tornadoes. By comparison, the A380 airliner's top speed is 283 m/s.) Stabilizer may employ a hybrid power system that uses electricity most of the time but augments with chemical energy when power demands are high. For example, if hydrogen powered turbine engines and hydrogen filled supply lines outperform electric motors and wires on a power per/kg basis, then hydrogen could be pumped up the tether's interior to supply turbine engines within the stabilizers. A hybrid system also provides redundancy if the electrical systems are damaged (e.g. by an extreme electromagnetic storm or an electromagnetic pulse (EMP) from a weapon).

Air pressure, and thus the force of wind shear at a given wind speed, decreases rapidly with increasing altitude. Therefore, the stabilizer power requirements will also decrease with increasing altitude. Anecdotal evidence suggests that the design wind speed can also vary with altitude, although this has yet to be investigated.

Operational costs associated with supplying power to the stabilizers can be estimated based on average wind speeds. Figure 14 shows the variation in average wind speed versus altitude based on data gathered from early radiosonde flights near New Jersey (Wentzien, 1955).
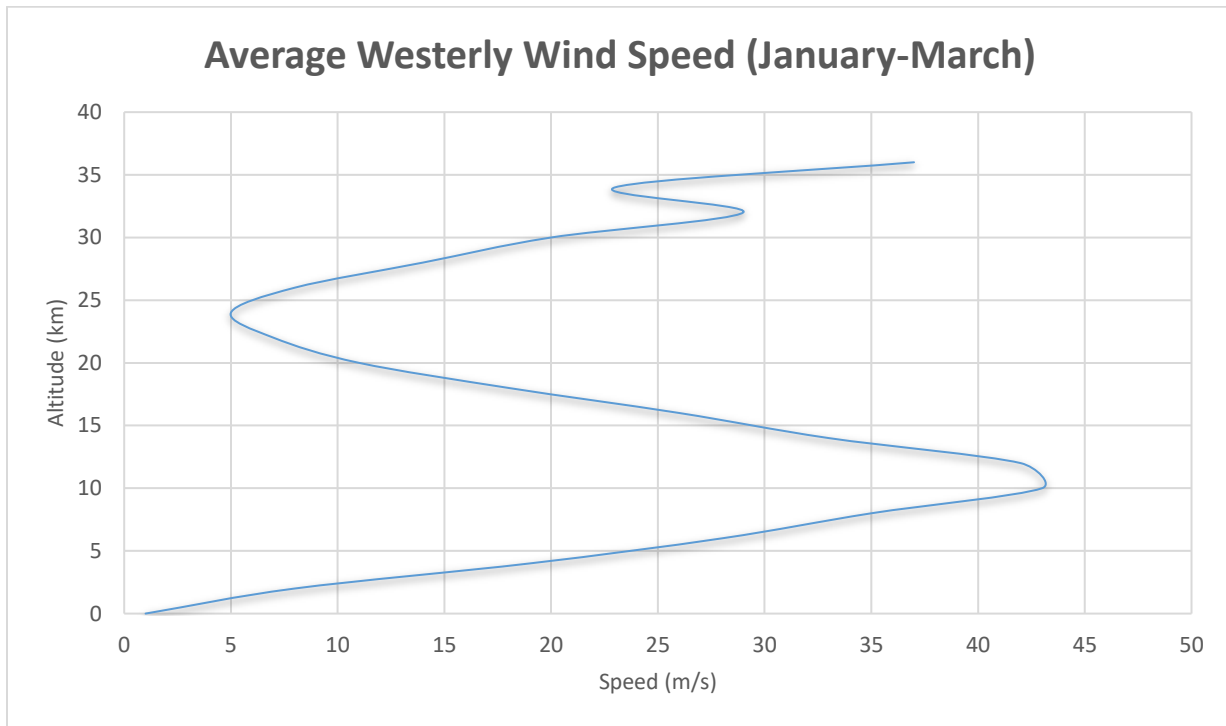
Figure 14: Average westerly wind speeds January through March

An estimate the total force of wind shear on a tether can be made using the following formula:

$$F_D = \frac{1}{2} C_D \rho U^2 A$$

Where:
      F_D is the Drag Force,
      C_D is the Coefficient of Drag,
 ρ is the air density,
      U is the wind velocity,

A is the wind cross-sectional area.

C_D is estimated to be 0.06 for an optimized airfoil. U is a function of altitude and is values are obtained by interpolating from the data plotted in Figure 14. A is computed using the tether's thickness and length of discrete section. The tether thickness is computed by approximating the cross-sectional area of an airfoil using half of an ellipse plus a triangle. Solving for the airfoil's thickness:

$$Thickness = \sqrt{\frac{CrossSectionalArea}{\frac{3\pi}{8} + \frac{3}{2}}}$$

Tether spacing was assumed to be 20km for the calculation. The tether is partitioned into sections based on altitude. The results of the analysis are plotted in Figure 15.
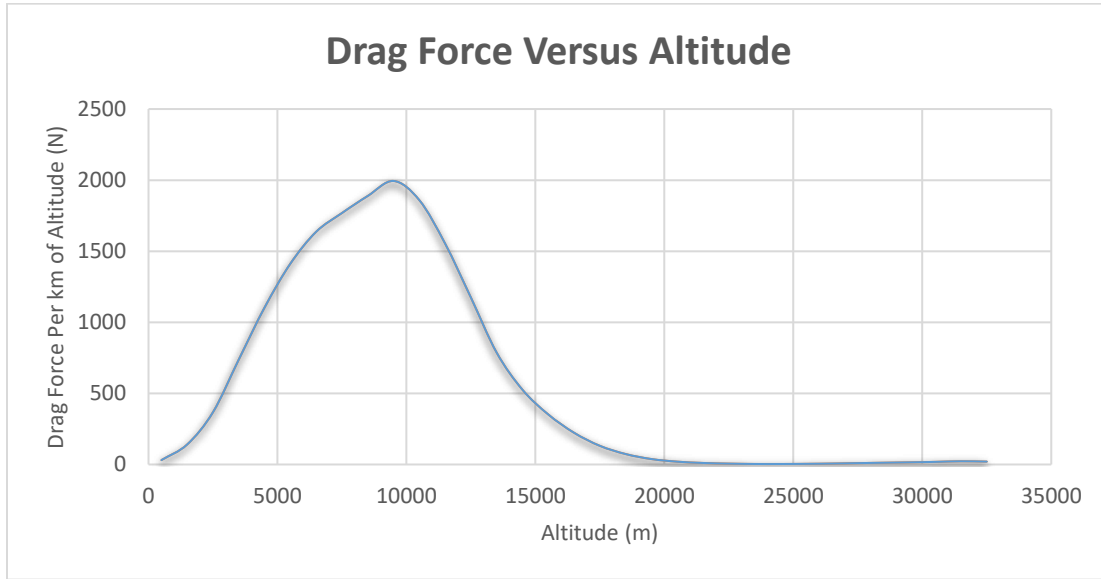
Figure 15: Relationship Between Wind Force on a Tether and Altitude

Note: Tether branching increases the tether's cross-section to the wind, but because tether branching occurs at elevated altitudes where the air is thin, this effect was omitted from the analysis.

Initially wind forces increase with altitude because wind speeds increase with altitude, but eventually the effect of lower air density dominates. There is relatively little wind force on the tether above 20km.

The total cross-wind force on one tether is estimated to be 17.951kN. To put this in perspective, the GE90-115B jet engine, used in many Boeing aircraft, generates up to 512.88kN of thrust at sea level (Aerospace-Technology.com, 2014). This is a force equivalent to the wind forces acting on 28.57 tethers.

The cost of generating a thrusting force in the air is well studied by the airline industry. To quickly estimate the cost, let us assume for the moment that the aeronautic stabilizers are powered by jet fuel. Using the Thrust-Specific Fuel Consumption (TSFC) value for a General Electric CF6 turbofan (which is 8.7 g/(kN·s)) we can convert the wind force on a tether directly into an estimate of fuel consumption per tether...

$$Fuel\ Consumption\ Per\ Tether = 17.951\ kN * 8.7 \frac{g}{kN \cdot s} = 156.17\ g/s$$

From this fuel consumption, and assuming that jet fuel costs approximately 1.64 USD/kg, we can estimate the operational cost per tether...

$$Operational\ Cost = 156.17 \frac{g}{s} \cdot 1.64 \times 10^{-3} \frac{USD}{g} \cdot 3600 \frac{s}{h} \cdot 24 \frac{h}{d} \cdot 365 \frac{d}{y} = 8,077,209\ USD/year$$

At 20 km tether spacing there would be a total of 1617 tethers, so the total operational cost will be approximately 13 Billion USD/year.

While this estimated cost is less than half of the projected revenue from running a stratospheric maglev, it is still high enough to be considered a significant economic factor. Additional studies aimed at refining this estimate and exploring ways to further reduce the operational costs associate with wind compensation are certainly warranted. Possible areas of study for refining the operational cost analysis include:

1. Transferring forces to the anchors. While the total cross-wind force on one tether is estimated to be 17.951kN, the tensile force within the tether (at the ring) is 35,774,kN. Thus, tensile force is almost 2000 times greater than the cross-wind force. Therefore, by moving the tether's anchor point upwind slightly, and allowing a slight curvature of the tether, a significant portion of the cross-wind force can be transferred to the anchor.
2. The wind speeds used in the analysis were for the windiest months of the year (January through March) and the data was retrieved from a very old study. Using more precise and up to date meteorological data would improve the operational cost estimate.
3. It was assumed that wind direction is the same for all altitudes. If this assumption is sometimes not true, then wind forces might partially cancel each other out along the length of the tether.
4. The tether cross-section to the wind was assumed to be the tether's airfoil thickness times the tether's length. If the wind direction were more along the length of the tether, then the wind cross-section, the total wind force, and the operational cost would be less. If the wind direction were sufficiently in line with a tether, then that tether's aeronautic stabilizers could be operated as power generating wind turbines. They could then supply power to the ring's electrical grid.
5. The cost of servicing the aeronautic stabilizers should be factored into the operational cost.

Key Points: What would the wind force on a tether be from a hurricane? What can we learn from the tethered blimps project? Compare to tall buildings – Citibank building in downtown New York.

Why Would People Choose to Live There?

Key Points: 95% of the time people currently live indoors, in trains, cars, planes, or ships. Ring transit provides fast access to premium cottage country. There are some parks and green spaces on the ring. What's a week in the life of a resident look like?

A massive sub-orbital structure like a tethered ring would attract many on the grounds of tourism. Since the space race beginning in 1955, many if not most modern national cultures have developed a great love and fascination with space, reaching apogee on July 20th, 1969 when the United States first landed humans on the moon with Apollo 11. It's been multiple generations since then and popular culture has evolved with current events, however there remains a great deal of precedent demonstrating humanity's interest in such endeavors. The success of the educational entertainment works of science communicators such as Carl Sagan, Bill Nye, Stephen Hawking, and Neil deGrasse Tyson prove a sustained modern interest in science and scientific feats even among younger audiences. And private companies such as *Space Adventures* prove that this interest can be translated into sales via their zero-gravity flight, sub-orbital spaceflight, and spacewalk space tourism packages, showing that private citizens are ready to spend thousands of dollars to experience mere seconds of this environment. Similar tourism experiences continue to share success.

