The Space Elevator
from Science Fiction to Engineering

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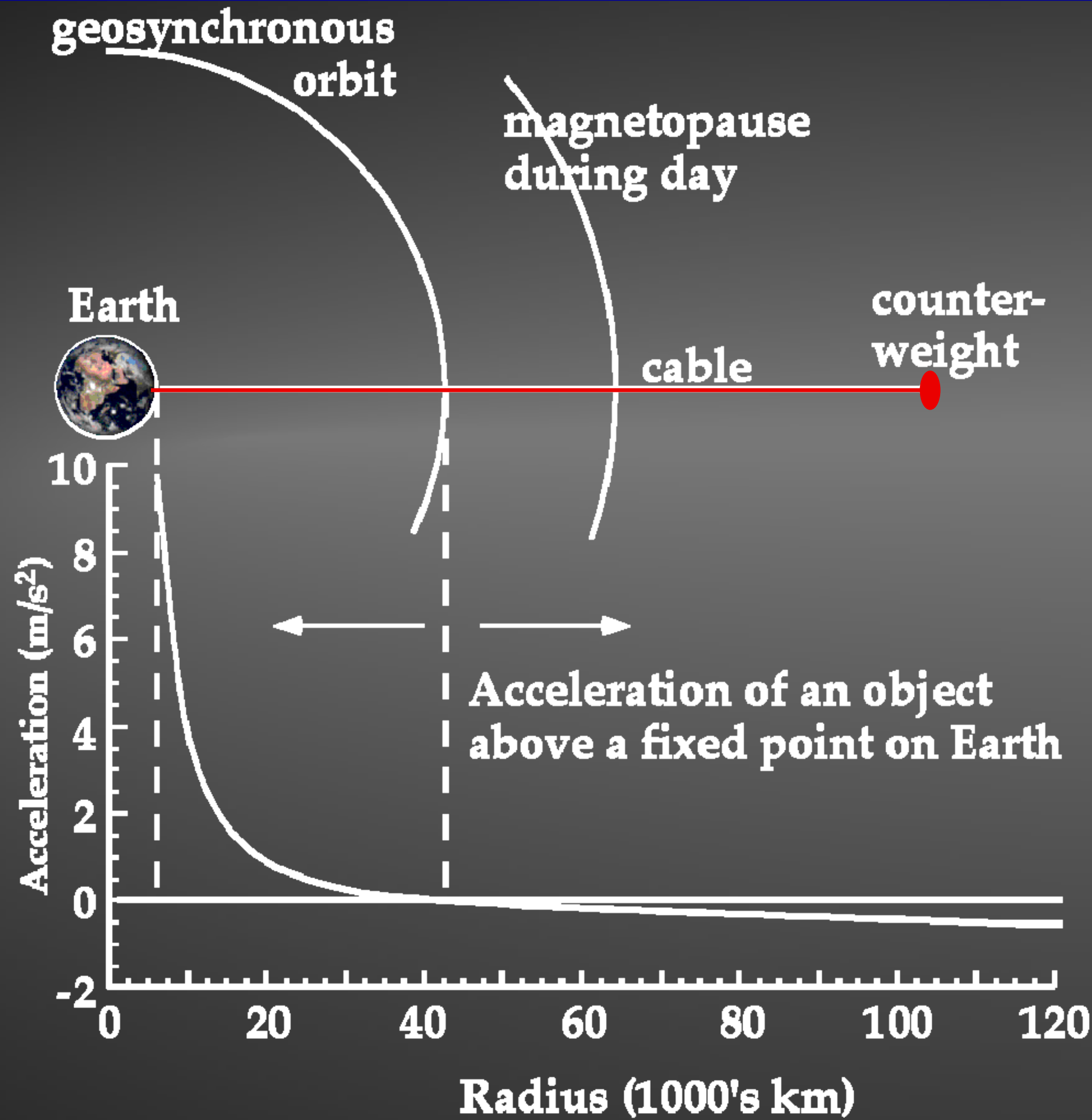
With additional material courtesy of
Brad Edwards
Carbon Designs, Inc

