Fisher Space Systems

Space Track Launch System
Tower

by
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(Note: Updated from the original concept paper titled Space Track Launch System - Tower, Copyright 2011. Major updates are in section 2.h, section 3, and section 4 beginning on page 15.)

1. Introduction

The Space Track Launch System (STLS) is a two stage launch system. The first stage is a tall tower with rotating ribbons (Fisher, J.F., 2007). The tower (figure 1) is from 100-150 km in height. At the top of the tower, there is a rotating truss which supports four ribbons (two ribbons from each end of the truss) made of high strength fiber composites. Counterweights (CW) (Fisher, J.F., 2010) are attached to the end of each ribbon.

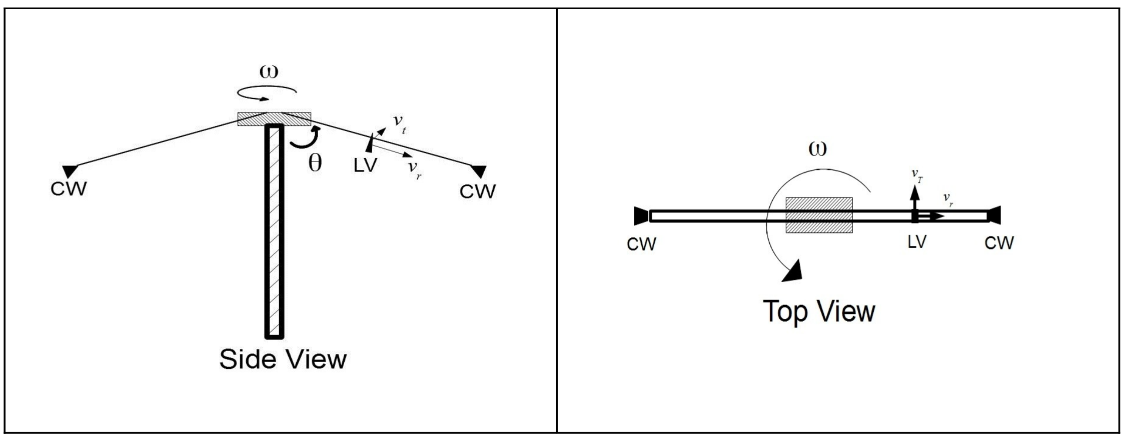

Figure 1. Space Track Launch System

The second stage is a liquid fueled launch vehicle (LV) designed to launch from the STLS (Fisher, J.F., 2009). The launch vehicle attaches to an ejector which is attached to an overcarriage (Fisher, J.F., 2010). The overcarriage has four tapered wheels which rest on top of the ribbon. The overcarriage and launch vehicle travel down the ribbon and are accelerated by the centrifugal force resulting from the distance from the axis of rotation and by the contact force (Coriolis force) provided by the rotating ribbon. At a predetermined point along the ribbon, the ejector fires and the launch vehicle detaches from the overcarriage and ribbon. The liquid propellant rocket engines ignite and the second stage proceeds into orbit. The overcarriage returns to the launch site to be refurbished and reused.

The system is unique for several reasons. First, the first stage is all electric and can be used up to three times a day. The electric motors restore rotational kinetic energy to the ribbons in approximately 8 hours. Second, the launch vehicle launches from a point along the ribbon as opposed to being released from the end of the ribbon as in previous concepts. For a 80 ton launch vehicle, launching from the end of the ribbon produces a compressive shock wave that will destroy the ribbon and damage the tower. When launched from the middle of the ribbon, the additional force on the ribbon is several orders of magnitude less than the tension in the ribbon. As such, the impulse from launch is absorbed by the ribbon and counterweights and the stress on the tower is greatly reduced. Finally, the second stage launch vehicle and overcarriage are reusable making the Space Track Launch System a completely reusable launch system. This paper presents an initial design for the tower beginning with the load at the top of the tower.

2. Tower Load

The load (figure 2) at the top of the tower at startup will consist of the mass of the counterweights, the ribbons, the ribbon support structure, the tower truss, the cable support columns, the turntable and gear assembly, the motors, the research station, the elevators, the guy wires, and a tower interface ring. During operation, the tower load will increase due to the mass of the 2^{nd} stage launch vehicle. The basic tower design is a second generation system. The first generation system will be approximately 100 km high and the load at the top will probably be lower than the final load for a 150 km high tower. But, to ensure scalability and to help determine the direction for technology development, the load at the top of the 2^{nd} generation systems will be assessed. The mass analysis begins with the ribbon support structure.

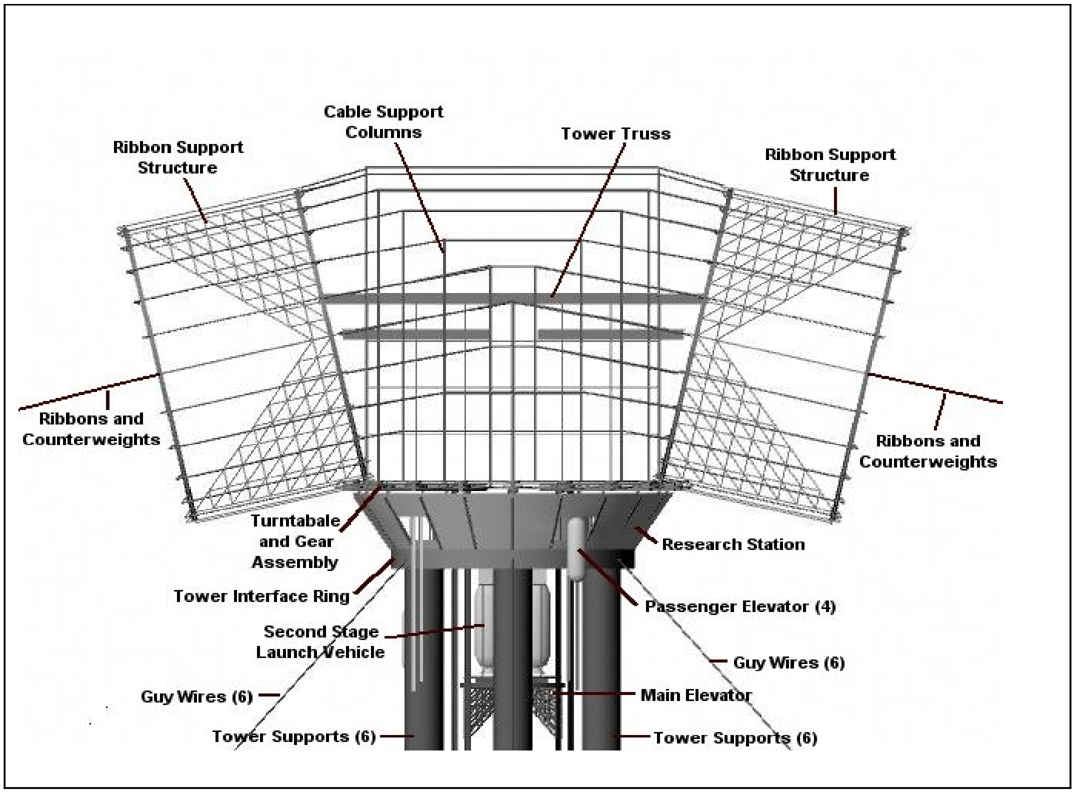

Figure 2. Tower Load

2.a. Ribbon Support Structure

As shown in figure 2 above, there are two ribbon support structures. Each structure supports two ribbons and 80 counterweights (Fisher, J.F., 2010). To estimate the mass, the physical properties of a new composite material known as M5® (M5®, 2006) will be used. M5® has a modulus of elasticity of 330 GPa, a tensile strength of 10 GPa, a compression strength of 2 GPa, and a density of 1700 kg/m^3. The mass for a single structure will first be determined and then doubled for the total load on the turntable.

The mass for a 400 km long carbon nanotube ribbon with 200 tons of counterweights rotating at an angle of 77^o from the vertical is approximately 3.9 x 10^5 kg. Together, the counterweights and ribbons exert a force of 1.7 x 10^7 N on the ribbon support structure. The ribbon support structure is approximately 32 m in diameter and consist of six ‘wings’ attached to the ribbon support ring and frame. There are two ribbons. Therefore, each ribbon exerts a force of 8.3 x 10^6 N on three wings. As shown in figure 3 below, each ribbon is wrapped around a rectangular beam which is 1.5 m wide and 0.1 m thick.