If completed, a massive sub-orbital tethered ring would consistently attract many temporary guests in tourism, however permanent residence would also be a desirable investment to many around the world. Residential skyscrapers have seen an increased interest in recent years, such as 432 Park Avenue in Manhattan, New York, towering at 425.5 meters, which sold its first apartment in January 2016 over the $17.75 million asking price. Similar cases can be seen in Princess Tower, Marina Torch, Elite Residence, 23 Marina, Cayan Tower, HHHR Tower, and Ocean Heights, etc., all in Dubai, and elsewhere across the world in Australia, Russia, South Korea, India, Canada, China, etc.

While further focus group market testing could be performed, there is strong evidence that affluent individuals would support and purchase residential housing on such a tethered ring. If apartments were made more affordable with less focus on spacious prestige, it's reasonable that citizens of a relatively lower class would also be very interested in permanent residence on a sub-orbital structure. Wealth-related status, the experience of consistently living in sub-orbit (similar to that of the interest in tourism), easy access of foods and other goods from around the world due to the low cost of transport via the tethered ring, diverse culture, cheap and easy world travel, and even a freedom or separation from a particular government-system (entirely depending on how the tethered ring was governed) could all factor into an individual's interest in permanent residence.

Living aboard the tethered ring would also be a massive boon to scientific researchers. Since its creation, the commercial spaceflight industry has been an incredible attractor of scientific researchers, as seen when the

Southwest Research Institute of Boulder, Colorado immediately purchased tickets for its scientists and prepared experiments aboard early Virgin Galactic and XCOR Aerospace flights. The impact that commercial spaceflight has had on research areas such as atmospheric science, life science, astrophysics, planetary science, education, and public outreach has been massive already. Stable residence on a massive sub-orbital tethered ring would immensely superior. A sub-orbital structure would allow research not available on platforms like the ISS (International Space Station) that hangs in orbit 330 to 435 kilometers above the earth. This is a truly significant market with high interest and support from scientific communities around the world.

How are People and Cargo Brought up to The Ring?

As a primary use of the ring is for terrestrial transport, and as the ring will support a sizable population of tourists and residents, a way to rapidly transport people and cargo between the surface and the ring is needed. This transport system needs to be safe, convenient, and comfortable for passengers and it needs to have a low operational cost. The system must be engineered to be resilient to natural, technological, and human-caused hazards and it must not be hazardous to the ring or the population centers that it serves.

The proposed solution is to access the ring from various terminals located within population centers on the ground using pressurized cable-climbing vehicles. Cables are strung between "ring elevator" terminals; one located on the ring and another on the ground. Cables are stabilized against wind shear using numerous electrically powered active aeronautic stabilizers that are distributed along the length of the cable. These stabilizers will use precision global position system technology and aeronautic thrusters to keep the cable from drifting off position. The stabilizers, plus some cable tension, will enable the climber cars can travel up and down the cable at high speeds. For example, if a vehicle speed of 200 km/h is achieved, then an "elevator ride" to or from the ring will take on the order of 10 minutes, assuming a ring altitude of 32km.

The climber cars will be designed to detach from the cable while they are being loaded or unloaded. Cables may be engineered to support more than one cable-climber at a time so that there can be several travelling up on one cable and down another at any given time to make the most efficient use of the cables.

The cable climbers will employ aeronautic stabilizers and precision global position system technology to help them to travel along a smooth trajectory as opposed to relying only on the cable for lateral support.

To make the cables resistant to lightning and magnetic storms, they will contain many short, overlapping, and insulated strands of conducting material. Overlapping the individual strands will cause a capacitance to be created between them and this will allow them to conduct AC current while making the overall cable resistant to the flow of DC current.

AC current will be used to deliver power the cars and stabilizers and will be supplied from, ideally, both terminals to provide redundancy and reduce the distance that the current must travel. To minimize energy loss through electromagnetic radiation, the cable will support a differential pair of conductors. To reduce the Ohmic losses due to skin effects, each cable of the pair will comprise a bundle of individually insulated strands. This will force current to travel through the entire cross section of each cable bundle, similar to Litz wires.

The current can be harvested by temporarily separating the differential pair and coupling inductively or by making a direct electrical contact with the conductors within the cables. It is then converted and supplied to various electric motors, environmental control systems, lights, and instrumentation within the climber cars and stabilizers.

The cable climbers must be designed to gently grip the cable is a way that will minimize the rate of wear on the cable while permitting the cable climber to travel smoothly at high speeds.

The cars may use regenerative breaking technology to recover the potential energy of the descending car. This energy can be returned to cable inductively and then returned to the electric power grid.

The cars and stabilizers must support backup power sources in case of failure of the primary AC power source. The backup power system for a car must be sufficient to maintain environmental control and to enable the car to return safely to the ground. The backup system may be designed to use energy from regenerative breaking to replenish its power reserves. The backup power system for the aeronautic stabilizers must be sufficient to keep them operating until primary power can be restored.

The cables will be tapered such that their tension per unit of cross-sectional area is constant along the length of the cable when it is supporting a climber car is at the bottom of the cable. Due to the nature of its use, this cable will need to be engineered with 4X engineering factor. The weight of the climber car, stabilizers, cable,

arrival/departure terminal, and the additional tensile force needed to help keep the cable taught is all supported by mechanically distributing the point loads evenly along a sufficiently long segment of the ring.

The primary purpose of the aeronautic stabilizers is to prevent the cable from being blown out of optimal position by winds. They use positioning technology to track where the cable is relative to where it is supposed to be, and electrically powered thrusters which thrust against the atmosphere to maintain the cable near its optimal position. The stabilizers also support aircraft warning lights.

The stabilizers must not interfere with the passage of a travelling climber car. A proposed method to meet this requirement is that, when a climber car approaches a stabilizer, it briefly detaches, moves away, hovers under its own power (i.e. like a quad-copter), and after the climber car passes it returns and reattaches. Stabilizers also need the ability to climb the cable, but at much slower speeds.

If a storm is forecast, then certain preparations will be made. Operation of climber cars would be suspended temporarily, and the ring side terminal would be evacuated to reduce weight. The cable could be slackened to allow it to curve and to reduce cable tension. These measures enable the ground station to support more lateral forces without increasing cable's tension at the ring station. Additional stabilizers could also be deployed. Potentially, for severe storms such as cyclones where there is a danger of flying debris, the cable could be temporarily detached from the ground station and partially retracted up into the ring-side station and out of harm's way. After the storm passed, the stabilizers will guide the cable back to the ground station for reattachment.

In addition to transport via the climber vehicles and cables, some stays may support pipelines for fluids and tube-travelling delivery drones. A handful of stays may support a pressurized staircase designed for athletic adventurers who wish to experience the challenge of a 32km vertical climb.

The ring may also support specialized re-entry vehicles that could be launched from the ring and set on a sub-orbital course for arbitrary destinations on the planet's surface. These vehicles would provide a very fast way for passengers or important cargo to be delivered quickly to where they needed to go. Afterwards, these vehicles would be shipped to a terminal and hoisted back up to the ring via cable climbing car.

How Does the Space Launch System Work?

Key Points: How do we make sure that the action of launching vehicles does not perturb the ring. It the altitude high enough to launch from. How do we make sure that launched vehicles to not orbit around to later impact the ring?

The space launch system accelerates space vehicles horizontally to high speeds so that they can achieve useful orbits with minimal additional propulsive thrust. The system's static load is supported by the ring. The system's dynamic loads (those associated with a launch) are supported using propulsive systems and thus are dissipated directly into the atmosphere. Even though the atmosphere outside the tube is rarified, vehicles are accelerated within an evacuated tube to help reduce heat shielding requirements and reduce noise in the immediate vicinity of the launch system.

If we assume that gentle accelerations of 2G's are required for the launch system, then to reach escape velocity a vehicle will need to be accelerated to 10782m/s and this will take, using…

$$t = v/a$$

… only 550 seconds or 9.2 minutes. Using…

$$s = \frac{1}{2}at^2$$

… we can calculate that the maglev launch track will need to be 2965782m or roughly 3000km in length.

At the end of launch sequence, the vehicle will exit the evacuated tube through a series of fast opening and closing airlock doors. As the vehicle passes through the airlocks, the vehicle's thrusters will fire up to help offset the effect of increasing air friction. The maglev track will dynamically adjust the acceleration force that it imparts to help smoothly transition the vehicle into hypersonic atmospheric flight. When the vehicle leaves the track, it will already be in an elliptical orbit where the perigee of the orbit is located near the end of the launch track and still within the stratosphere. The vehicle will travel rapidly through the remaining atmosphere to reach space. As it will be travelling at supersonic speed and will generate a supersonic boom, the exit of the launch system is best placed over an ocean. Once in space, a vehicle can avoid reentering the atmosphere on its next pass by using its thrusters to move the perigee of its orbit to a higher altitude.

Vehicles can return from space to the ring to be decelerated by the maglev system through a reverse procedure if sufficiently precise and reliable navigation of the vehicle within the stratosphere can be mastered; however, it is perhaps inadvisable to subject the ring and its inhabitants to the risk of loss of control of a returning vehicle.

What Altitude is Needed for a Maglev Launch Accelerator?

Key points: Refence Star Tram.

The higher that the vehicle exits the launcher, the less residual atmosphere it will have to travel through to reach space. The density of air as a function of altitude can be approximated with the following equation, which uses data from the 1976 Standard Atmospheric Calculator (Digital Dutch, 2017):

$$\rho = e^{(c_4 a^4 + c_3 a^3 + c_2 a^2 + c_1 a + c_0)}$$

…where:

ρ is air density in kg/m^3,

a is altitude in meters, and

$c_4 \ldots c_0$ are the following constants…

c_4	-3.957854E-19
c_3	6.657616E-14
c_2	-3.47217E-09
c_1	-8.61651E-05
c_0	2.16977E-01

Air friction can be calculated using:

$$F = \frac{1}{2} C_d \rho v^2 A$$

…where:

F is the force of drag,

C_d is the coefficient of drag,

v is the velocity, and

A is the cross-sectional area of the vehicle.