Space Elevator Basics



The SE in Literature

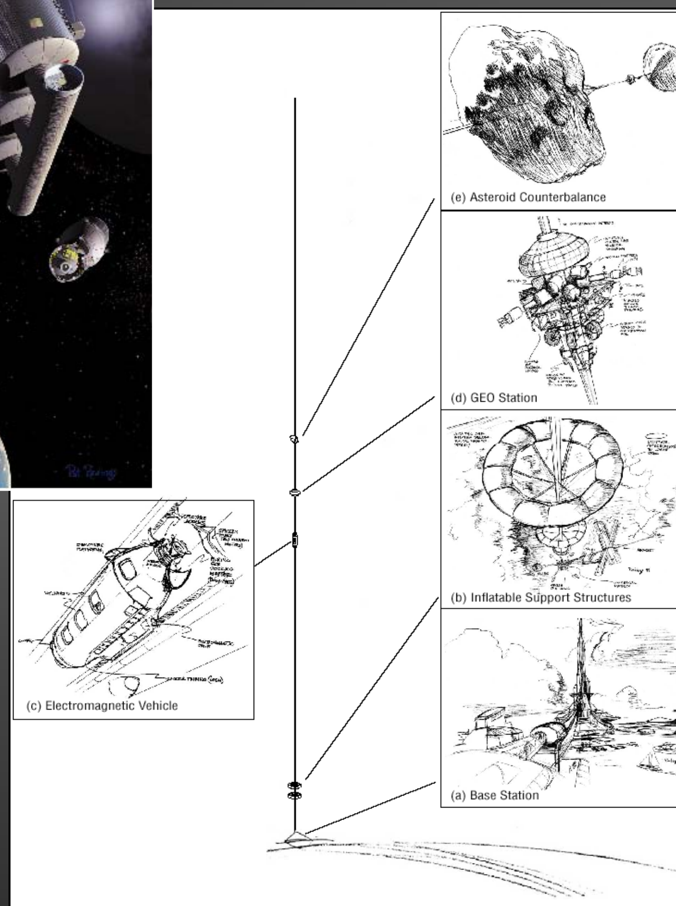
- Artsutanov, Y. **1960**. V Kosmos na Elektrovoze, Komsomolskaya Pravda, (contents described in Lvov 1967 Science 158:946).
- Isaacs, J.D., Vine, A.C., Bradner, H., and Bachus, G.E. **1966**. Satellite Elongation into a true ‘Sky-Hook’. Science 151:682.
- Pearson, J. **1975**. The Orbital tower: a spacecraft launcher using the Earth’s rotational energy. Acta Astronautica 2:785.
- Clarke, A.C. **1979**. The Space Elevator: ‘Thought Experiment’, or Key to the Universe. Adv. Earth Oriented Appl. Science Techn. 1:39.


В космос — на электровозе

Russian original article (scanned and OCRed)