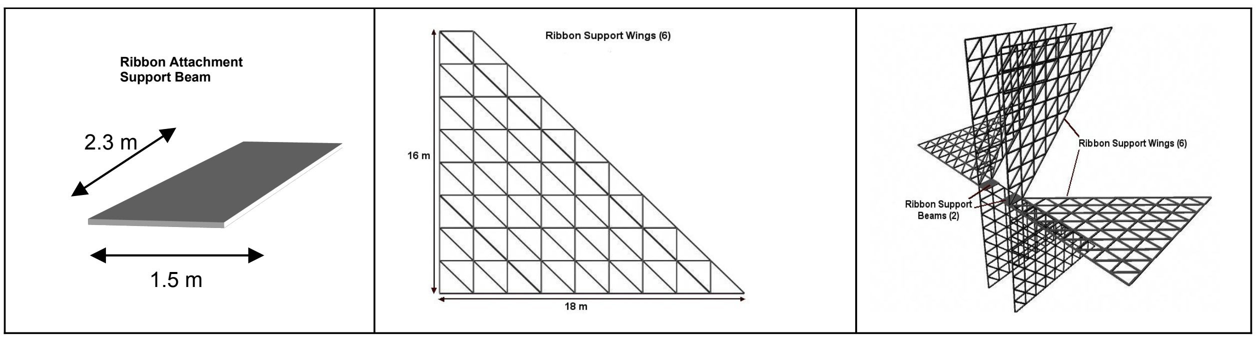

Figure 3. Ribbon Support Structure

The beam is modeled as a cantilever with uniform load (Shigley, L. and Mitchell, L., 1983, p.805). The maximum deflection is given by,

$$y_{\max} = -\frac{wl^4}{8EI} \qquad (1)$$

where w is the load per unit length equal to 8.3 x 10^6 N/m, l is the length to be determined, E is the modulus of elasticity for M5® equal to 3.3 x 10^{11} N/m^2, and I is the area moment of inertia. For a rectangular cross section, the area moment of inertia, I, is given as,

$$I = \frac{bh^3}{12} \qquad (2)$$

where b is the thickness equal to 0.1 m and h is the length to be determined.

Solving equation 1 above for the area moment of inertia, using a maximum deflection of 1 mm and a safety factor of 6, gives the area moment of inertia, I, as 9.5 x 10^{-2} m^4 which in turn gives the length as approximately 2.3 m. Therefore, the volume of the beam is approximately 0.34 m^3 giving it a mass of 574.0 kg.

As shown in figure 3, the rectangular beam is attached to the tip of three wing shaped trusses. Each wing tip supports a lateral load of 2.8 x 10^6 N. This load is transferred uniformly to the base of the wing by the columns, beams, and struts of the wing shaped truss. The base of the wing is connected to two ribbon support rings and a frame. Using the compression strength of M5® with a safety factor of six gives the mass of a 2 m beam or column of 28.2 kg. There are 44, 2 m beams and 44, 2 m columns for a total mass of 2,481.6 kg. There are 44, 2.8 m struts for a total mass of 1,754.8 kg. The total mass of one wing is 4,236.4 kg. There are three wings for a total mass of 12,709.1 kg. The wing tips are attached to the ribbon support beam which has a mass of 574.0 kg giving a total estimated mass of 13,284 kg for one ribbon support structure. There are two ribbons and therefore, two support structures for a total mass of 26,568 kg. The masses are summarized in table I below.

Subsystem	Mass
Beams & Columns	2.5 x 10^3 kg
Wing Struts	1.8 x 10^3 kg
Subtotal	4.3 x 10^3 kg
X 3	1.3 x 10^4 kg
Ribbon Beam	5.7 x 10^2 kg
Subtotal	1.4 x 10^4 kg
X 2	2.7 x 10^4 kg

Table I. Ribbon Support Structure

2.b. Ribbon Support Ring and Frame

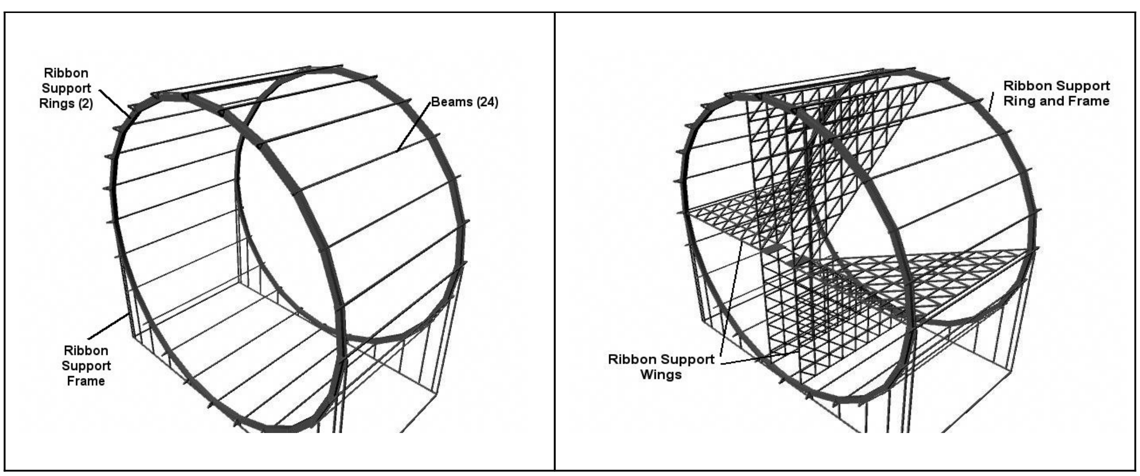

Figure 4. Ribbon Support Ring and Frame

The ribbon support structure is attached to two 32 m diameter rings. This diameter was chosen to accommodate a variety of second stage launch vehicles (Fisher, J.F., 2009). The ribbon support ring and frame are shown in figure 4 above.

The rings are supported by 24 beams. Each beam has silicon carbide bearings which allow the whole assembly to rotate. The assembly must rotate from 0 to 90 degrees in an effort to keep the gravitational and Coriolis acceleration forces perpendicular to the ribbon and to be in position to restore rotational kinetic energy after launch. Each bearing supports a load of 3.5 x 10^5 N. The properties of silicon carbide are such that the mass of the bearings are insignificant compared to the rest of the structure. The bearings are spaced approximately 4.2 m apart on the ribbon support ring. The 4.2 m section of ring is modeled as a rectangular beam with simple support and uniform load (Shigley, L. and Mitchell, L., 1983, p. 807).

The maximum deflection is given by,

$$y_{\max} = -\frac{5wl^4}{384EI} \qquad (3)$$

where the load per unit length, w, is 8.3 x 10^4 N/m, the distance between supports, l, is 4.2 m, and the modulus of elasticity, E, is 5.5 x 10^{10} N/m^2 (safety factor of 6). With a maximum deflection of 1 mm, the area moment of inertia is 6.1 x 10^{-3} m^4. From equation 2 above and with a width, b, of 0.5 m, the height, h, is approximately 0.5 m. This gives the volume of one ring as 26.9 m^3 and therefore, a mass of 4.6 x 10^4 kg, or for two rings, 9.2 x 10^4 kg.

The rings are supported by 24 beams. Each beam supports a load of 6.9 x 10^5 N. A torsion stress analysis shows that an area of approximately 3.6 x 10^{-3} m^2 per beam is sufficient to handle this load. Each beam is 18 m long which result in a mass of approximately 110.2 kg. There are 24 beams for a total mass of 2,643.8 kg.

The rings and beams are supported by a frame. The frame is made of the same size area as the beam but of differing length. The columns are 16.6 m, 12.4 m, 8.4 m, 5.0 m, 2.3 m, and 0.7 m in length. There are 4 columns of each length. The beams that make up the frame are 33.1 m and 18 m in length. The total mass of the frame is approximately 1,734.6 kg. The total mass of the ribbon support ring and frame is approximately 9.6 x 10^4 kg and is summarized in table II below.