Consider a cylindrical launch vehicle that is 2.4m in diameter with a cylindrical nose cone. This vehicle's coefficient of drag will be approximately 0.15 (Cronvich, 1983). Assume that the vehicle is magnetically accelerated within a vacuum tube to the appropriate Earth escape velocity for its launch altitude. When it exits the tube, it will experience atmospheric drag. The initial amount of drag will depend on the launch altitude and is shown in Figure 16.
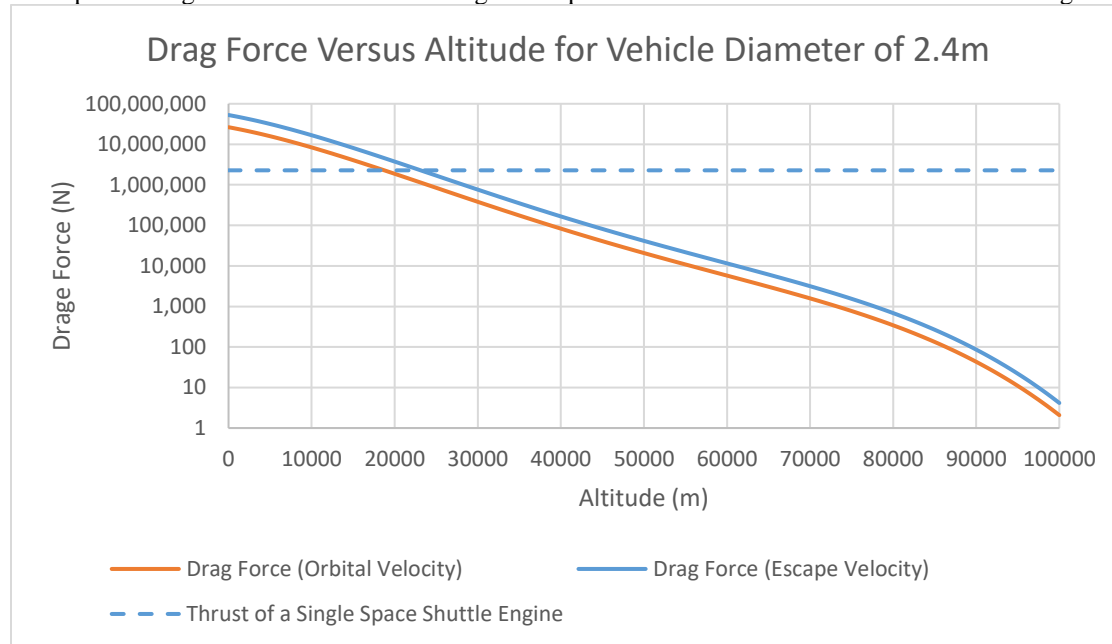
Figure 16: Atmospheric Drag Versus Altitude for a 2.4m Diameter Cone Tipped Vehicle

The graph shows the force for both orbital velocity at the launch altitude and escape velocity at the launch altitude. In practice, the launch velocity will be somewhere in between. The dotted line shows the thrust of a single Aerojet

29

Rocketdyne RS-25 engine, otherwise known as the space shuttle main engine (SSME). The graph shows that if a vehicle were equipped with an RS-25 engine and launched at escape velocity from an evacuated tube at 23km elevation, then the vehicle's engine would provide sufficient thrust to maintain its velocity despite the air resistance. Let's assume that the vehicle is equipped with an engine and the engine is used to maintain its velocity despite air friction. If the vehicle were accelerated and launched horizontally, then then the vehicle would travel tangentially to the planet's surface and eventually exit the atmosphere due to the curvature of the planet's surface away from the relatively straight trajectory of the vehicle. Figure 17 shows how the atmospheric drag on the vehicle would fall off over time for various launch altitudes.
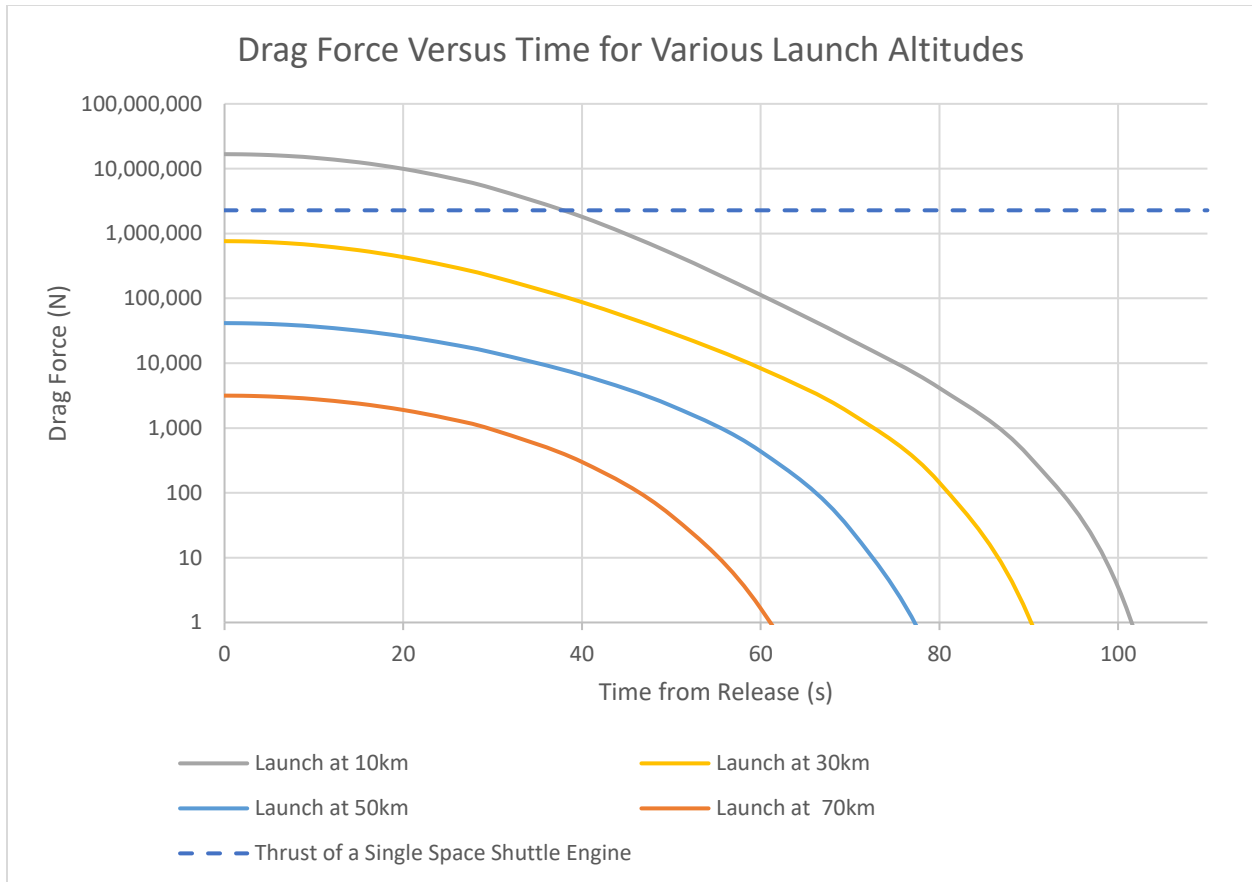
Figure 17: Drag Force Versus Time for Various Launch Altitudes

The same vehicle launch from 30km would need an engine only 1/3rd as powerful as an RS-25. If that vehicle were launched at an altitude of 50km, then an engine 1/60th as powerful would suffice.

Figure 17 shows that time spent in the atmosphere would be brief - on the order of one minute in duration. Therefore, the launched vehicle would not need to carry a lot of fuel to compensate for atmospheric friction. To help put this in perspective, the Space Shuttle's main fuel tank provided enough propellant to supply three RS-25 engines for about 8.6 minutes. A maglev launched vehicle, launched at an altitude of 30km with a single 1/3rd size engine, would need approximately 1/100th the amount of propellant stored within the Shuttle's external tank to compensate for atmospheric drag during launch. If the engine were a SCRAMJET, then potentially even less propellant would be needed because the engine could combine fuel with oxygen in the atmosphere.

The engineering complexity of the launch vehicle goes down with increased launch altitude. If a launch system were built on The Plateau of Tibet, with an exit altitude of roughly 6km, then atmospheric drag upon exit would be approximately one order of magnitude greater than the amount that could be compensated for using state of the art rocket engine technology. Thermal and mechanical stresses on the vehicle would be such that new technologies would be needed to engineer the vehicles to be safe and reliable.

If a launch system were built at an altitude of 23km, then the launched vehicle would be complex but it could be built using components, such as rocket engines, like those used to propel rockets today. It would achieve comparable

safety and reliability to ground based rocket launch systems; however, cost per kg launched would be much lower. However, at this launch altitude, if the vehicle's engine(s) were to fail to fire as the vehicle exited the tube, then passengers would not survive the vehicle's rapid rate of deceleration due to air friction even if their bodies were well supported by deceleration couches.

If a launch system were built at an altitude of 32km, then the launched vehicle could still be built using existing technologies, it would be less complex than a ground based rocket launch system, and it would be able to operate more safely and more reliably. Full reusability of the launched vehicles would be relatively easy to achieve. At this launch altitude, if the vehicle's engine(s) were to fail to fire as the vehicle exited the tube, then passengers could survive the vehicle's rapid rate of deceleration due to air friction if their bodies were well supported by deceleration couches.

The optimal altitude depends on many engineering factors and on the level of market demand for launch services. If there is strong demand for the ability to launch lighter vehicles and to carry sensitive payloads, then it may be necessary to position the launch systems at an altitude above 32km. The Tethered Ring could be architected with a special extra-high-altitude section that is dedicated to supporting a launch system.

What Launch Rates Can It Achieve?

A single launch system would comprise an evacuated tube that needs to resist only a small amount of atmospheric pressure, a maglev track, an array of atmospheric thrusters designed to absorb the dynamic loads, and energy delivery systems. As energy is required to launch vehicles, the rate at which energy can be delivered to the system will correlate with the rate at which the system can launch vehicles. Each kilogram launched will need to acquire roughly 50MJ of kinetic energy. In addition, we must assume that there will be efficiency losses in the maglev system and factor in the power consumed by the atmospheric thrusters. If we estimate that, all told, 200MJ of energy is needed to launch one kilogram, then a 200MW power supply (i.e. a little more than the peak power output of a Nimitz-class aircraft carrier) would allow a launch system to launch 1kg/sec, 60kg/minute, 3600kg/hour, 86.4 metric tons per day, or 31,536 metric tons per year.
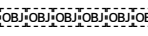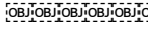
What are some comparable projects/endeavors?

<TBD>

Logistics

How do you move it into position after it has been raised?

A possible way to maximize the ratio between ring economic value and construction cost is to construct the ring is depicted in Figure 18

ed within the Pacific Ocean and where no part of the ring is on land (see [OBJ][OBJ][OBJ][OBJ][OBJ][OBJ]Figure 18[OBJ][OBJ]est (See [OBJ][OBJ][OBJ][OBJ][OBJ][OBJ]Figure 18b) so that it will be better able to serve population centers located around the Pacific Rim.