The Space Elevator in Science Fiction

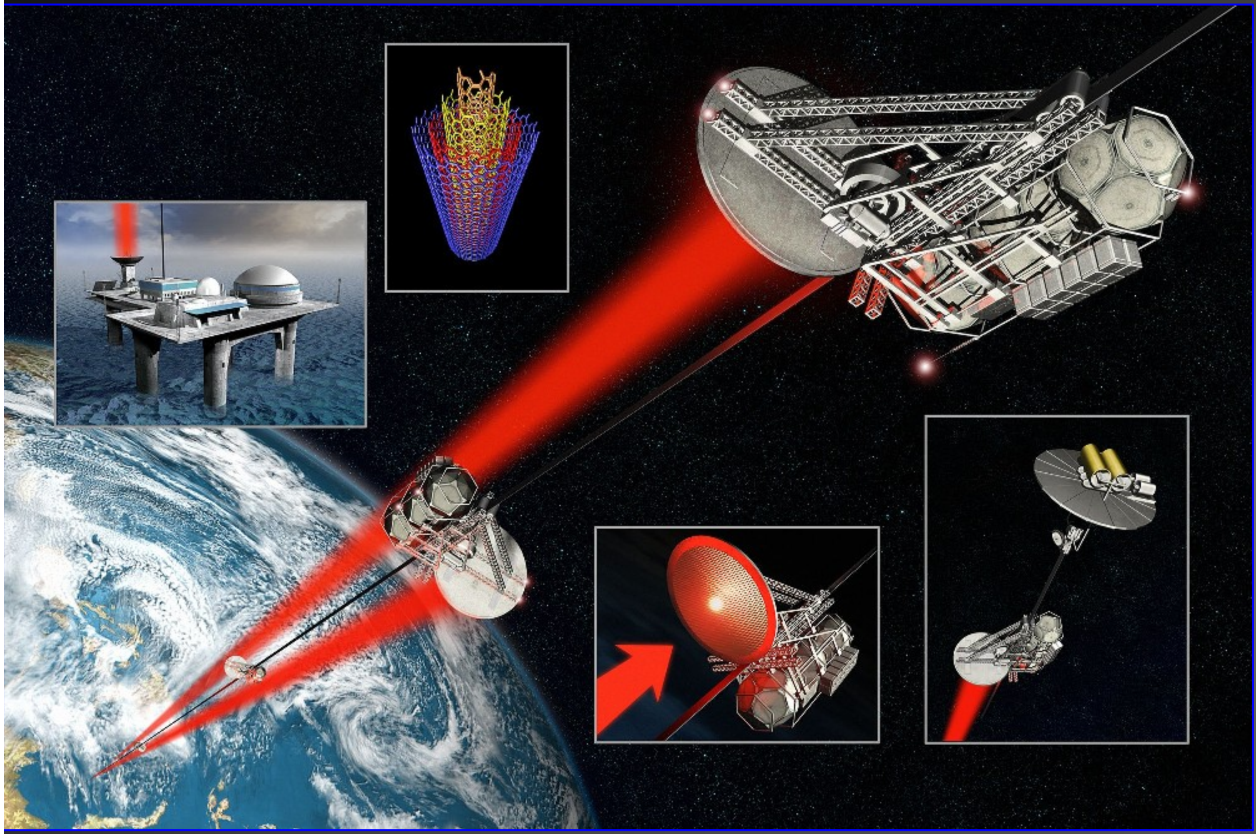
From SciFi to NASA



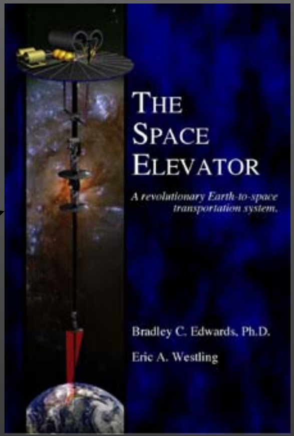
- Capture an asteroid and bring into Earth orbit
- Mine the asteroid for carbon and extrude 10m diameter cable
- Asteroid becomes counterweight
- Maglev transport system
- Tall tower base
- Large system
- 300 years to never...

From Smitherman, 1999

Proposed System: Overview

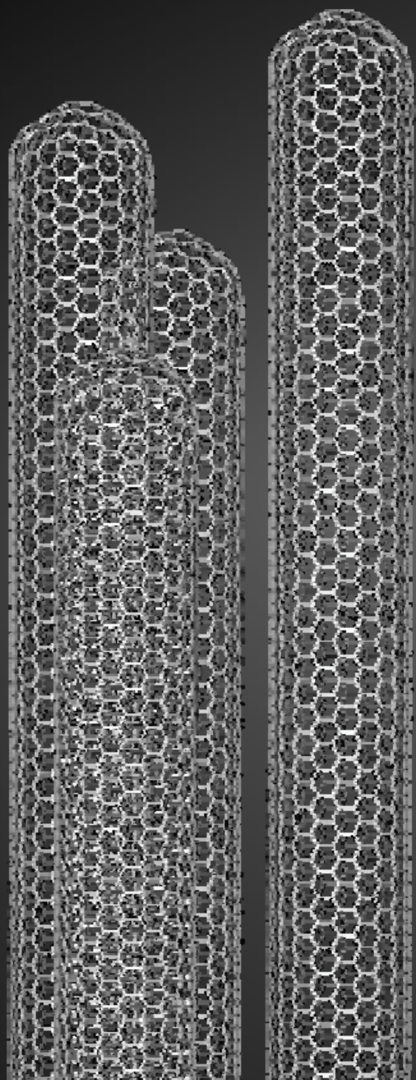


- First elevator: 20 ton capacity (13 ton payload)
- Constructed with existing or near-term technology
- Cost (US$10B) and schedule (15 years)
- Operating costs of US$250/kg to any Earth orbit, moon, Mars, Venus, Asteroids



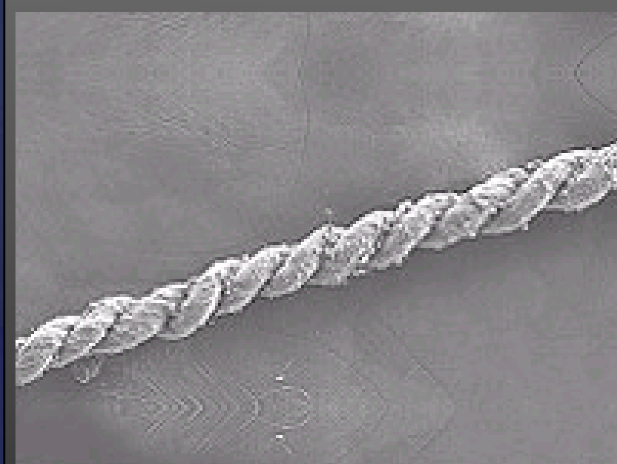
Book by Brad Edwards and Eric Westling

Carbon Nanotubes (CNTs)