Subsystem	**Mass**
Ribbon Support Rings	9.2 x 10^4 kg
Ring Support Beams	2.6 x 10^3 kg
Ring Support Frame	1.7 x 10^3 kg
Total	9.6 x 10^4 kg

Table II. Ribbon Support Ring and Frame

2.c. Ribbon Support Truss

As shown in figure 5 below, the ribbon support truss is similar to a standard box beam truss design. The ribbon support truss attaches to the ribbon support ring and frame at 5 attachment points located at the base of the frame. The ribbon support ring is attached to its counterpart via high tension CNT cables attached to the ring support beams. The mass of the cables is insignificant when compared to the rest of the structure and therefore, will not be considered in the mass analysis. The ribbon support ring and frame is titled 13^{o} from the truss to support the ribbon at the required angle for launch.

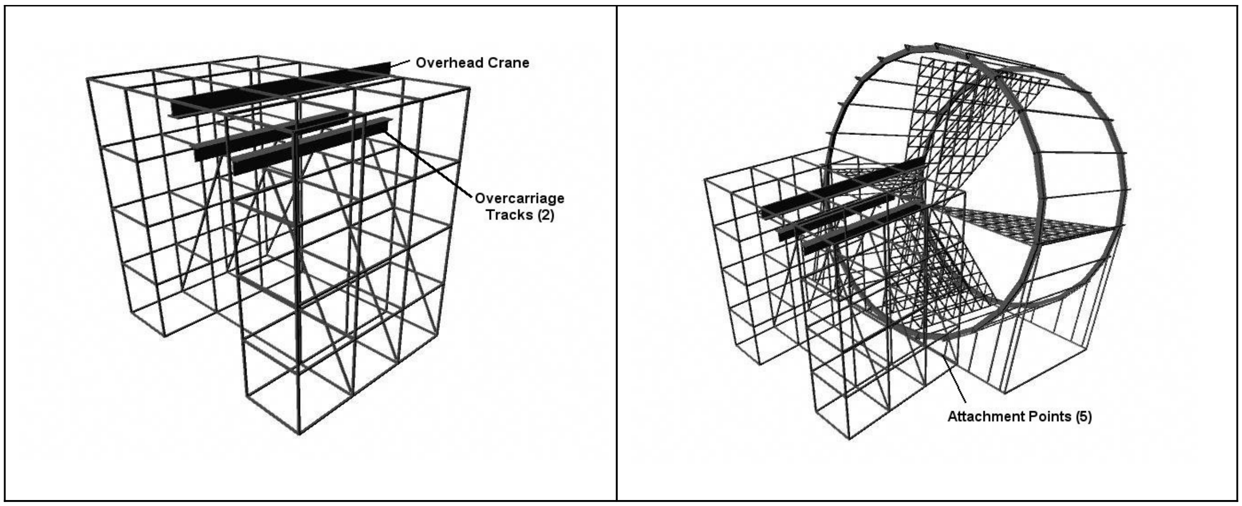

Figure 5. Ribbon Support Truss

The ribbon support truss is made of 120, 5 m beams, 64, 5 m columns, 6, 17.3 m struts, 2, 15 m overcarriage tracks, 2, 15 m overcarriage beams, 1, 20 m overhead crane track, and 1, 20 m overhead crane beam. The beams, columns, and struts each have a cross sectional area of 3.6 x 10^{-3} m^2. The total mass is therefore, 6.3 x 10^3 kg. The tracks and track beams each have a cross sectional area of 0.1 m^2. The total mass is 1.7 x 10^4 kg. The total mass of the ribbon support truss is approximately 2.3 x 10^4 kg and is summarized in table III below.

Subsystem	Mass (kg)
Beams, Columns, & Struts	6.3 x 10^3 kg
Tracks & Track Beams	1.7 x 10^4 kg
Total	2.3 x 10^4 kg

Table III. Ribbon Support Truss

2.d. Cable Support Columns

To distribute the load around the turntable, the ribbon support rings are connected together via high tension cables which are held in place by towers connected to the turntable (figure 6). There are 24 towers evenly spaced around the turntable. First, consider the 10 towers at the ends of the ribbon support truss, 5 towers at each end. The bottom of the ring support frame is connected directly with the tower truss and turntable at 5 points on its base. The top 5 points of the ring are connected to the top 5 points of the opposite ring via cables. The cables are held in place by the 10 towers which are connected to the turntable.

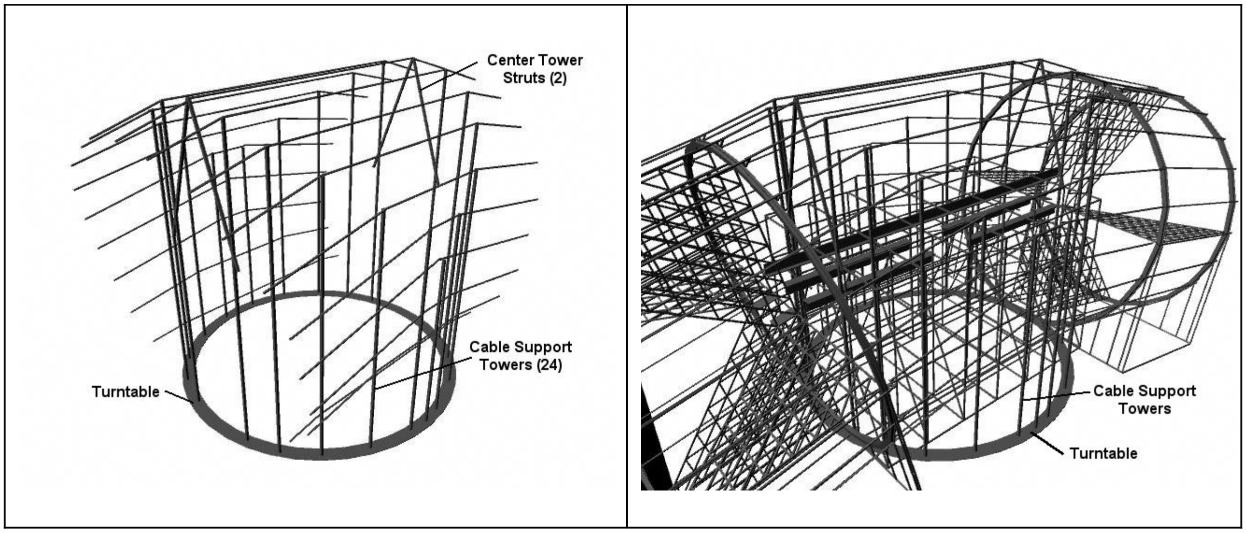

Figure 6. Cable Supports and Turntable

The load on the center tower is 1/24th of the load from one ribbon support ring or approximately 6.9 x 10^5 N. To make way for the 2nd stage launch vehicle, this load is divided by two support struts each 13.9 m long connected to the top of the ribbon support truss. Each strut, therefore, has a load of 3.4 x 10^5 N. The critical load is 2.1 x 10^6 N for a safety factor of six. The strut will be modeled as an Euler column. The critical load for an Euler column is given by (Shigley, L. and Mitchell, L., 1983, p. 145),

$$P_{cr} = \frac{\pi^2 EI}{l^2} \quad (4)$$

where P_{cr} is the critical load equal to 2.1 x 10^6 N, E is the modulus of elasticity for M5® equal to 3.3 x 10^{11} N/m^2, I is the area moment of inertia to be determined, and l is the length of the column equal to 13.9 m. Solving equation 4 for the area moment of inertia gives I equal to 1.3 x 10^{-4} m^5. The area moment of inertia for a rectangular strut is given by equation 2 above. For a hollow rectangular beam, $b_o = h_o$ = 0.25 m and $b_i = h_i$ = 0.22 m giving a wall thickness of 1.5 mm and a cross sectional area of 0.014 m^2. Further analysis shows that this is indeed an Euler column. The mass of one strut is 333.2 kg and for all four struts the mass is 1,332.7 kg.

The remaining eight towers attached to top of the ribbon support truss are of different lengths. Four of the towers are 32.8 m and four are 31.1 m in length. The critical load for each tower is 2.1 x 10^6 N. From equation 4 above, the area moment of inertia, I, is 6.9 x 10^{-4} m^4 for the tallest tower. For a hollow rectangular column, $b_o = h_o$ =

0.32 and $b_i = h_i = 0.22$ m with a wall thickness of 5.0 mm. Analysis shows that this is an Euler column. Therefore, the mass of the 32.8 m column is 3,011.0 kg. There are four of these columns for a total mass of 12,044.0 kg. Using the same area for the 31.1 m column gives its mass at 2,855.0 kg and with four towers, 11,420.0 kg.