(a)   (b)
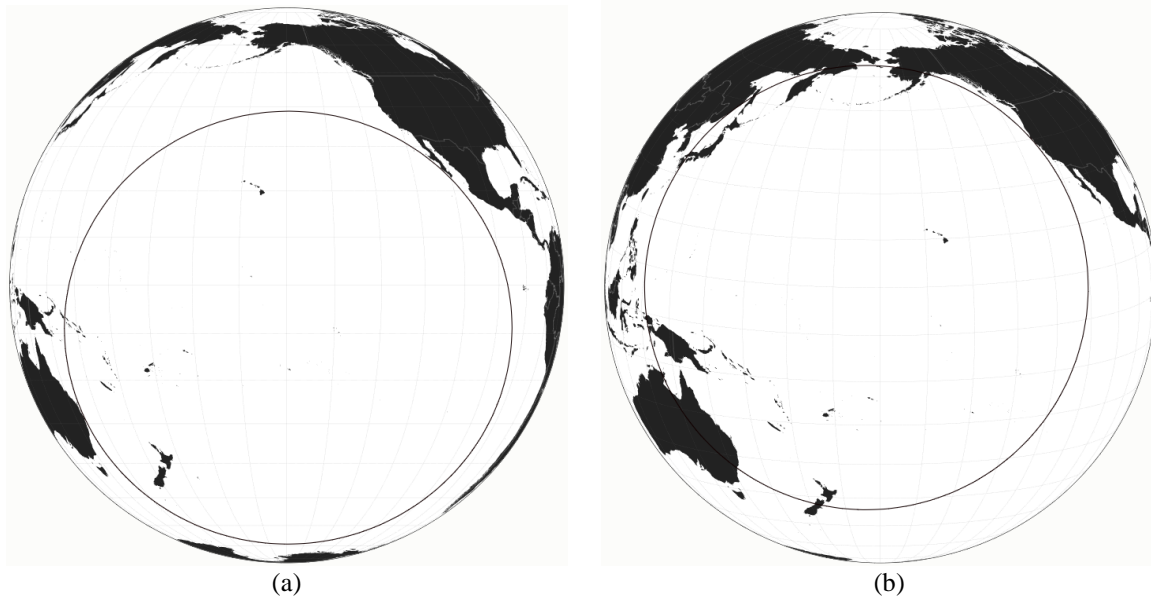
Figure 18: Tethered Ring: a) constructed and erected in the Pacific Ocean, and b) repositioned to serve population centers located around the Pacific Rim.

Most of the tether anchors will simply need to travel across the ocean to reposition the ring. Some anchors will need to take an indirect path to navigate around small islands. For larger islands and continents, such as Australia, the tethers will need to be handed off to from sea anchors to anchors that are designed to travel across land. The mobile "land anchors" will be designed to travel on highways or by rail and they will distribute the tethers' pulling force (approximately 1000N per meter of ring) along the length of the roadway or rail as opposed to concentrating it all at discrete points, as is done in the case of the ocean anchors. All anchors will include winching systems that are designed to maintain the correct tension even if it is necessary for the anchors to meander somewhat during their journeys.

How can the Traversed Countries be Convinced to Support the Project?

The boundary between public airspace and private air rights is defined by national or local law (Airspace, 2017). However, all countries whose territory or airspace intersects with the ring, its tethers, or its anchors, either during its construction, while it is being repositioned, or when it is in its final position, will be stakeholders and will need to approve the project plan. For example, if we consider the Pacific Rim location proposed illustrated by Figure 18, above, many of these countries, such as the USA, New Zealand, Australia, Indonesia, Japan, and Russia will be directly under the ring in its final position. These countries will directly benefit as the ring will facilitate trade and nurture economic prosperity. Many other countries, such as Canada, Mexico, The Philippines, China, and South Korea are quite close to the ring in its final position and are likely to want to negotiate to have the plans provide them with their own "marine nodes" and elevators located conveniently close to their shores. Some countries, such as Papua New Guinea and the Solomon Islands will need to grant permission for the ring to pass over their countries while it is being repositioned, but these countries will not be directly under the ring when it is in its final position. Clearly, the political challenge of bringing all stakeholder countries into agreement is certainly a subject worthy of further study. Potentially there are alternate final positions for the ring that are geopolitically advantageous.

As with many other infrastructure projects, the project may be funded by selling negotiables such as bonds, property on the ring, and parcels of transportation service to citizens of the traversed countries. By encouraging many such citizens become stakeholders in the project, it is likely that these citizens will lobby for their country's governments to be supportive of the project as such support would help to protect their investments.

How is the Moving Ring Isolated from Perturbations?

The ring is mechanically isolated from the residences, transit system, elevators, and launch systems. Without isolation, motions created within these facilities could jar the moving ring's magnetic levitation system, interfering with its smooth and low-power operation. Active mechanical actuators will be employed to filter higher frequencies from transient forces, effectively dampening them just as suspension systems do in vehicles. Lower frequency forces

will be actively dampened using aeronautic systems (e.g. electrically powered air turbines) generating thrust within the rarified atmosphere. Tether tensions may also be adjusted dynamically to reduce the load on the aeronautic systems.

Key Points: Perturbation Analysis

How do you Demolish it at the End of its Operational Life?

At the end of the ring's operational life, it will need to be repositioned back to its original construction site and then lowered back to the surface of the ocean – essentially reversing the steps used during its construction and deployment. The moving ring's velocity will be lowered as the ring is lowered. Eventually brought to a complete stop. Via regenerative breaking, the moving ring's considerable kinetic energy will be recovered and returned to the electric grid.

Achieving Sufficient Levels of Component and System Reliability

In modern society, people are conditioned to expect components to wear out, break down, and need repair or replacement. However, the rate at which everyday products wear out driven by factors such as cost competitiveness and the economic incentives of planned obsolescence. Many people are unaware of just how reliable engineers can make systems and components when faced with requirements that are uncompromising in their demand for extremely low failure rates.

Extremely high overall reliability of a system (or extremely low Mean Time Between Failures (MTBF)) is sometimes achieved using redundant parallel components. The system failure rate can be computed if the MTBF of the components, the Mean Down Time (MDT) of the components, and the number of redundant components is known. Such techniques are employed to optimize server farms where RAID (redundant array of independent disks) is employed to ensure that data is never lost despite frequent hard drive failures.

There are many remarkable engineering achievements of high system and component reliability that have not depended heavily on use of redundancy to achieve their results. For example, a Digital Micro-mirror Devices (DMDs) has several hundred thousand microscopic mirrors each which tilts back and forth hundreds of times per second. In these devices, the mirror hinge lifetime is 3×10^{12} mirror cycles (Douglass, 2003). Within jet aircraft engines, the first-stage turbine blades achieve 20,000hr and longer service lives operating in gas path temperatures of 1400 °C by using single crystal blades coated with a thermal barrier of yttria-stabilized zirconia (YSZ) (Chupp, 2007). Despite the extremely harsh conditions that they endure, these blades are millions of times more reliable than the pistons within automobile engines. Space probes provide are another example of the levels of reliability engineers can achieve when the mission demands it. Probes are complex, highly optimized for minimal weight, exposed to the harsh environment of space, and are developed as much as 20 years before their primary missions' end. They routinely succeed in capturing images and gathering invaluable data from remote corners of our solar system. Our civilization's track record on "reliability engineering" is quite impressive when one considers specifically those case studies where achieving high reliability was critical to success.

While many of our past successes are truly impressive, reliability engineering continually improves due to rapid advances in computational multi-physics modeling, materials science, robotics, and quality control. For example, industrialized Computerized Tomography (CT) scans are now being commercialized to allow manufacturers to inspect the insides of manufactured parts for cracks, voids, and other defects that could potentially lead to device failures in the field. From an engineering reliability stand point, the Tethered Ring is well within our civilization's current capabilities. The moving rings travel in a vacuum supported without physical contact by solid state magnetic levitation technology; therefore, they do not suffer from wear. The moving rings do experience hoop stresses so their materials are not subject to the effects of creep. The maglev system can be designed with ample redundant components to ensure that the overall system has an infinitesimally low failure rate. The tethers represent a more significant reliability challenge as they are under great strain; however, they can be routinely inspected and periodically replaced to ensure that tether structural failure is rare. The architecture requires that the tethers overlap to provide ample redundancy as well, a requirement that is driven by other risk factors such as resilience to acts of terror and accidental aircraft collision.

With today's engineering know-how, a Tethered Ring can be designed that will exceed the required levels of structural safety established for buildings and structures used by the public.

How is it Maintained?

Key points: Drones and robots. System to provide these drones and robots with power.

<TBD>

Hazard and Risk Profile Assessment

A completely dispassionate assessment of a megaproject's risk profile is fundamental to advancing the project both technically and economically. A proper assessment helps to prioritize system's engineering efforts, creates more options for acquiring much needed resources, makes insurance costs easier to predict, and allows the project to be matched with partners and investors that share a similar risk-profile. Pioneering spirits will generally tolerate a well-understood amount of risk, when a project's scope, vision, and the types of big problems that it addresses align well with their primary goals.

This section is organized by hazard class. Within each hazard class, the most pertinent hazards and their relationship to the project are described. For each, possible methods of mitigating risk are explored. Hazards are organized into three categories: 1) natural, 2) anthropogenic (hazards caused by human action or inaction), and 3) engineering hazards (e.g. component, system, power failures, etc.). Within each category, the hazards are loosely organized based on distance from the ring to the source of the hazard, starting with the furthest and working inward.

There are many hazards associated with living on the Earth's surface that will be lessened or eliminated by choosing to visit or live on the ring. There are several existential threats that are perhaps mitigated to a degree by furnishing our civilization with the means to affordably access space. These anti-hazard topics are not addressed in this section.

Natural Hazards

Space Radiation

Space radiation is defined here as the ionizing forms of radiation - primary Galactic Cosmic Rays (GCRs) and Solar Energetic Particles (SEPs). At the surface of the Earth the flux of Space radiation is lowest because high energy particles dissipate due to collisions with atoms in the atmosphere. The flux of space radiation does not increase continuously with increased altitude but rather lessens after the Pfozner Limit which occurs at around 15-20km before increasing again as one heads out into deep space.

To put the hazard of space radiation in perspective, a resident of the ring would receive lower doses of ionizing radiation than a smoker's lungs receive from the Polonium-210 in found in tobacco smoke. (Note that "Levels of polonium-210 in tobacco smoke are not believed to be great enough to significantly impact lung cancer in smokers" (Harley NB, 1980)).

The primary mechanism by which space radiation is understood to be harmful is in fact indirect – particle collisions are thought to generate free radicals which, in turn, damage DNA. Therefore, free radical scavenging agents such as amifostine (WR-2721) may help to counter such effects (Koukourakis, et al.). As more people take up residence in the stratosphere, medical science will likely rally to develop additional protective compounds and treatments. These mitigations may become commonplace just as the application of sunblock to protect people against UV rays is widely accepted by the general population today.

The effects of ionizing radiation on the physiology of living tissue is certainly a subject deserving of further study. Such medical progress will help human civilization prepare to emigrate even further away from our planet.

Intense Magnetic Storms

Key Points: Clarington event of 1859. In March of 1989 an intense magnetic storm disabled the electrical grid in Quebec. Two aspects: Induced currents in the structure and people's exposure to space radiation.