- Carbon nanotubes: measured at 200 GPa (54xKevlar)
  - **Sufficient to build the elevator**
- Mitsui(Japan): 120 ton/yr CNT production, US$100/kg
  - **Sufficient to build the first elevator**
- CNT composite fibers: 3-5% CNTs, 3 GPa, 5 km length
  - **Not strong enough yet but a viable plan is in place to get there (Carbon Designs, Inc.)**

5km continuous 1% CNT composite fiber

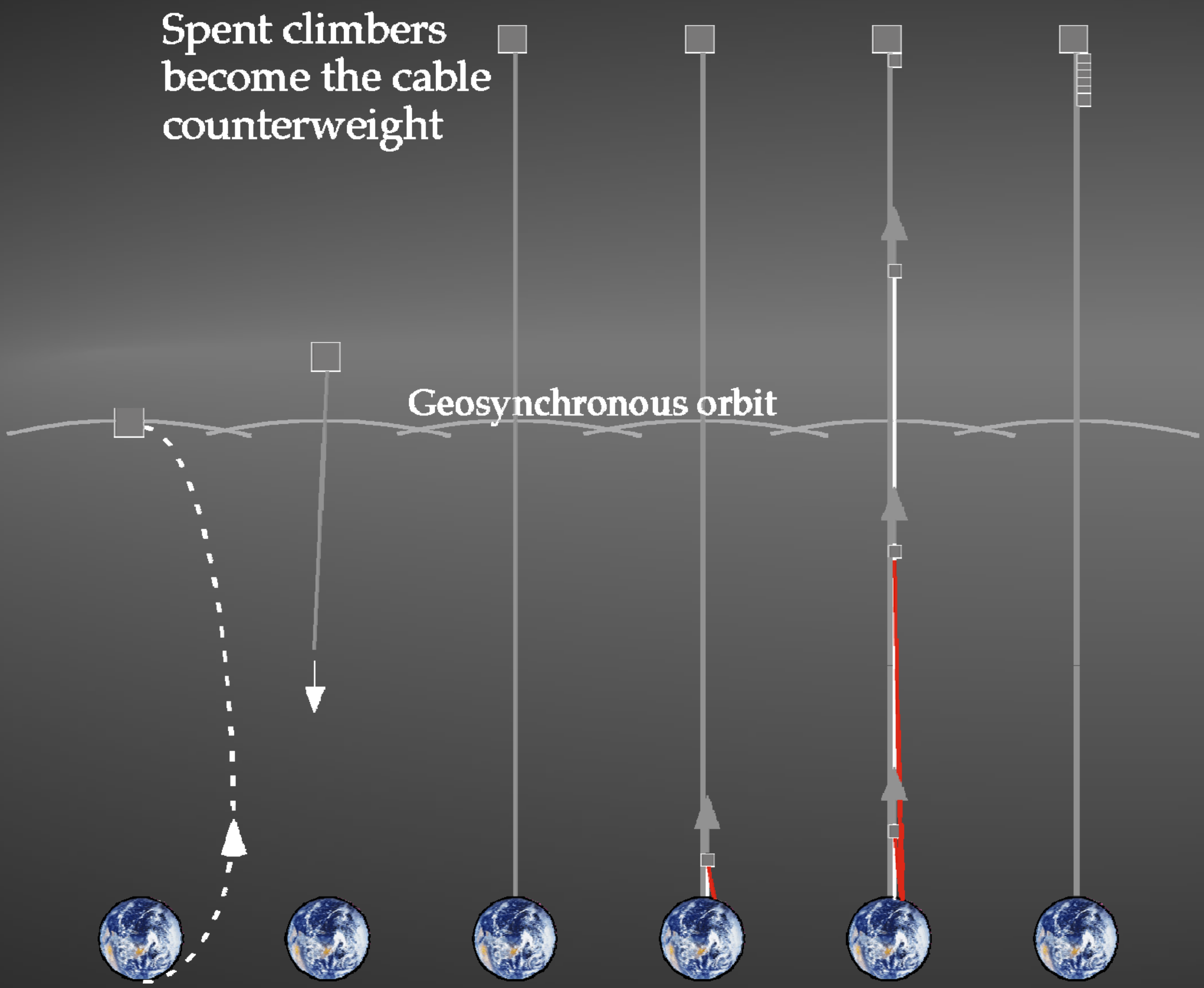


Deployment Overview

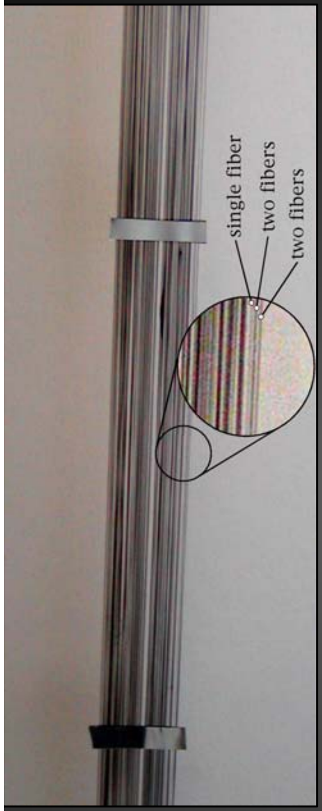
After deploying the pilot ribbon, 230 construction climbers ascend, each adding more ribbon material and strengthening the ribbon by 1.3% each.

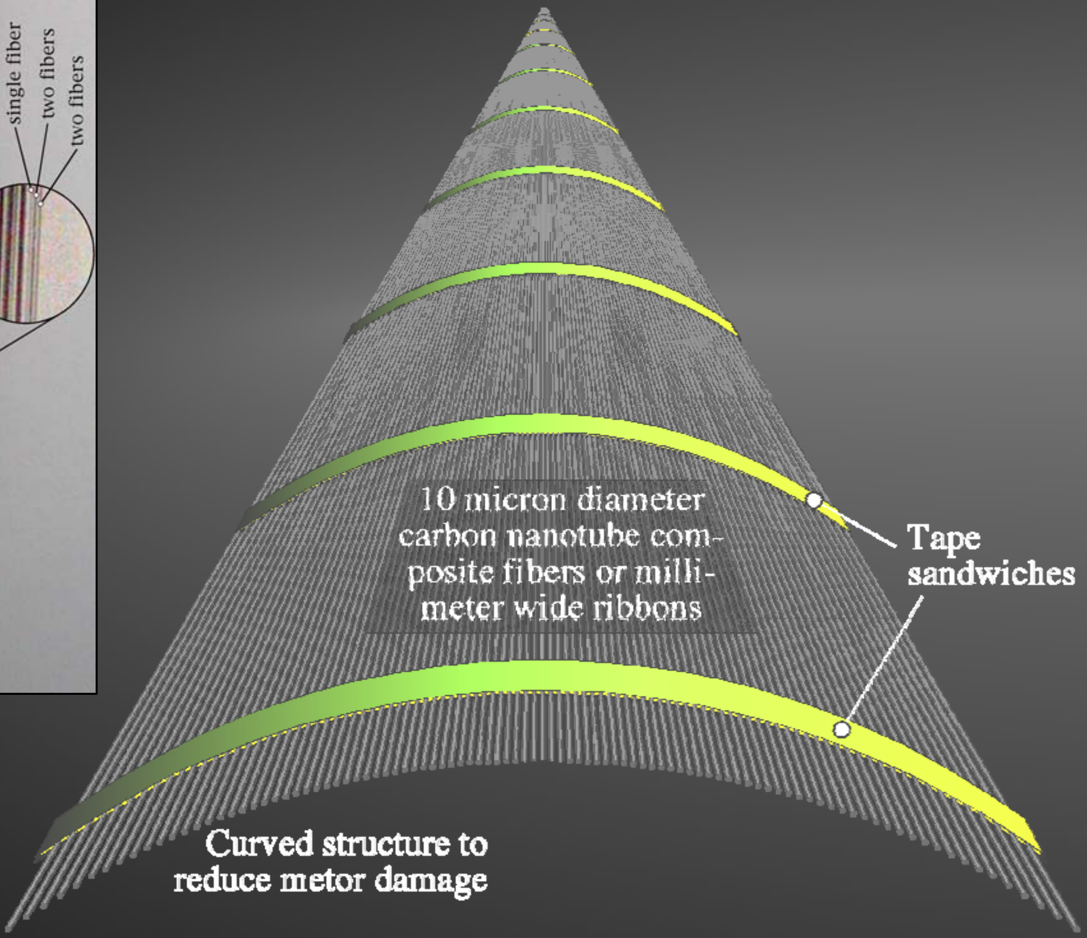
The first construction climber is limited to 900 kg by the strength of the pilot ribbon.