The remaining 14 towers are attached to the turntable. Each tower supports twice the load with an upper cable and a lower cable. Using a safety factor of 6, the critical load is 8.4×10^6 N for each tower. The tallest of these last 14 towers is 28.9 m. Using equation 4 above, the area moment of inertia is 2.2×10^{-3} m^4. This gives $b_o = h_o =$ 0.5 m and $b_i = h_i = 0.45$ m. The area is 4.8×10^{-2} m^2. There are four towers 28.9 m high, four towers 25.4 m high, four towers 21.4 m high, and two towers 16.9 m high. Using the same area for all towers gives a mass of 9,337.4 kg, 8,208.4 kg, 6,896.3 kg, and 2,731.0 kg respectively. The total mass for all towers is 51,970 kg and is summarized in table IV below.

Subsystem	**Mass**
4 Struts @ 13.9 m	1.3×10^3 kg
4 Col @ 32.8 m	1.2×10^4 kg
4 Col @ 31.1 m	1.1×10^4 kg
4 Col @ 28.9 m	9.3×10^3 kg
4 Col @ 25.4 m	8.2×10^3 kg
4 Col @ 21.4 m	6.9×10^3 kg
2 Col @ 16.9 m	2.7×10^3 kg
Total	5.1×10^4 kg

Table IV. Cable Support Columns

2.e. Turntable and Gears

The turntable consists of an upper rotating table and a lower support table. The upper rotating table is held into position by the gear assembly. There are 20 identical gear sets that make up the gear assembly. The total load on the upper rotating table is 1.2×10^7 N and is summarized in table V below.

2.e.1 Turntable

As shown in figure 6 above, to accommodate the ribbon support structure, the ring and frame, the truss, and the cable support columns, the upper table has an inner diameter of 30 m and an outer diameter of 33 m. Assuming a uniform load distribution with bearings centered on the table at a radius of 15.75 m, the load per unit length, w, is approximately 1.2×10^5 N/m. The table is modeled as a simple support with uniform load distribution with 40 bearings spaced 2.5 m apart. Using equations 2 and 3 above with a safety factor of 6, the table dimensions are outer radius 16.5 m, inner radius 15.0 m, thickness 0.2 m. This gives the upper rotating table a mass of 50,470 kg. The gear assembly supports the lower table at 20 locations. Therefore, it has the same inner and outer radius but a thickness of 0.53 m giving it a mass of 133,745 kg.

Subsystem	Mass (kg)
Ribbon Support Structure	2.7 x 10^4 kg
Ring and Frame	9.6 x 10^4 kg
Ribbon Support Truss	2.3 x 10^4 kg
Ribbon Mass	1.9 x 10^5 kg
Counterweight	2.0 x 10^5 kg
Sub Total	5.4 x 10^5 kg
x 2	1.1 x 10^6 kg
2^{nd} Stage Launch Vehicle	1.0 x 10^5 kg
Cable Support Columns	5.1 x 10^4 kg
Mass Total	1.2 x 10^6 kg
Load = Mass x 9.81	1.2 x 10^7 N

Table V. Load on Upper Table

2.e.2 Gears

The upper rotating table is held into position by the gear assembly. The gear assembly is shown in figure 7 below. There are 20 identical gear sets that make up the gear assembly. The gear assembly is driven by a power divider ring that is in turn driven by four 6,700 hp high temperature superconducting motors (American Superconductor, 2010). Each motor has a mass of 25 metric tons.

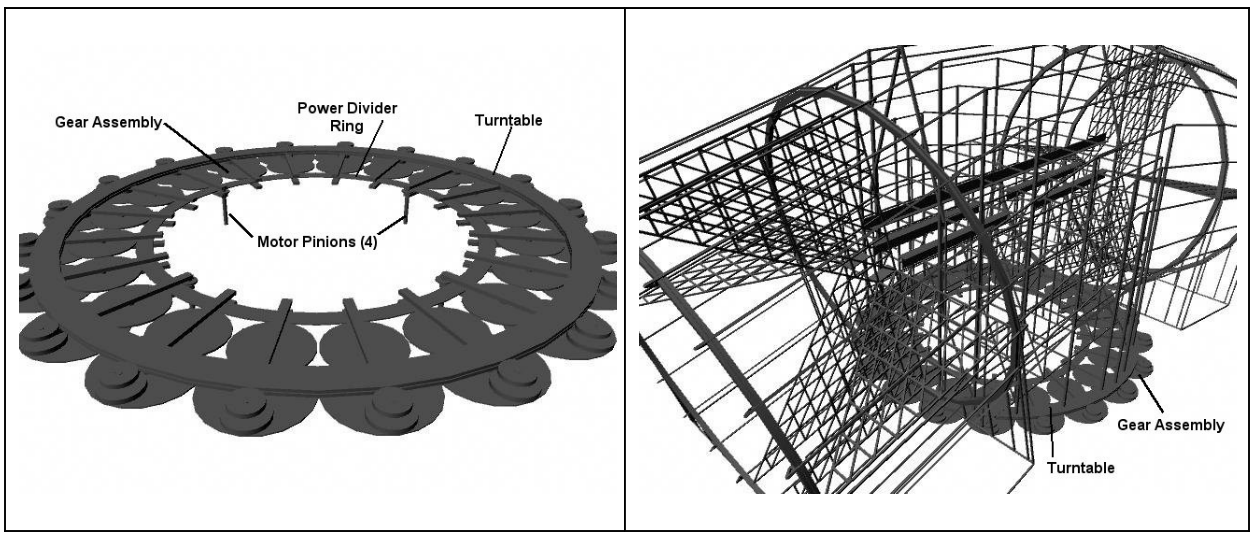

Figure 7. Turntable and Gear Assembly

The HTS motors produce their maximum torque at 230 rpm. The power divider ring is required to shift from the shaft speed produced by the HTS motor down to the rotation rate of the turntable (approximately 0.1 rpm). If not for the power divider ring, the face width of the gears would be to wide resulting in massive gears. The power transferred from the HTS motors to the power divider ring is approximately 26,800 hp.

The power transferred from the ring to each 1st stage gear is approximately 1,340 hp. The mass of the gears is determined using the procedures outline in the referenced material (Shigley, L. and Mitchell, L., 1983, p. 606).

The diameters for the gears are determined using standard procedure when determining gear sizes from one rotation rate to another. In addition, the gears have to fit within the available space. Starting with the turntable and working back, the HTS motor pinion is determined to be 0.9 m in diameter. The load transferred to the power divider ring is approximately 4.8 x 10^5 N resulting in a face width of 10.0 cm. The HTS motor pinion withstands the heaviest load transfer of all the gears. Therefore, a torsional analysis was performed on the HTS motor pinion and found to be well within the parameters of the M5® material. Therefore, the mass of the HTS motor pinion is approximately 101.1 kg. Together, the HTS motor and pinion have a mass of 25,101 kg. There are four HTS motors and pinions resulting in a combined mass of 100,404 kg.

To match up with the HTS motor pinion, the power divider ring also has a face width of 10 cm. The ring has an inner diameter of 21.0 m and an outer diameter of 23.0 m. This gives the power divider ring a mass of 11,750 kg.

The outer diameter surface of the power divider ring is matched to the 1st stage gear. Therefore, the 1st stage gear has a face width of 10 cm. The 1st stage gear has a diameter of 4.0 m and a mass of 2,136 kg. The 1st stage pinion is mounted to the first stage gear and has a face width of 5.0 cm and a diameter of 0.5 m. This gives the 1st stage pinion a mass of 17 kg. Together, the 1st stage gear and pinion have a mass of 2,153 kg.

The 1st stage pinion is matched to the 2nd stage gear. Therefore, its face width is also 5.0 cm. The diameter of the 2nd stage gear is 5.0 m giving it a mass of 1,669 kg. The face width of the 2nd stage pinion is also 5.0 cm but its diameter is 1.0 m giving it a mass of 67 kg. Together, the 2nd stage gear and pinion have a mass of 1,736 kg.

A transfer gear is required to transfer the power from under the lower support table to the upper rotating table. The transfer gear has a lower gear connected to an upper gear via a drive shaft. The diameter of the lower gear is 2.0 m with a face width of 5.0 cm and the diameter of the upper gear is 1.5 m with a face width of 20.0 cm. The 20.0 cm face width is required to match the face width of the upper table. The masses of the gears are 267 kg and 601 kg respectively for a total of 868 kg.