Meteors and Space Debris

Key points: Flux of meteors is low due to ring being within atmosphere. Is there a need for defense? What would happen in the event of collision. How would a defensive system work? What would that defensive system weigh?

Atomic Oxygen

Volcanic Eruptions and Ash-clouds

Particles of volcanic ash from a volcano can be carried upwards by air currents and laterally by winds. The particles could accumulate on the tethers, interfere with cable climbers, aeronautic stabilizers, and tether inspection and maintenance robots. If carried by strong winds, the particles could be abrasive to some surfaces. Sulfur dioxide, also found in ash clouds, can be corrosive to some materials.

The tethers should not be anchored where they would be directly in the path of a lava flow or where their tether might be damaged directly by pyroclasts from an erupting volcano. Ash clouds, on the other hand, are difficult to avoid, can travel for significant distances, and can affect many tethers simultaneously; therefore, the tethers will need to be engineered to withstand the abrasive effects of wind-born ash and the corrosive effects of sulfur dioxide.

Some possible mitigations include sheathing the tethers with a tough rubberized compound. When there is an ash-cloud incident during cold weather, the rubber can be electrically heated to make it sufficiently soft and malleable to be resistant to abrasion.

Environmental systems for the habitats should include filters and pumps that would not jam up due to the presence of fine particles of volcanic ash. Likewise, cable climbers, aeronautic stabilizers, and tether inspection and maintenance robots should use sealed bearings, corrosion resistant materials, and other design features that will ensure uninterrupted operation if they are immersed for extended periods of time within an ash-cloud.

At lower latitudes, where a significant amount of ash could accumulate on top of the tethers, snow and ice clearing robots may be used to periodically sweep away the ash (see "Ice Storms and Ice and Snow Accretion", below). These robotic sweepers also must be designed to operate reliably in conditions where ash accumulation poses a hazard.

Sprites and Their Siblings

Seismic Events

Forest Fires

Icebergs and Ice Sheets

Cyclones

Ice Storms and Ice and Snow Accretion

Atmospheric ice can accrete onto tethers and elevator cables through precipitation (e.g. freezing rain and wet snow) or frost. Snow can accumulate on the top of the tethers and icicles could form beneath. The shedding of large pieces of ice could pose a hazard to people and property beneath a tether. The weight of accumulated ice and snow would sag the tethers leading to unacceptable deformation of the ring. Excessive ice or snow build-up would interfere with the smooth operation of cable climbers, aeronautic stabilizers, and tether inspection and maintenance robots.

Engineering the tethers and cables to tolerate significant ice/snow build-up would be costly, would not adequately address the falling ice hazard, and would not stop ice/snow from interfering with automated machinery; therefore, the tethers need anti-icing systems that are designed to prevent ice/snow accumulation on the tethers, the elevator cables, and the various components that attach to them.

The anti-icing system should not add significant weight to the tethers, as this would increase the overall cost of the project. As ice/snow build-up is weather dependent, higher than normal operational costs are acceptable as anti-icing systems are likely to be in a stand-by state most of the time. Several novel concepts have been proposed to address this challenge.

Robots that clear ice/snow and apply an anti-icing fluid

If ice accretion conditions are forecast, specialized robots could be deployed to travel along the tether to remove any accumulated ice or snow and then apply a suitable anti-icing fluid to prevent accumulation. The pseudoplastic Type II fluids used on airliners might be appropriate anti-icing fluids as they can withstand wind shears of up to 190km/h.

Mechanically flexed outer sheath

The tethers could be wrapped in a flexible rubber sheath, and a sheath deforming machines could travel between the sheath and the inner core of the tether. The machine would warm the sheath material from the inside (if needed) to make it flexible and to weaken the adhesion between the ice and the sheath material. The machine would then deform the sheath material to mechanically break up and dislodge the layer of accumulating ice before it became too thick.

Sound transducers may be activated to inhibit ice crystal formation. Sound waves could potentially be used to shatter ice so that it would shed from tether. These transducers could be installed permanently within the tether or brought in as needed by fleets of anti-icing and snow removal robots.

Beamed Energy

Microwave energy could be focused from space onto sections of tether where ice or snow build-up is detected. Power harvesting antennas within the tethers could converted the energy directly into heat or power harvesting "rectennas" could convert it into DC current for powering deicing devices. An advantage of beamed energy that it can be rapidly deployed when and where it is needed. However, the microwave energy would need to be able to penetrate storm clouds. It should also not interfere with or damage radio equipment, or cause harm to living things. Therefore, beamed energy may be more suitable as part of a secondary emergency anti-icing system.

Lighting

Anthropogenic Hazards

Terrorism

Key points: Separation between the mass stream and the habitats. Fact that people can't go outside. Could a sniper shoot the moving ring? A single commandeered aircraft could only impact one tether. What would happen if it did? What would happen if multiple commandeered planes executed a coordinated attack. Could a falling tether do significant damage to people/property on ground? Could the aeronautic stabilization systems enable a tether to dodge an airplane?

War

Key Points: Would it be a target? How quickly could it be redeployed if it was taken down?

Civil Disorder

Key Points: Too many people gather in one place, causing the rated load of the habitat to be exceeded.

Aviation and Shipping

Engineering Hazards

Catastrophic Moving Ring Maglev System Failure

Key Points: If magnetic confinement fails on one ring, it flies off into space and the remaining rings lose altitude. If magnetic confinement fails on all rings, they all fly off into space and excess mass is auto-dumped into the ocean. Drag chutes will deploy. The aeronautic stabilization systems will help to land the ring softly. Habitats must be designed to survive in the ocean long enough to enable rescue.

Maglev Launch System Failure

Maglev Transit System Failure

Habitat Environmental Systems Failure

Habitats

Key points: How much would a habitat weigh? How would it differ from living in a home on Earth? What is the temperature and air pressure like outside? Environmental systems use of the exterior atmosphere to refresh air and collect water. Relate to apartments in sky scrapers. Relate to how much time people spend indoors. Mention likelihood that people will also have cottages. Economics of owning a habitat. Maintaining even weight distribution.

Habitats are a key component to fulfilling the purpose of the ring. These habitats will be used for tourism, research, and real estate, all of these creating an ROI to build and maintain the ring. 250,000 inhabitants are envisioned to be on the ring at any given moment, with each individual having on average 11.8m^2 of living space.
The structure of the habitats is self-supporting, as they can be attached to the ring at any side of the habitat (top, bottom, or from any of the sides). The weight must be distributed to no more than 100kg/m of the ring, and therefore attached at every meter. Because of this weight restrictions, it's necessary to use architecture and materials with a high strength to weight ratio. Concepts such as geodesic domes, tensile structures, Buckminster Fuller architecture, and grid shells are valid when looking at the necessary design criteria. Carbon fiber comes to mind as a light yet strong building material for this application, though more common material such as bamboo proves to be a compatible as well[1].
Life support and environmental areas necessary to address include oxygen, humidity, temperature, pressure, waste management, water, and power. The environmental systems conceptualized for the habitats are heavily based on those of the ISS ECLSS, since this is the best isolated closed system existing today. Some life support systems are also based on those used in submarines.
Because the ring will always be 30 to 80 km from sea level, there will still be a certain amount of rarified atmosphere. Not much is known about the Mesosphere (50-80km), though the Stratosphere (17-50km) has large amounts of atmosphere still, which may be useful for the environmental systems. The altitude of the ring ensures atmospheric protection from the Thermosphere, Mesosphere and portions of the Stratosphere.
Finally, ensuring a quality of life on the ring is necessary to ensure the full utilization of the habitats. Not only must the habitats be biologically safe for the inhabitants, but a social aspect must be available. The habitats are connected by the high-speed transit system. Tourist attractions such as hotels, restaurants and recreational activities will be made available. Scientific research facilities and a space launch system will ensure more economic sustainability and professional growth prospects. Since human occupation of the ring is so essential to achieve the ring's purpose, the habitats are key to creating a healthy and lively ring society.

Environmental:
Heavily based on the ISS ECLSS: "The International Space Station Environmental Control and Life Support System is a life support system that provides or controls atmospheric pressure, fire detection and suppression, oxygen levels, waste management and water supply"
Key differences are more water supply and gravity.
References and resources:
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090029327.pdf
https://www.nasa.gov/centers/marshall/pdf/104840main_eclss.pdf
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050092399.pdf

[1] Sharma, Bhavna, et al. "Engineered bamboo for structural applications." Construction and Building Materials, vol. 81, 23 Feb. 2015, pp. 66–73., doi:10.1016/j.conbuildmat.2015.01.077.
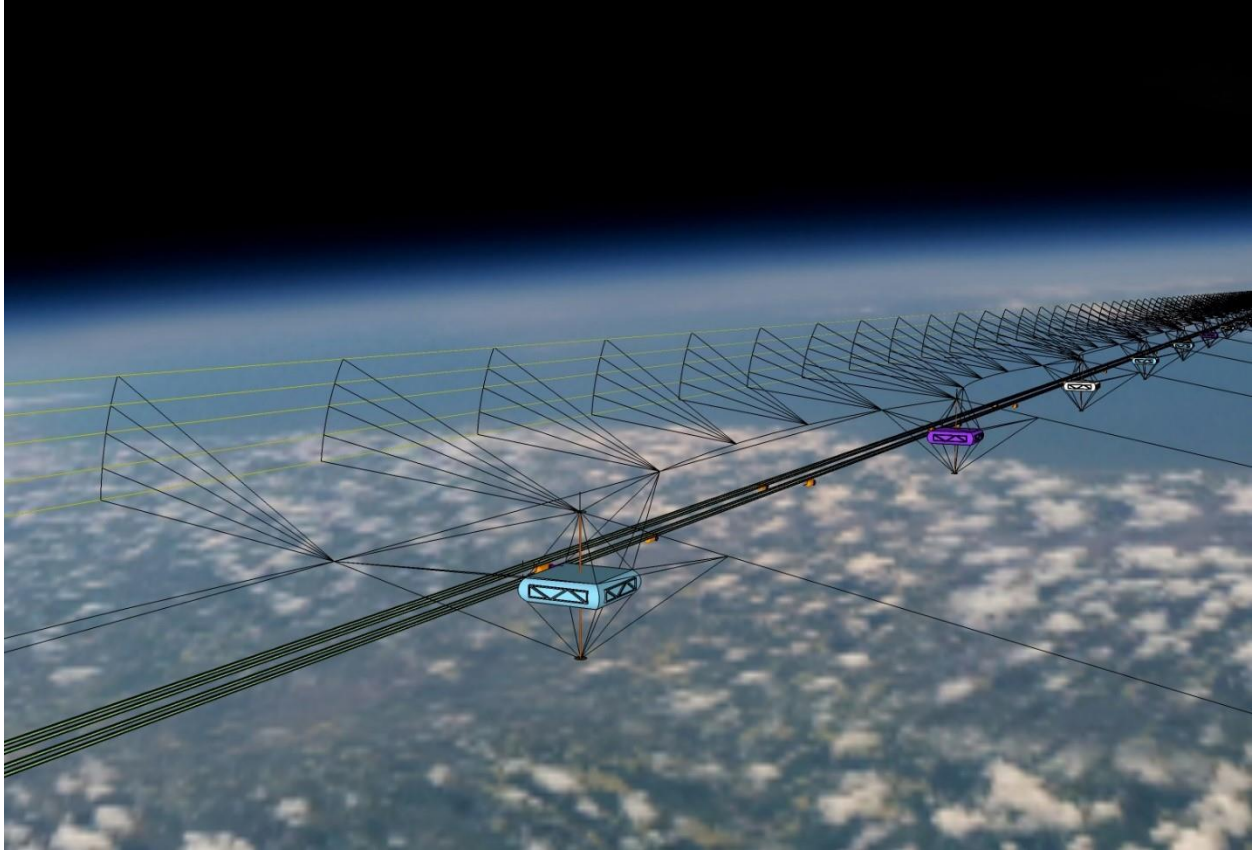
Architecture:
Weight calculated to hold 100kg/m
127sqft per inhabitant (?)