My work focuses on the first construction climber.



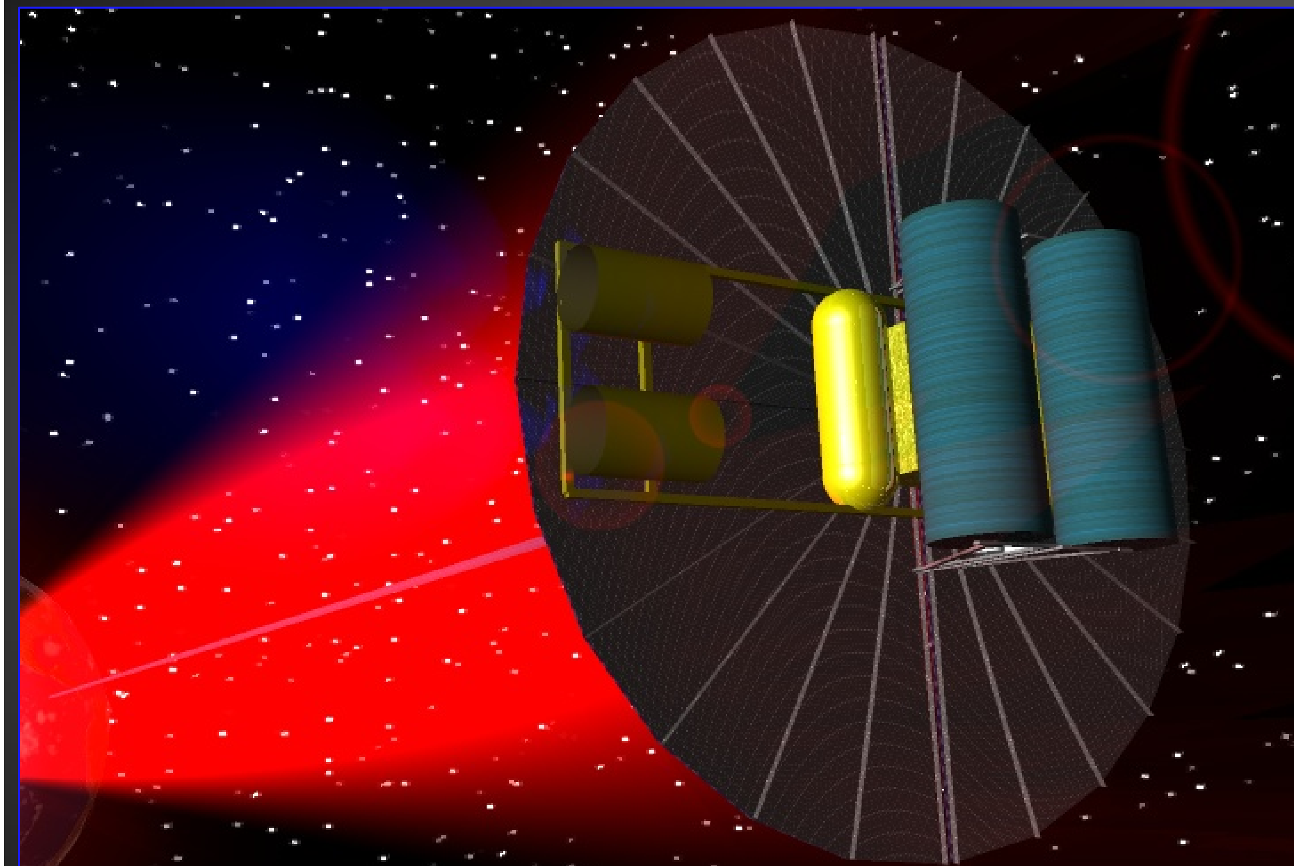
Ribbon Design





- The final ribbon is one-meter wide and composed of parallel high-strength fibers
- Interconnects maintain structure and allow the ribbon to survive small impacts
- Initial, low-strength ribbon segments have been built and tested