The gears are held into place with upper and lower gear supports. The lower gear support is modeled as a cantilever with an end load. The maximum deflection is given by (Shigley, L. and Mitchell, L., 1983, p.804),

$$y_{\max} = \frac{-Fl^3}{3EI} \qquad (5)$$

where F is the end force equal to 1.2 x 10^4 N, l is the distance from the support to the load equal to 5.0 m, E is the modulus of elasticity for M5® equal to 1.1 x 10^{11} N/m^2 (safety factor of 3), and I is the area moment of inertia for a rectangular beam. For a maximum deflection of 1.0 mm, the dimensions of the lower gear support are 0.5 m wide and 0.2 m thick. This gives the mass of the lower gear support as 1,421 kg. Using the same dimensions for the upper gear support gives the total mass for the two supports as 2,842 kg. The mass of the gear set is 7,599 kg. The total mass of the turntable, the 20 gear sets, the power divider ring, and the HTS pinion is 4.4×10^5 kg and is summarized in table VI below.

2.f. Turntable and Gear Assembly Support

The turntable and gears are supported by 20 braces attached to a load bearing ring. The ring serves as the interface between the rotating structure and the stationary towers (figure 8). Each brace supports a load of 8.1×10^5 N. The braces provide the structure for the research station.

Subsystem	**Mass (kg)**
Upper Rotating Table	5.1×10^4 kg
Lower Support Table	1.3×10^5 kg
HTS Motors & Pinions	1.0×10^5 kg
Power Divider Ring	1.2×10^4 kg
20 Gear Sets	1.5×10^5 kg
Total	4.4×10^5 kg

Table VI. Turntable and Gears

The brace consist of a 6 m horizontal beam, a 6 m vertical column, and an 8.5 m strut. The strut must support a load of 1.1×10^6 N. Modeled as an Euler column (equation 4) with the critical load of 6.6×10^6 N gives the area moment of inertia, I, as 1.5×10^{-4} m^4 and an area of 4.2×10^{-2} m^2 for a 20.0 cm square strut. Adding the mass of one beam, one column, and one strut gives the mass of one brace as 1,461 kg. The mass of 20 braces is 2.9×10^4 kg.

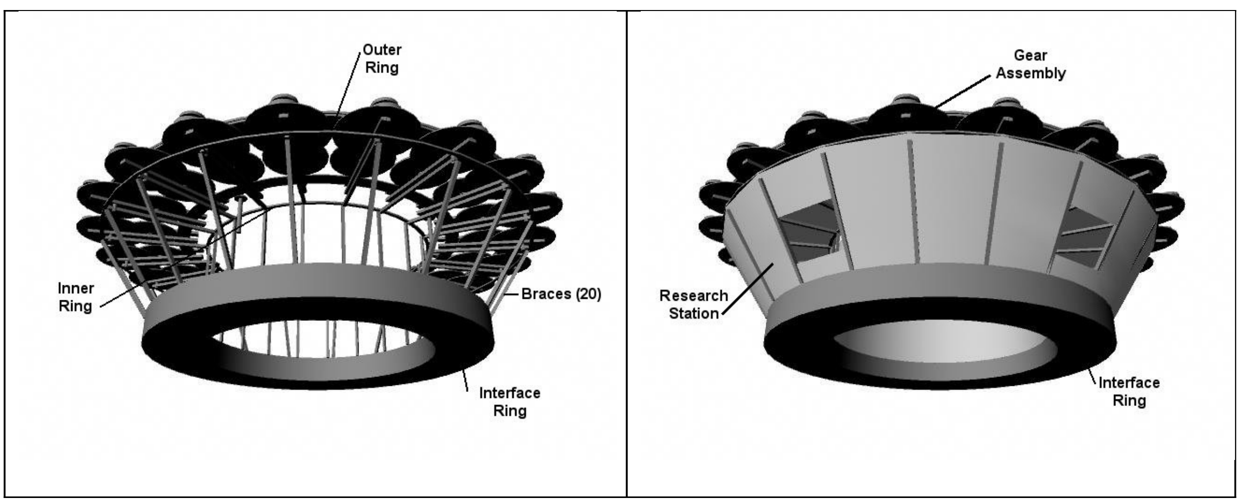

Figure 8. Turntable and Gear Assembly Support

There is an outer ring and an inner ring at the base of the gears to handle the lateral stresses. Both rings are of the same area dimension as the strut. The outer ring in 15.75 m in radius and has a mass of 7.1 x 10^3 kg. The inner ring has a radius of 9.75 m and a mass of 4.4 x 10^3 kg.

The research station is modeled as an inverted truncated cone with a base radius of 15.75 m, a height of 6 m, and a top radius of 9.75 m. The station is hollow through the center to allow passage of the 2nd stage elevator. With a wall thickness of 5 cm, the station has a mass of approximately 1.3 x 10^5 kg. The total mass of the turntable support and gear assembly is 1.7 x 10^5 kg and is summarized in table VII below.

Subsystem	Mass (kg)
20 Braces	2.9 x 10^4 kg
Outer Ring	7.1 x 10^3 kg
Inner Ring	4.4 x 10^3 kg
Research Station	1.3 x 10^5 kg
Total	1.7 x 10^5 kg

Table VII. Turntable and Gear Assembly Support

2.g. Elevators

There are five elevators, one main elevator that services the second stage launch vehicle and four passenger elevators. The main elevator (figure 9) carries the second stage launch vehicle to its launch position at the center of the rotating truss. It also serves as a heavy cargo elevator for the research station. The passenger elevators (figure 10) carry the flight crew and passengers to the research station to transfer to the 2nd stage launch vehicle. The passenger elevators also deliver light cargo and supplies to the research station. All five elevators hang from the top of the tower. Therefore, the elevators add significantly to the load of the tower.

2.g.1. Main Elevator

The overcarriage and second stage launch vehicle, when fueled, has a mass of 100 ton. The elevator consist of the second stage support structure which rest on a rotating table and is lifted into position by two scissor jacks. The jacks rest on a support base which in turn rest on three trusses. The trusses are attached to six carbon nanotube ribbons. Each ribbon has a 15 ton counterweight to counter balance the elevator with load and is driven by a ground based electric motor.

The support structure consists of two 10 m tracks, one meter wide and 10 cm thick. The one meter wide tracks are attached to eight braces. Each brace consist of a 5.0 m beam, a 15.5 m strut, and a 15 m column. The mass of the eight braces and two tracks is approximately 5.1 x 10^3 kg.

The second stage support structure rest on a rotating table and is lifted into position by two scissor jacks. Scissor jacks with lifting capacities of 54 metric ton are commercially available (ECOA Industrial Products, Inc., 2004). Each jack has a shipping mass of approximately 9,435 kg making the total mass about 18,870 kg for the two jacks. Advances in design will most likely reduce this mass significantly, but for an initial mass estimate, 18,870 kg will suffice. The rotating table adds another 13,400 kg making the total mass 32,270 kg for the rotating table and scissor jack assembly.

The scissor jacks rest on a platform base. The platform is modeled as a cantilever with uniform load of 5.0 x 10^3 N/m. This gives the platform a thickness of approximately 5 cm. With a surface area of 64 m^2, the platform base has a mass of approximately 5.4 x 10^3 kg.