Lifestyle:
High-speed transportation system to maintain a community life.

Vacation destination
Research facilities
High-rise real estate

How Much Less Would a Visitor or Resident Weigh on the Ring? (Include in Habitats?)

What is the inter-habitat transit system like?

Key Points: Bi-directional with collector lanes and express lanes so at least four lanes total. Potentially travel within evacuated tubes. Weight is supported by atmosphere. As people disembark from a transit car, the transit system will take on an equivalent amount of ballast mass by pumping water from the habitat to the transit car. Preferentially waste water will be loaded from the habitat to the car and fresh water will be loaded from the car to the habitat.

How does cost vary with design parameters such as circumference and altitude?

Key Points: The cost of the ring goes down with increasing diameter. Cost versus altitude. Cost versus latitude.

Design Variants

Key Points: Non-constant altitude around the ring.

Economics

What does it cost to build?

Key Points: Tether cost, magnetic levitation system cost, energy cost to spin it up.

What are the operational costs?

Key Points: How much magnetic friction? Maintenance costs? Aeronautic stabilization system power. Parts replacement costs?

What would launch costs to LEO, GTO, SSO, etc. be relative to current costs?

How much business could it potentially win from the airline industry?

What would a tourist do during a vacation to the ring?

Key Points: Linear parks, orbital launches.

What kinds of Space Industries would low cost access to space potentially enable?

Key Points: Mining rare minerals can be mined and radioactive waste that's a biproduct of mining can be left on the moon or asteroid where the mining took place as opposed to creating a disposal problem. Helium-3, used in Neutron detectors at ports and border crossings, is traditionally gathered by gathering the off-gasses from tritium decay in Thermonuclear weapons, but it is in short supply on Earth.

Energy Storage and Transmission

The moving rings can also be used for electricity storage and transmission. For example, if 1GW of power was generated in Australia and there was a market for that power in California, then the power could be used to accelerate the moving ring as it passes over Australia and it could be recovered by decelerating the ring as it passes over California. The moving ring would in fact be traveling at two slightly different speeds which would generate hoop stresses, but the change in ring speed associated with such a power transfer is very small since the kinetic energy of the ring is large. Consider…

$$Energy\ Delta = \left(\frac{1}{2}mv_1^2 - \frac{1}{2}mv_0^2\right)$$

$$Power\ Transfer = \left(\frac{1}{2}mv_1^2 - \frac{1}{2}mv_0^2\right)/sec$$

$$v_1^2 - v_0^2 = \frac{2\ Power\ Transfer}{m/sec}$$

$$v_1^2 = \frac{2\ Power\ Transfer}{m/sec} + v_0^2$$

$$v_1 = \sqrt{\frac{2\ Power\ Transfer}{m/sec} + v_0^2}$$

$$Velocity\ Difference = \left[\sqrt{\frac{2\ Power\ Transfer}{m/sec} + v_0^2}\right] - v_0$$

Using $v_0 = 16869$m/s, $Power\ Transfer = 1GW$, and $\frac{m}{sec} = 100kg * 36\% * v_0$, we can determine that the change in the moving ring's velocity is only 0.098 m/s, or 0.000593%. Therefore, the strain on the moving ring will be 0.00000593. If the moving ring were made of steel with a modulus of elasticity of 200GPA or 10^9N/m^2, and it had a cross sectional area of 0.0045m^2, then it will experience a hoop stress of:

$$HoopStress = Strain * MoudulsOfElasticity * CrossSectionalArea$$

$$HoopStress = 0.00000593 * 200x10^9\frac{N}{m^2} * 0.0045m^2 = 5337N$$

… which is a trivial amount of stress for a steel ring with a cross-sectional area of 0.0045m^2.

For such a power transmission system to be viable, the linear motors that accelerate and decelerate the moving ring will have to be efficient – close to the efficiency of the step-up and step-down transformers that are used for electric power transmission over transmission lines.

The moving ring can be used for economical grid energy storage, which can make renewable electricity sources such as wind, tidal, and solar power more practical via supply-demand leveling. The total energy density of the moving ring at its proposed operational speed is 177MJ/kg. In comparison the energy density of a lithium-ion battery is 0.8748MJ/kg (Panasonic, 2016), an industrial flywheel is 0.5MJ/kg (Douglas, 2009), and the theoretical maximum for a flywheel (sans maglev technology) is 9.7MJ/kg (Lam, 2017). Therefore, the moving ring has significant inherent value as an energy storage device if there is an addressable market for temporary energy storage. The moving rings store $5.72x10^{10}$ kW·hours of energy. If we varied the amount of energy in these rings by just ±0.25% to enable the energy storage application, then the moving ring's effective storage capacity would be

286,076,423 kW·hours. "By 2020, GTM Research expects average lithium-ion battery costs to hit $217 per kilowatt-hour." (Lacey, 2016). At these prices, 286,076,423 kW·hours of storage capacity would be worth just over 60B USD. However, a market for this amount of energy storage has yet to materialize. According to the National Renewable Energy Laboratory, there was a total of 53 gigawatt-hours of lithium-ion cell production capacity in 2015, but only 40% of that was used (Lacey, 2016). The industrial batteries market is projected to grow from USD 7.45 Billion in 2015 to USD 10.84 Billion by 2021 (Markets and Markets, 2016), although that market is dominated by cranes, forklifts, and mining equipment. The Smart Grid and Renewable Storage segment is estimated to be 10%-15% of the total industrial market in the 2016-2022 timeframe.

On a smaller scale, the energy storage application could serve as a demonstrator project that would have the side benefit of establishing the viability of high-speed maglev technology. Flywheels that use carbon fiber, magnetic bearings, and operate within a vacuum are already manufactured for industrial power storage purposes (Douglas, 2009).

The concept of repurposing the ring's underwater construction sheath, after the ring is completed, to house a next generation super-collider has been considered. Figure 19 shows how the Tethered Ring's circumference and a hypothetical construction date in the future (orange square) appears to follow a trend of cyclotron circumference increasing with each generation (blue circles).
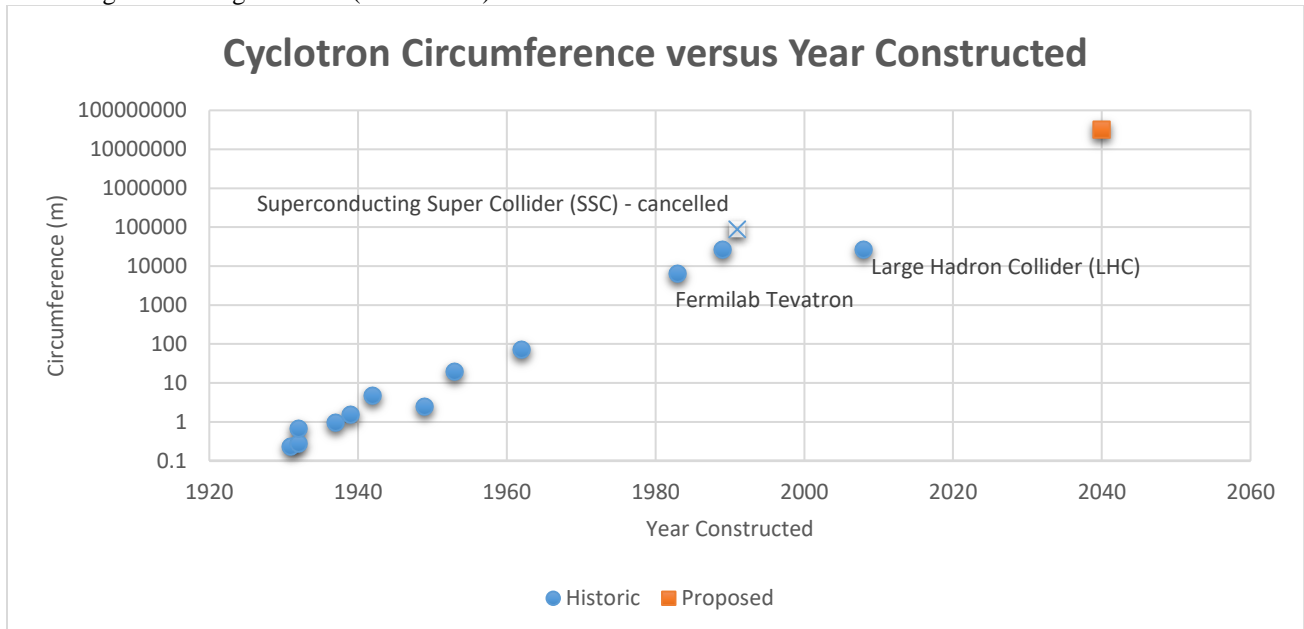
Figure 19: Trend of cyclotron circumference versus year of construction.

The Future Circular Collider (FCC) and other plans call for the construction of new, even larger, supercolliders (Zimmermann, 2015). These early plans do not specify circumferences and dates that suggest that they will be able to maintain the pace established by past projects. This may be due to practical considerations such as the high cost of operating tunnel boring machines. It may be deemed essential for the historical trend to continue unabated to maintain the pace of discovery. If this is the case, then physicists may consider housing the FCC within the construction casing and later exploit the low cost per-kilogram launch capabilities of the Tethered Ring to help them to construct even larger diameter cyclotrons off-world.

Cost Relationships

Cost Versus Specific Strength
Cost Versus Altitude
Cost Versus Diameter
Cost Versus Moving Ring Speed

Renewable Energy??? Benefits Summary

Key Points: Reduction in carbon fueled airlines, reduction is carbon fueled rockets, more people see the planet from space –> overview effect -> policy and behavioral changes, used to store and dispatch energy to make renewable energy more practical.

Impact and Support on Climate Adaptation Initiatives

The Tethered Ring would yield positive impact and support for climate adaptation initiatives by the experience offered to residents and guests. A necessary catalyst to accomplish key activities to respond to climate change lie in collective decisions in policy. Plainly put, we need more people in the world to understand climate reality, so we can convince our political decision-makers to make the necessary decisions to scale back our impact on the environment. Sometimes only specific experiences offer what it takes to change someone's perspective.