Initial Spacecraft



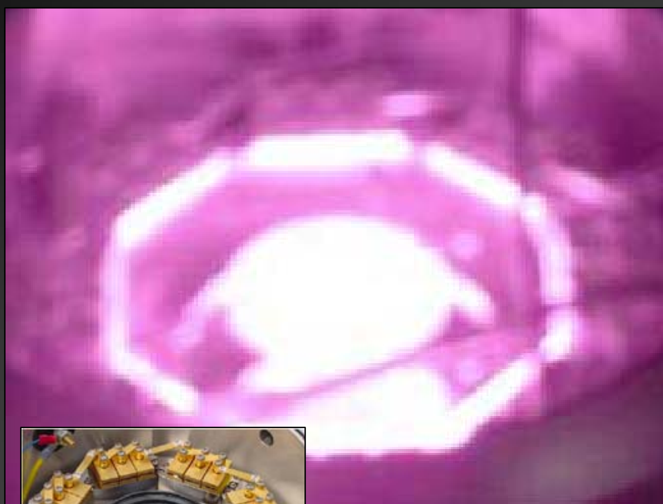
- Deployment spacecraft built with current technology
- Photovoltaic arrays receive power from Earth
- An MPD electric propulsion moves the spacecraft up to high Earth orbit
- Four 20-ton components are launched on conventional rockets and assembled
- Mass budget originally based on shuttle launch capacity

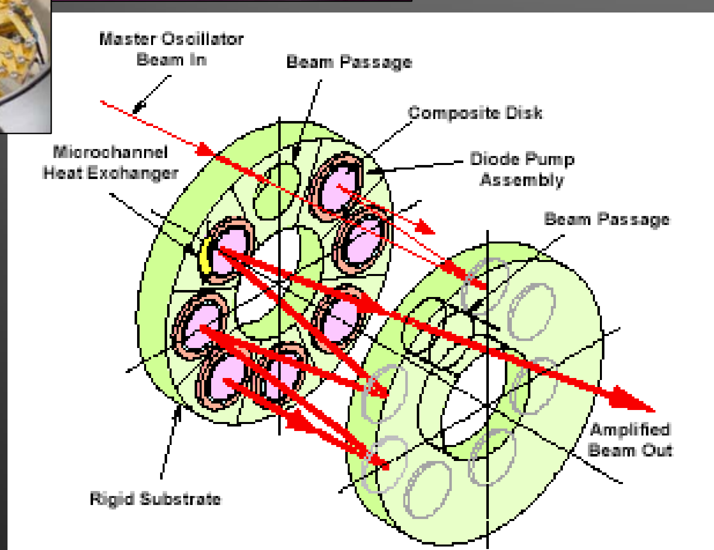
Climbers

- Climbers built with current satellite technology
- Drive system built with DC electric motors
- Photovoltaic array (GaAs or Si) receives power from Earth
- 7-ton climbers carry 13-ton payloads
- Climbers ascend at 200 km/hr (or more)
- 8 day trip from Earth to geosynchronous altitude