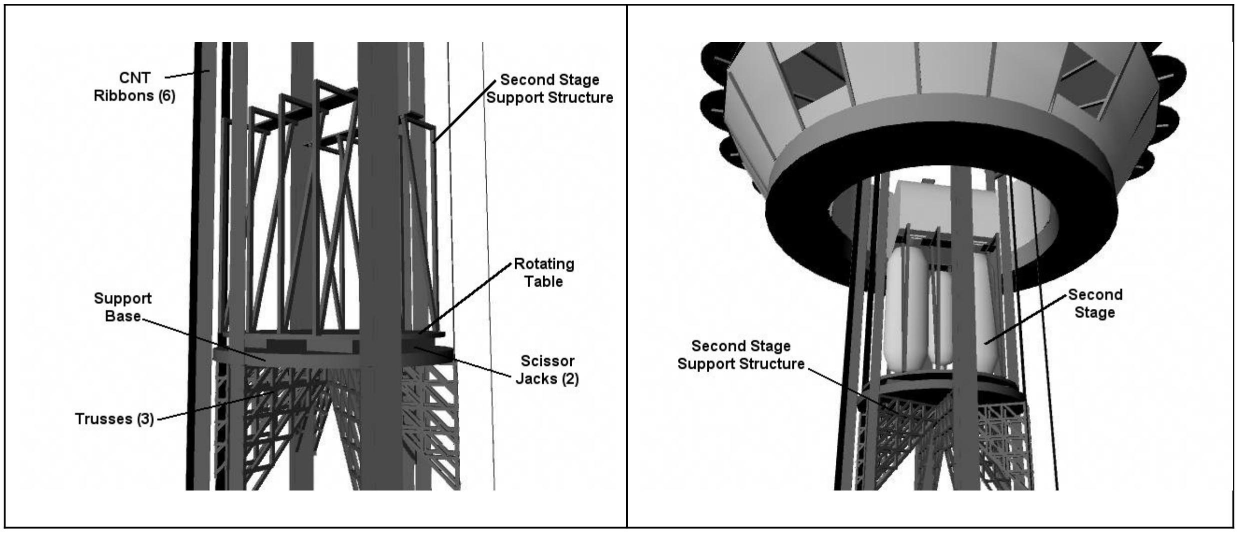

Figure 9. Main Elevator

The platform base is supported by three trusses. Each of the three trusses supports an estimated load of 4.7 x 10^5 N. The truss is 10 m long and therefore, supports a uniform load of 4.7 x 10^4 N/m. Modeled as a simple support with uniform load with one meter separation between column supports, gives a 10 m long top beam an area of 8.5 x 10^{-3} m^2. Using the same area for all the support columns, beams, and struts gives the total mass of one truss as 4.6 x 10^3 kg. There are three trusses for a total mass of 1.4 x 10^4 kg.

The 2^{nd} stage elevator is supported by six CNT ribbons. The total load for the six ribbons is approximately 2.4 x 10^6 N. This includes six 15 ton counterweights which are used to counter balance the 2^{nd} stage launch vehicle. Therefore, each ribbon supports a load of 4.0 x 10^5 N. Maximum tension occurs with the elevator and 2^{nd} stage launch vehicle at the bottom and the counterweights at the top. Using a CNT ribbon with a tensile strength of 25 GPa (safety factor of 6) gives a cross sectional area of 1.8 x 10^{-5} m^2 for the CNT ribbon. Each ribbon is approximately 300 km long (for a complete loop) and there are six ribbons for a total mass of 4.2 x 10^4 kg.

The 2^{nd} stage elevator with counterweights is supported from the top of the tower. The total mass supported is approximately 1.9 x 10^5 kg and is summarized in table VIII below. This represents an additional load of 1.9 x 10^6 N at the top of the tower.

2.g.2 Passenger Elevator

The primary purpose of the passenger elevator (figure 10) is to carry passengers and crew to the 2^{nd} stage launch vehicle. The elevator also takes light cargo and researchers to the research station. The elevator serves as an escape vehicle in the event of a catastrophic failure of the tower. Therefore, it will be designed to separate from the elevator ribbon or station, thrust away from the tower, reenter the atmosphere, and land in a designed recovery area. In essence, the passenger elevator is a small reentry vehicle.

Subsystem	**Mass (kg)**
8 Braces & 2 Tracks	5.1×10^3 kg
Rotating Table & Jacks	3.2×10^4 kg
Platform Base	5.4×10^3 kg
Bridge Trusses	1.4×10^4 kg
Six CNT Ribbons	4.2×10^4 kg
Six Counterweights	9.0×10^4 kg
Total	1.9×10^5 kg

Table VIII. Main Elevator

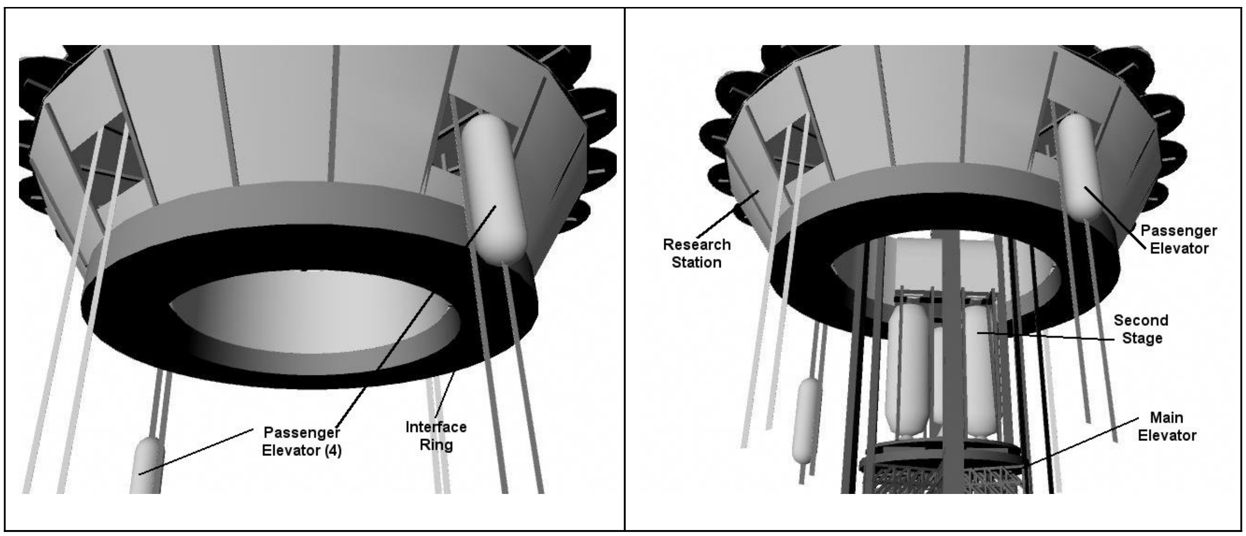

Figure 10. Passenger Elevator

The elevator can carry a maximum of 12 people. The mass estimating database compiled by Georgia Institute of Technology (Rohrschneider, R.R., 2002) is used to estimate the mass of the elevator. The database uses the English system of units to determine the weight of each component. Adding the weight of each component gives a total reentry weight for the elevator. The weight is then converted to the metric system for a total mass.

Several of the components are interrelated and depend on the reentry weight of the vehicle to estimate the component weight. In this case, an “educated guess” is made on the reentry weight and several iterations are done to approximate the total weight. The mass relationships are based on 1970s technology. To account for improvements in component technology, George Tech assigns a technology reduction factor (TRF). Table IX below summarizes the results of the third iteration for the total estimated weight of the passenger elevator. This results in an estimate weight of 11,688 lb or a mass of 5,302 kg.

A counterweight of similar mass is used to counterbalance the passenger elevator. The entire assembly is connected to a CNT ribbon and raised and lowered from the research station by ground based electric motors. The mass of the ribbon is approximately 1,756 kg making the total mass of one passenger elevator an estimated 12,360 kg. With the main elevator and four passenger elevators, the total mass hanging from the research station is approximately 2.4 x 10^5 kg.

Component	Reference	Initial Weight (lb)	TRF (%)	Final Weight (lb)
Fuselage	6	1,165.3	0	1,165.3
Crew Cabin	6	1,252.0	0	1,252.0
Thermal Protection	1	2,120.6	35	1,378.4
Reaction Control	3	159.3	0	159.3
Prime Power	6	352.0	0	352.0
Electrical Control & Distribution	3	705.5	18	578.5
Hydraulics	3	13.3	0	13.3
Surface Control	1	35.9	0	35.9
Avionics	1	2,281.8	50	1,140.9
Environmental Control & Life Sup	3	2,971.1	0	2,971.1
Personnel Equip	3	2,523.0	0	2,523.0
Propellants	1, 2, & 10	118.3	0	118.3
Total		13,698.1	14.67	11,688.0

Table IX. Estimated Weight of the Passenger Elevator

2.h. Torque and Precession

Torque is produce when the electric motors restore rotational kinetic energy to the system and precession occurs due to an unbalanced lateral load at the top. Both torque and precession are controlled by a 100 m section of inflated cylinders called a torque buffer. The torque buffer bleeds off the torque produced by the electric motors during restoration of rotational kinetic energy. Gyroscopic stabilization of the tower prevents tip displacement due to the lateral force. Pressure variation in the inflated cylinders is used to keep the lateral force from setting up uncontrollable oscillations and keep tip displacement to a minimum.