Traveling globally has been scientifically demonstrated to improve a person's disposition in five behavioral domains: emotions, extraversion, agreeableness, conscientiousness, and openness to new experiences. (Neyer, F. J., Mund, M., Zimmermann, J. and Wrzus, C. , 2014). A series of studies, many of which focused on students who have spent time abroad during studies, reached similar conclusions that having or recollecting to experiences in a new culture unlock creativity and problem-solving capabilities. This improved creativity and behavioral dispositions are rooted in experiences where familiar tasks warrant and lead to different solutions due to different culture. A similar research study, published in 2017 in the Journal of Research in Personality, finds that people with open-mindedness have a different visual perspective of reality, by more likely experiencing a visual perception phenomenon called "binocular rivalry" (Antinori, A., Carter O.L., Smillie, L.D., 2017). They literally see the world in a different way. Despite the efforts of dedicated activists and Nobel laureates, sometimes a new perspective can only be achieved by a new experience. But once that experience has happened, it literally changes our view.

Allowing up to 250,000 people at any given time, The Tethered ring gives residents and guests the newest perspective available in the world. This perspective, connected to any association to the global climate may serve as a new vote, new voice, and new influence on how we make decisions for new progressive and constructive developments.

The sheer number of travelers on the ring serves as a secondary positive impact on climate change, as it inherently a more carbon-sensitive mode of transportation. In 2016, more than 25 million people flew from top airports in Korea, Japan, and Australia. If a fraction of these travelers could turn to the tethered ring for their destinations around the Pacific region, their associated costs and impact air travel has on climate change would be displaced.

Strategies for starting small and scaling up.

1. Physical demonstrator to stir up hype, demonstrate physics. Small scale models could be done by pumping fluid around segmented tubing. If a small enough model can be constructed, might be something profs of intro physics may be interested in.
2. Build larger demonstration, utilizing industry partnerships to also demonstrate tech. Less home-baked-DIY and relying on Hyperloop Transportation Technologies, Hendo, Zodiac, ElectroImpact, academia, etc.
3. First practical structure, built somewhere remote and beautiful, for observation and recreation. Full embodiment of technology, and at a small scale. Profit-generating.
4. Following significant investment, strategic acquisitions are made of several key technologies, allowing for continued funding and development.
5. First near-space tethered ring. Tenants of ring are generally composed of scientists funded by wealthy nations, large corporations, and well-endowed universities. A small number of extremely wealthy technocrats take up residence for the view and to oversee their ventures.
6. 2nd near-space tethered ring. Much larger radius enables mag-lev slinging of mass into LEO enabling a dot-com-like boom in space based startups. The additional space of this ring allows for many more habitats than earlier rings, although it is still incredibly premium space. Successful, retired people are able to plan on trips to the ring. Some of the more established players in the blossoming space-based economy uproot their terrestrial

offices altogether, relocating to the ring. Facilities develop for the receiving and processing of space-derived materials and wares. Humanity's first off-world pregnancy leads to humanity's first off-world birth.
7.   3rd near-space tethered ring fully encompasses the Pacific Ocean following overwhelming support by the United Nations Department of Near-Earth Development. This ring becomes the Ellis Island for Mars Colonists seeking to return to Earth. A safe harbor and launching point for Humanity's next diaspora into the stars.

Other

The Geopolitical Impact of a Tethered Ring

The Tethered Ring has the potential to shift global politics and improve relations between nations. Due to the sheer size and scope of The Tethered Ring, not only will it serve as a bridge between nations, it will require an unprecedented degree of international cooperation to be constructed.

The Tethered Ring has the potential to alter migratory patterns as well as transform the travel industry.

The Tethered Ring also has the potential to reduce global conflict through a shared common interest in the ring as well as the ring's ability to provide a broader global perspective and shared sense of purpose. Rather than a typical sense of nationalist pride, people will begin to see each other as global citizens with a shared sense of responsibility for the planet.

Constructing the Tethered Ring will be one of the greatest engineering feats the world has ever known. It will require the brightest minds from all over the world working towards a common goal. It will also require collaboration between governments to provide protection and allow access and to the ring as well as the coordination of the collection and distribution of natural and man-made resources for the manufacturing process.

The Tethered Ring will be the creation of new real estate in international waters. This will bring forth many new questions regarding ownership, laws, governance, and liability among many others.

Table 3: Projects involving international cooperation include the 150B International Space Station (ISS), The 14B International Thermonuclear Experimental Reactor (ITER), the 9B Large Hadron Collider (LHC), and the International Whaling Commission (IWC). Table does not show all member countries.

	ISS	ITER	LHC	IWC
Australia		X^4	X^2	X
Canada	X		X^2	
China		X	X^2	
EU	X	X	X	X^3
India		X		X
Japan	X	X	X^1	
Russia	X	X	X^1	
S. Korea		X		X
USA	X	X	X^1	X

1. Observer States
2. Non-member states with co-operation agreements
3. The EU encourages their member countries join individually
4. Through a Non-Member Partnership Agreement

How Would a Society Living on the Ring be Governed?

Key Points: Should the entire ring be treated as a single piece of property located in "international waters" and governed by a single set of laws, or should the various portions of the ring that cross over national boarders be considered the property of those nations?

Initially, using a Port Authority as a model of governance may be appropriate for the Tethered Ring. A Trust or
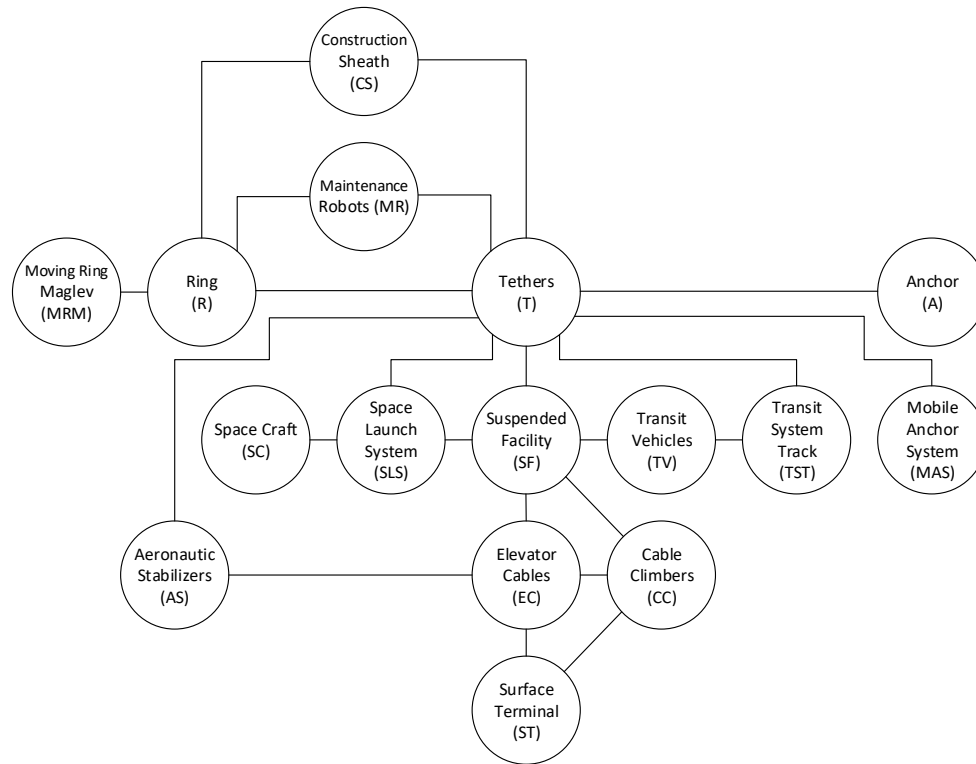
Board would be composed of individuals representative of equity, capitol, or other interests in the ring. Some seats in this Trust may result from treaty or negotiation with Trans-Pacific international parties. Statues and standards would be regulated and administered by this body to ensure effective distribution – and redistribution – of ring assets. As population in the ring grows to accommodate ever-increasing economic activity, additional governing bodies should be allowed to form. Standards set forth by the UNs Port State Control would help ensure a minimum of safety and labor rights.

How does it compare to other proposed space infrastructures?

Key Points: How do you benchmark a space access infrastructure idea?

	Modular Space Station	Tethered Ring	Space Elevator
Delta-V to V_esc from Structure	0.11 km/s	10.7 km/s	~0 km/s
Avg Launch-Mass for Construction	419,455 kg [ref]	0 kg	Varies wildly by concept
Average TRL of sub-systems and components	TRL 9	TRL TBD	~TRL 3
Scientific Applications	Microgravity research, propulsion research (VASMIR), life science.		
Economic Applications	Standardized lab bays enabling research in biomed, material science, robotics, and agriculture. Very limited Space tourism. Hosting commercial prototypes (Made4space 3D printer, Bigelow Aerospace's BEAM module).		

Basic Technical Elements and Their Interconnections

Construction Sheath (CS)

Maintenance Robots (MR)

Moving Ring Maglev (MRM)

Ring (R)

Tethers (T)

Anchor (A)

Space Craft (SC)

Space Launch System (SLS)

Suspended Facility (SF)

Transit Vehicles (TV)

Transit System Track (TST)

Mobile Anchor System (MAS)

Aeronautic Stabilizers (AS)

Elevator Cables (EC)

Cable Climbers (CC)

Surface Terminal (ST)

References

Aerospace-Technology.com. (2014, November 13). *The most powerful commercial jet engines*. Retrieved from Aerospace-Technology.com: http://www.aerospace-technology.com/features/featurethe-most-powerful-commercial-jet-engines-4434003/

Airspace. (2017, 5 31). Retrieved from Wikipedia: https://en.wikipedia.org/wiki/Airspace

Ausic, P. (2014, Sept 24th). *Will More Seats Help the Airbus A380 Pay Back Its Development Cost?* Retrieved from 247WallSt.com: http://247wallst.com/aerospace-defense/2014/09/24/will-more-seats-help-the-airbus-a380-pay-back-its-development-cost/

Chupp, R. E. (2007). Turbine Science and Technology - Turbomachinery Clearance Control. *NASA Technical Report Server*, 9.

Cronvich, L. L. (1983). Missile Aerodtnamics. *John Hopkins APL Technical Digest, 4*(3), 176. Retrieved 8 25, 2017, from http://www.jhuapl.edu/techdigest/views/pdfs/V04_N3_1983/V4_N3_1983_Cronvich.pdf

Digital Dutch. (2017, 8 24). *1976 Standard Atmosphere Calculator*. Retrieved from Digital Dutch: https://www.digitaldutch.com/atmoscalc/table.htm

Dodson, B. (2012, September 3rd). *Wood pulp extract stronger than carbon fiber or Kevlar*. Retrieved from New Atlas: http://newatlas.com/cellulose-nanocrystals-stronger-carbon-fiber-kevlar/23959/

dotancohen. (2017, 12 27). *Space Exploration beta*. Retrieved from Stack Exchange: https://space.stackexchange.com/questions/88/total-mass-sent-into-orbit-over-all-history

Douglas, E. (2009, March 13). *Next-gen Of Flywheel Energy Storage*. Retrieved from Product Design and Development (via Wayback Machine): https://web.archive.org/web/20100710052927/http://www.pddnet.com/article-next-gen-of-flywheel-energy-storage/

Douglass, M. R. (2003). DMD reliability: a MEMS success story. *Society of Photo-Optical Instrumentation Engineers (SPIE) Proceedings, 4980*, 1.

Frank, K. (2017, 5 17). *Global Cities*. Retrieved from Knight Frank: http://www.knightfrank.com/globalcities/download.aspx

Harley NB, C. B. (1980). *Polonium-210: a questionable risk factor in smoking related carcinogenesis. Banbury Report 3: a safe cigarette? p. 93-104.* Cold Spring Harbor: Cold Spring Harbor Laboratory.

Harwood, W. (2014, August 27). *NASA commits to $7 billion mega rocket, 2018 debut*. Retrieved from CBS News: http://www.cbsnews.com/news/nasa-commits-to-heavy-lift-mega-rocket/

Hon Regina Ip, A. C.-l. (2015, April 22). LCQ7: Financial arrangement of the three-runway system project at Hong Kong International Airport. Retrieved from http://www.info.gov.hk/gia/general/201504/22/P201504210517.htm

Hsu, J. (2011, April 11). *Total Cost of NASA's Space Shuttle Program: Nearly $200 Billion*. Retrieved from Space on NBCNews.com: http://www.nbcnews.com/id/42543397/ns/technology_and_science-space/t/total-cost-nasas-space-shuttle-program-nearly-billion#.WPhUYYWcFaT

Industrial Batteries Market by type (Lead-Acid, Nickel-Based, Lithium-Based), end-user industry (Telecom & Data Communication, Uninterruptible Power Supply (UPS)/Backup, Industrial Equipment, Grid-Level Energy Storage), and region - Global Forecast to 202. (n.d.).

Koukourakis, M. I., Giatromanolaki, A., Zois, C. E., Kalamida, D., Pouliliou, S., Karagounis, I. V., . . . Claridge, T. D. (n.d.).

Koukourakis, M. I., Giatromanolaki, A., Zois, C. E., Kalamida, D., Pouliliou, S., Karagounis, I. V., . . . Claridge, T. D.-0.-1. (n.d.). Normal tissue radioprotection by amifostine via Warburg-type effects. *Scientific Reports. 6. ISSN 2045-2322. PMC 4978965 . PMID 27507219*.

Krebs, G. (2017, 12 27). *Chronology of Space Launches*. Retrieved from Gunter's Space page: http://space.skyrocket.de/directories/chronology.htm

Krebs, G. D. (2017, April 10). *Orbital Launches of 2016*. Retrieved from Gunter's Space Page: http://space.skyrocket.de/doc_chr/lau2016.htm

Lacey, S. (2016, June 28). *Stem CTO: Lithium-Ion Battery Prices Fell 70% in the Last 18 Months*. Retrieved from Greentech Media: https://www.greentechmedia.com/articles/read/stem-cto-weve-seen-battery-prices-fall-70-in-the-last-18-months#gs.jEdwWFo

Lam, M. (2017, 10 26). *Flywheels*. Retrieved from Atomic Rockets: http://www.projectrho.com/public_html/rocket/basicdesign.php#id--Power_Storage--Flywheels

Larsonneur, R. (2009). Principal of Active Magnetic Suspension. In G. S. Maslen, *Magnetic Bearings* (p. 27).

Markets and Markets. (2016, September). *Industrial Batteries Market by type (Lead-Acid, Nickel-Based, Lithium-Based) - Global Forecast to 2021*. Retrieved from Markets and Markets: http://www.marketsandmarkets.com/Market-Reports/industrial-batteries-market-36754108.html?gclid=CjwKCAjwj8bPBRBiEiwASlFLFR3CQ5rG7hxduyNX0PFM2I9dIruoCFgzrq8EOg5NjziGRj6DAs5IRxoCXtsQAvD_BwE

Martin, P. K. (2013). *NASA'S Efforts to Maximize Research on the International Space Station.* Office of Audits, Office of the Inspector General. Retrieved from https://oig.nasa.gov/audits/reports/FY13/IG-13-019.pdf

Maslen, A. T. (2009). Hardware Components. In E. H. Gerhard Schweitzer, *Magnetic Bearings: Theory, Design, and Applications* (p. 95). Springer-Verlag Berlin Heidelberg.

McCurry, J. (2015, April 21). *Japan's maglev train breaks world speed record with 600km/h test run*. Retrieved from The Guardian: https://www.theguardian.com/world/2015/apr/21/japans-maglev-train-notches-up-new-world-speed-record-in-test-run

NOAA. (2016, November 6). *Aurora*. Retrieved from National Oceanic and Atmospheric Administration : http://www.swpc.noaa.gov/phenomena/aurora

NOAA. (2016, November 6). *Galactic Cosmic Rays*. Retrieved from National Oceanic and Atmospheric Administration: http://www.swpc.noaa.gov/phenomena/galactic-cosmic-rays

NOAA. (2016, November 6). *Geomagnetic Storms*. Retrieved from National Oceanic and Atmospheric Administration: http://www.swpc.noaa.gov/phenomena/geomagnetic-storms

O'Kane, S. (2015, November 24). *Neil deGrasse Tyson: 'The delusion is thinking that SpaceX is going to lead the space frontier'*. Retrieved from The Verge: https://www.theverge.com/2015/11/24/9792854/neil-degrasse-tyson-interview-delusions-of-space-enthusiasts

Panasonic. (2016, January 25). *Lithium Ion NCR18650B*. Retrieved from Wayback Machine: https://web.archive.org/web/20150722042425/http://industrial.panasonic.com/lecs/www-data/pdf2/ACA4000/ACA4000CE417.pdf

Pinkfroot Ltd. (2017, 5 11). *planefinder.net*. Retrieved from http://visual.ly/airline-route-visualisation?view=true

Selding, P. B. (2016, May 2). *SpaceX New Price Chart Illustrates Performance Cost of Reusability*. Retrieved from SpaceNews: http://spacenews.com/spacexs-new-price-chart-illustrates-performance-cost-of-reusability/

Snibbe, K. (2017, March 14). *The dream of high-speed rail in California is taking longer and costing more*. Retrieved from The Mecury News: http://www.mercurynews.com/2017/03/14/the-dream-of-high-speed-rail-in-california-is-taking-longer-and-costing-more/

Statista. (2017, 5 19). *Revenue of commercial airlines worldwide from 2003 to 2017 (in billion U.S. dollars)*. Retrieved from Statista: https://www.statista.com/statistics/278372/revenue-of-commercial-airlines-worldwide/

The Seattle Times. (2011, September 24th). *Boeing celebrates 787 delivery as program's costs top $32 billion*. Retrieved from TheSeattle Times: http://www.seattletimes.com/business/boeing-celebrates-787-delivery-as-programs-costs-top-32-billion/

TorayCA. (2017, 5 23). Retrieved from http://www.toraycfa.com/pdfs/T1000GDataSheet.pdf

Watson, P. C. (n.d.). Retrieved from http://www.hist-geo-space-sci.net/5/175/2014/

Wentzien, W. C. (1955, April). Winds and Temperatures to Forty Kilometers. *Journal of Meterology*, 161. Retrieved from http://journals.ametsoc.org/doi/pdf/10.1175/1520-0469(1955)012%3C0160%3AWATTFK%3E2.0.CO%3B2

Yiming Chen, S. Z. (2016, September). Computationally Efficient Carrier Integer Ambiguity Resolution in Multiepoch GPS/INS: A Common-Position-Shift Approach. *IEEE Transactions on Control Systems Technology, 24*(5), 1541 - 1556. Retrieved from http://ieeexplore.ieee.org/document/7349142/

Zimmermann, M. B. (2015). *Future Circular Collider (FCC) Study.* Retrieved from APS Physics: http://www.aps.org/units/fip/newsletters/201502/collider.cfm

References

Carlson, P. and Watson, A. A.: Erich Regener and the ionization maximum of the atmosphere, Hist. Geo Space. Sci., 5, 175-182, doi:10.5194/hgss-5-175-2014, 2014.

Dayananda, Mathes A., "Correlation Studies of Cosmic Ray Flux and Atmospheric and Space Weather." Dissertation, Georgia State University, 2013. http://scholarworks.gsu.edu/phy_astr_diss/65

Aviation Safety, Boeing Commercial Airplanes. (August 2014). *Statistical Summary of Commercial Jet Airplane Accidents, Worldwide Operations | 1959 – 2013*. Settle, WA: Aviation Safety, Boeing Commercial Airplanes. Retrieved from http://www.boeing.com/resources/boeingdotcom/company/about_bca/pdf/statsum.pdf

Birch, P. (1982). Orbital Ring Systems and Jacob's Ladders. *Journal of the British Interplanetary Society*.

Bowers, S. (2007, June 8). *Space Fountains and Orbital Rings*. Retrieved from Encyclopedia Galactica: http://www.orionsarm.com/eg-article/4851dd2124500

Flight Tracker Overview. (2015, August 22). Retrieved from Flight Aware: http://flightaware.com/live/

Hall, C. M. (1889-04-02). *US Patent No. US400664 (A), Process of Reducing Aluminum from its Fluoride Salts by Electrolys.*

ISEC. (2013, April). *ISEC Releases Space Elevator Concept of Operations Report*. Retrieved from http://spaceref.com/space-elevator/isec-releases-space-elevator-concept-of-operations-report.html#Comments or http://www.isec.org/index.php/store/isec-reports

Knapman, J. (n.d.). STABILITY OF THE SPACE CABLE. *IAC-06-D4.3.04*.

Lofstrom, K. (1985). The Launch Loop. *AIAA*.

Roberts, J. (2015). *Global Cities Skyscrapers 2015.*

Dodson, Brian. "Wood pulp extract stronger than carbon fiber or Kevlar." *Gizmag.[Online]* 3.9.2012 (2012).

"Geomagnetic Storms." *Geomagnetic Storms*. NOAA / NWS Space Weather Prediction Center, n.d. Web. 11 Mar. 2017. <http://www.swpc.noaa.gov/phenomena/geomagnetic-storms>.

Neyer, F. J., Mund, M., Zimmermann, J. and Wrzus, C. (2014), Personality-Relationship Transactions Revisited. J Pers, 82: 539–550. doi:10.1111/jopy.12063

Anna Antinori, Olivia L. Carter, Luke D. Smillie, Seeing it both ways: Openness to experience and binocular rivalry suppression, In Journal of Research in Personality, Volume 68, 2017, Pages 15-22, ISSN 0092-6566, https://doi.org/10.1016/j.jrp.2017.03.005.
(http://www.sciencedirect.com/science/article/pii/S0092656617300338)