A carbon nanotube material with a safety factor of six is chosen for the fabric of the tower. Again, this is a second generation Space Track Launch System. It is assumed that the CNT material will have properties similar to that projected for the CNT fiber, i.e. a working tensile strength of 25 GPa (SF = 6), a density of 1300 kg/m^3, and an effective modulus of elasticity of 10^{12} N/m^2.

2.h.1 Torque

A torque of approximately 10^9 N-m is produced at the top of the tower when rotational kinetic energy is restored after launch. If not removed, the torque would limit the inflated cylinders to 10 or 15 m in length which is unacceptable in a 150 km tall tower. The torque is removed by a 100 m section of tower called the torque buffer.

As shown in figure 11 below, the torque buffer is made up of 10 layers. Each layer has approximately 60, 10 m long 1 m diameter (L/D =10, Euler beam theory applies) inflated cylinders pressurized with hydrogen. Each layer is separated by an interface ring connected to six guy wires which are connected tangentially to the ring at a 45^o angle to the axis. The guy wires have a mass of about 10^6 kg each and produce an opposing force of about 10^7 N. Each layer removes about 10^8 N-m of torque from the system.

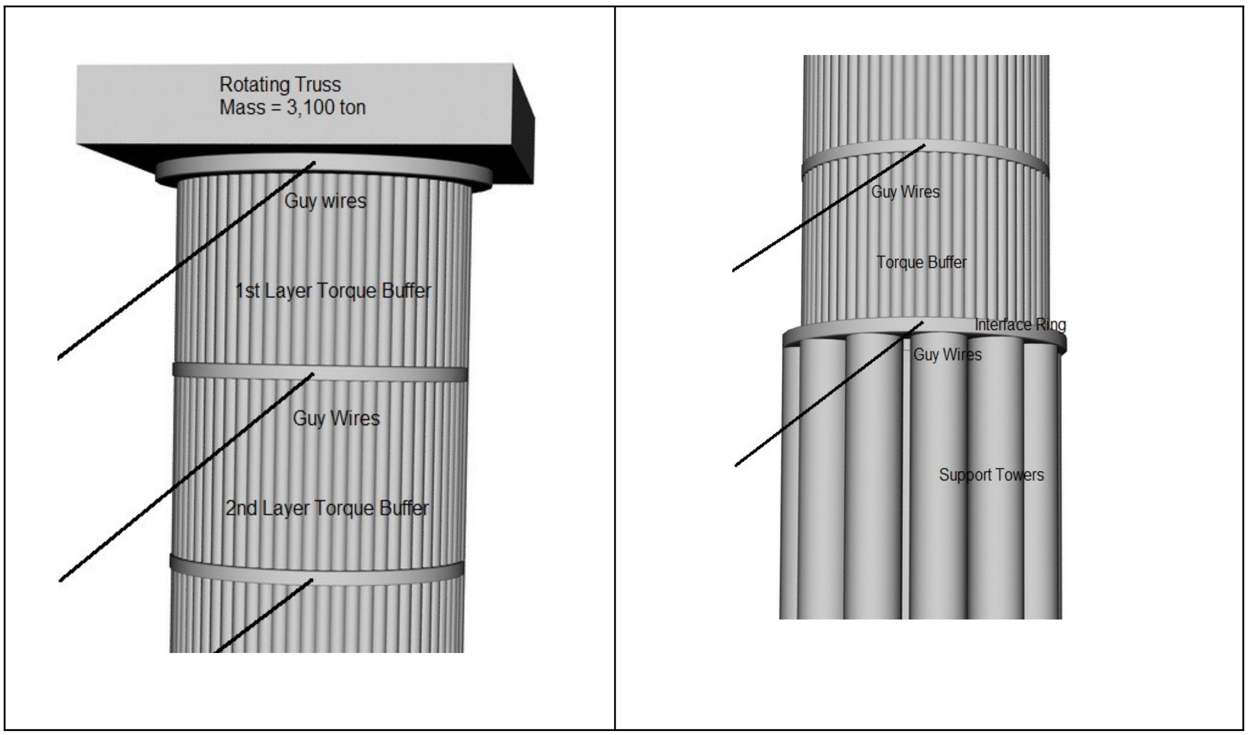

Figure 11. Torque Buffer & Support Towers

The interface rings have a radius of approximately 9.75 m and are modeled as a simple support with uniform load (equation 3). The separation between supports is approximately 2.0 m. A separation of 2.0 m is required if there is a failure or replacement of an inflated cylinder. Assuming a uniform load distribution, each of the inflated cylinders supports a load of 5 x 10^5 N. Using the M5® material, gives a mass of approximately 10^4 kg per interface ring. Adding the mass of the 600 inflated cylinders, the hydrogen gas, 60 guy wires, and 10 interface rings gives an additional load of approximately 8.7 x 10^7 N. The total load on the support towers is approximately 10^8 N and is summarized in table X below.

Counterweight	2.0×10^5 kg
Ribbon	1.9×10^5 kg
Ribbon Support Structure	2.7×10^4 kg
Ribbon Support Ring & Frame	9.6×10^4 kg
Ribbon Support Truss	2.3×10^4 kg
SubTotal	5.4×10^5 kg
X2	1.1×10^6 kg
Cable Support Columns	5.1×10^4 kg
Turntable & Gears	4.4×10^5 kg
Turntable & Gear Assembly Support	1.7×10^5 kg
Main & Passenger Elevators	2.4×10^5 kg
2^{nd} Stage Launch Vehicle	1.0×10^5 kg
Torque Buffer	8.9×10^6 kg
Total Mass	1.1×10^7 kg
Total Load	1.1×10^8 N

Table X. Tower Load

2.h.2. Precession

The tower will want to precess due to an unbalanced lateral load at the top. This lateral load is caused by the difference in force due to the rotation of the Earth and its effect on the center of mass of the ribbons and counterweights. The maximum force occurs at the equator when the velocity of the center of mass is in the same/opposite direction as the tangential velocity of a point on the Earth. For example, when looking down on the tower and the tower is rotating in a counterclockwise direction, the tangential velocity of the center of mass on the southern side is approximately +463 m/s and the tangential velocity of the center of mass on the northern side is approximately -463 m/s. This results in a maximum force of 8.8×10^6 N in the southern direction.

The precession is held in check by two methods, gyroscopic stabilization and pressure variation in the inflated cylinders. First, there is a gyroscopic stabilization of the tower. The Space Track Launch System will be the largest gyroscope in the known universe. Tip displacement will be opposed by a restoring force setup by the angular momentum of the tower. The restoring force is given by,

$$F_x = \frac{L_z}{h_g^2}\left(\frac{dS}{dt}\right) \quad \text{(Seth, 2010)}$$

where L_z is the angular momentum of the tower, h_g is the height above ground and dS/dt is the tip displacement velocity. In accordance with the theory, the faster the displacement, the stronger the restoring force.

Second, the lateral force will eventually set up a displacement and the oscillation will grow out of control. Therefore, the pressure in the cylinders on the leeward side will increase to offset this displacement. Using a combination of gyroscopic stabilization and pressure variation in the cylinders, the tip displacement can be keep at a minimum.

3. Support Tower

As mentioned in section 2 above, the total load on the support tower is approximately 10^8 N. At this point, the torque buffer has removed all lateral forces on the towers making the critical buckling load the driving design parameter. The torque buffer cylinders are angled at about 0.5°. This increases stability and allows for the addition of inflated cylinders as the load increases. The support tower analysis is based on a dissertation written by Raj Kumar Seth (Seth, 2010). The diameter of the inflated cylinder and the thickness of the material are 4.0 m and 5.0 x 10^{-4} m respectively giving an R/t ratio of 4000. The radius and thickness will be kept constant during the analysis. Realize that this is a preliminary analysis to show feasibility and not the final design. Diameter and thickness can be varied during the actual design to optimize the tower.

As a result of the slight angle, the radius at the bottom of the torque buffer is 10.6 m giving a circumference of about 70 m. With a diameter of 4 m, 16 inflated cylinders can be placed around the circumference. Assuming that the Euler beam theory applies, the critical buckling load is given by,

$$P_{cr}=\frac{\pi^2 E' I}{L^2} \quad \text{(Seth, 2010)}$$

where P_{cr} is the critical buckling load, E' is the effective modulus of elasticity which depends on the pressure in the inflated cylinder, L is the length of the cylinder (fixed-guided), and I is the area moment of inertia. The area moment of inertia for a multi-beam tower is given by,

$$I=N[\pi R t(r^2+R^2)] \quad \text{(Seth, 2010)}$$

where N is the number of inflated cylinders equal to 16, R is the radius of the cylinder equal to 2.0 m, t is the thickness of the material equal to 5 x 10^{-4} m, and r is the radius of the last interface ring supporting the torque buffer equal to 10.6 m.

Solving for the area moment of inertia, I, and setting the critical buckling load, P_{cr}, equal to the load, the length, L, of the first 16 cylinders is approximately 760 m. The L/D is 188 and, therefore, complies with the Euler beam theory. Each layer of cylinders has an interface ring with guy wires attached. Because of the slight angle, the radius of the interface ring increases and thus the number of cylinders increase. As the area moment of inertia increases, the length of the cylinders increase. A spreadsheet was developed to handle the calculations inserting the appropriate values for the hydrogen gas density at various altitudes and then switching to helium below 20 km. The results are shown in Table XI below.

Altitude (km)	Load (N)	# of Cyl.	Length (km)	MPC (N/m^2)	Bend Mom (N-m)
150 ≤ H ≤ 149	1.1×10^8	16	0.8	1.3×10^9	1.5×10^{10}
149 ≤ H ≤ 148	1.2×10^8	27	1.5	2.1×10^9	6.6×10^{10}
148 ≤ H ≤ 144	1.5×10^8	48	3.2	3.7×10^9	3.6×10^{11}
144 ≤ H ≤ 137	2.2×10^8	93	7.0	7.0×10^9	2.6×10^{12}
137≤ H ≤ 124	5.3×10^8	193	13.5	1.4×10^{10}	2.3×10^{13}
124 ≤ H ≤ 104	1.9×10^9	383	19.6	2.3×10^{10}	1.8×10^{14}
104 ≤ H ≤ 84	8.9×10^9	661	20.7	3.8×10^{10}	9.2×10^{14}
84 ≤ H ≤ 61	2.3×10^{10}	953	22.2	5.6×10^{10}	2.8×10^{15}
61 ≤ H ≤ 36	4.2×10^{10}	1266	25.3	7.2×10^{10}	6.5×10^{15}
36 ≤ H ≤ 10	6.9×10^{10}	1624	25.7	5.4×10^{10}	1.4×10^{16}
10 ≤ H ≤ 0	1.5×10^{11}	2028	10.0	1.2×10^{11}	2.5×10^{16}

Table XI. Support Tower Load

The maximum payload capacity (MPC) is given by,

$$W'_{MPC} = \left[\frac{\sigma}{R/t}\right] - \left[\left(\frac{2H\rho g}{R/t}\right) + H\rho'_g g\right] \quad \text{(Seth, 2010)}$$

where the quantity *σ/R/t* is the maximum internal pressure allowed by the material, *σ* is the working tensile strength of the material equal to 25 GPa, *H* is the length of the inflatable section, *ρ* is the mass density of the material equal to 1300 kg/m^3, *g* is the acceleration due to gravity equal to 9.81 m/s^2, and ρ'_g is the density of the gas used for the internal pressure given by,

$$\rho'_g = \frac{\mu\sigma}{R_g T\left(R/t\right)} \qquad \text{(Seth, 2010)}$$

where *μ* is the molecular mass (2.0×10^{-3} kg/mol for hydrogen, 4.0×10^{-3} kg/mol for helium), R_g is the gas constant equal to 8.314 J/K/mol, and *T* is the average temperature at the required altitude based on US Standard Atmosphere.

The first section of tower is connected to the second section of tower via an interface ring (figure 11). The ring connects all the support towers together resulting in a more stable configuration. Guy wires are attached at the intersection and hydrogen gas bottles are mounted on the ring to replace hydrogen gas that dissipates from the support tower. Dissipation of hydrogen gas is estimated to be about 100 moles per day (Choi, S. and Sankar, B.V., 2008). The hydrogen bottles are sized to provide approximately a 170 day supply of hydrogen gas. The mass of the tower, the gas, the guy wires, the sleeve, ring, and hydrogen bottle are determined and added to the tower load for the next section of tower. At an altitude of 20 km, helium gas is used as the working fluid to prevent the possibility of a hydrogen gas explosion.

A base load of 7.2×10^7 N over an area of 12.6 m^2 results in a load per unit area of 5.7×10^6 N/m^2 or about 850 psi. Concrete for this loading is readily available and relatively inexpensive. The diameter at the base of the support towers is about 3 km allowing an entire base station to be placed within the structure. There are six entry ways onto the main elevator (figure 12). Therefore, aerospace companies wishing to launch from the Space Track Launch System can have access from one of six different tracks that lead onto the elevator.

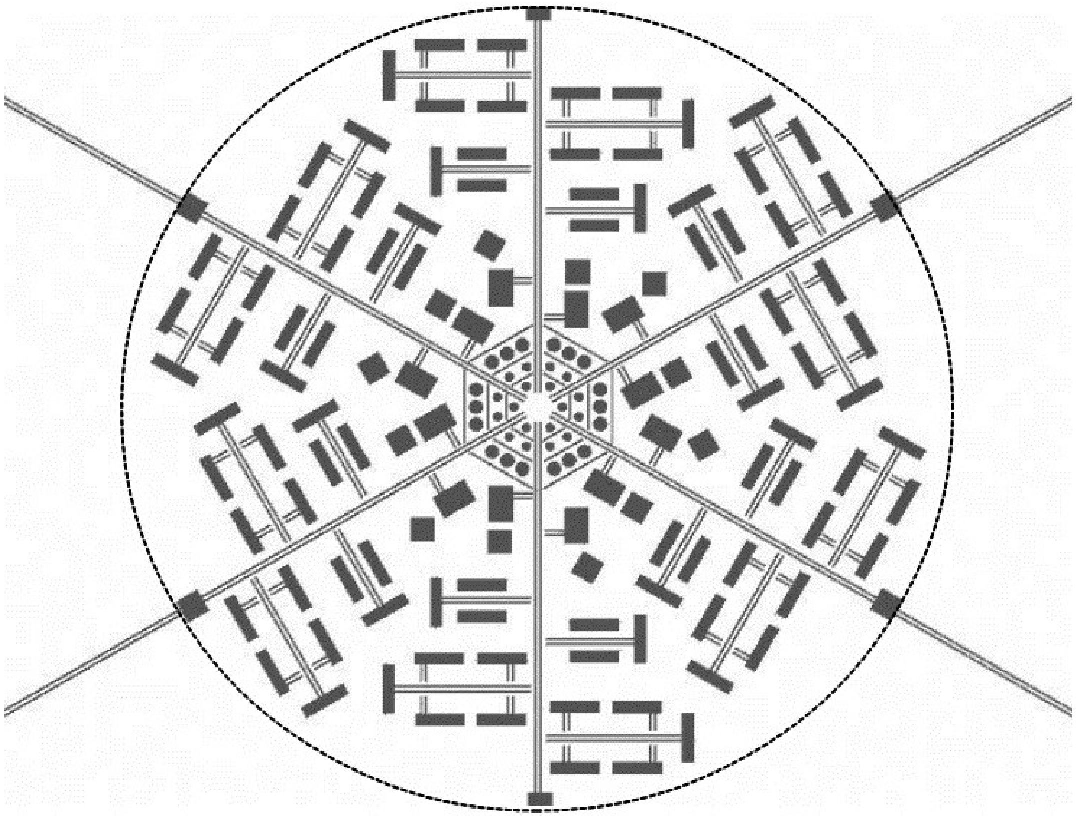

Figure 12. Base Station

4. Conclusion

This paper presents an initial design and mass estimate for the first stage of the second generation Space Track Launch System. The first stage is all electric and can be used four to five times per week. The electric motors restore rotational kinetic energy to the ribbons in approximately 8 hours. The tower material, fill gas, guy wires, and interface rings result in a base load of 7.2×10^7 N per tower. The towers supporting the research station and rotating truss have a base diameter of 3 km. There are six tracks leading into the base station complex.

Aerospace companies can line up along the track for easy access to the launch system from six different access ports. With two sets of ribbons, two second stage launch vehicles can be launched for each recharge cycle resulting in eight to ten launches or approximately 24,000 to 30,000 kg of mass into low earth orbit per week. The overcarriage can accommodate a wide variety of launch vehicles making the Space Track Launch System an economical and universal launch system.

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