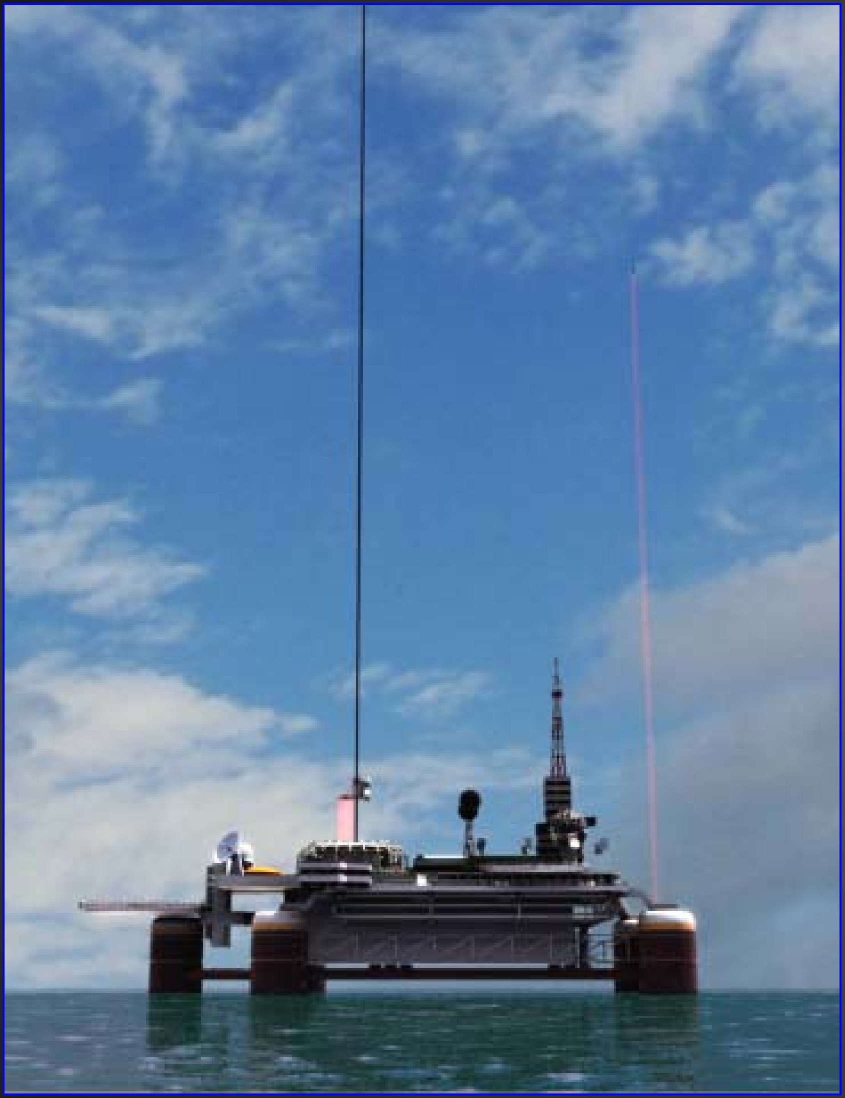
Power Beaming

- Power is sent to deployment spacecraft and climbers by laser
- Solid-state disk laser produces kWs of power and being developed for MWatts
- Mirror is the same design as conventional astronomical telescopes (Hobby-Eberly, Keck)



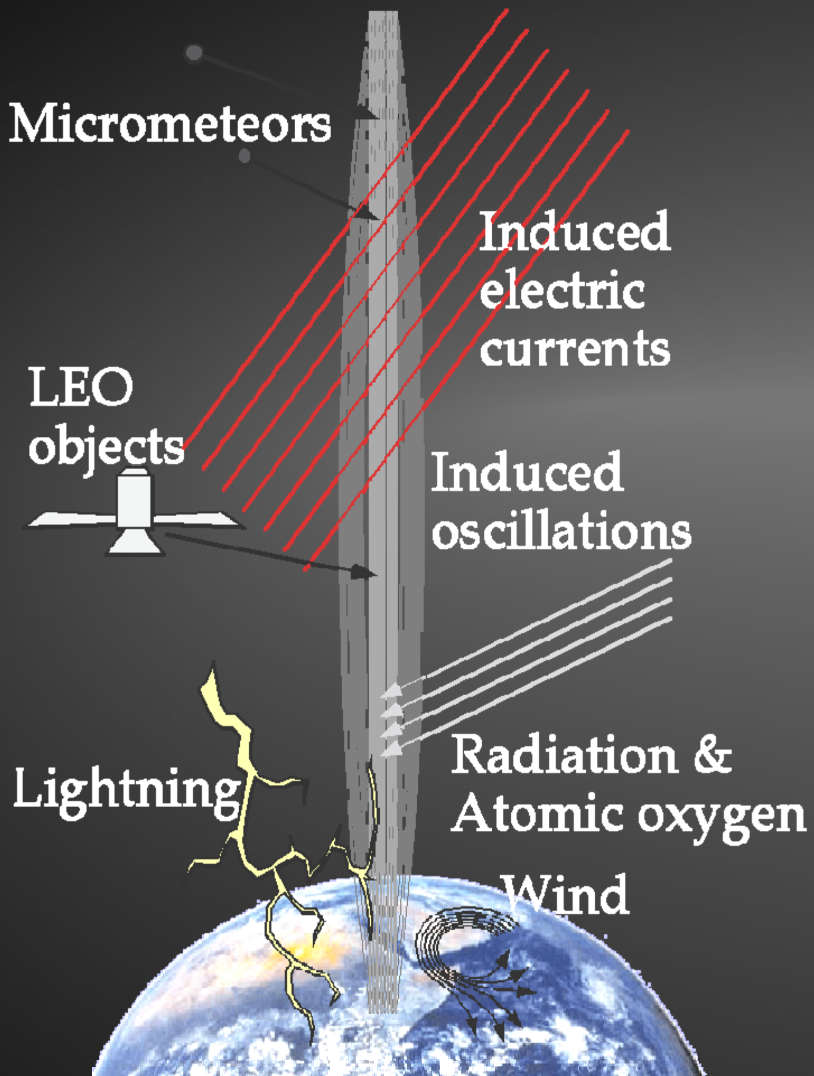


Anchor



- Anchor station is a mobile, ocean-going platform identical to ones used in oil drilling
- Anchor is located in eastern equatorial pacific, weather and mobility are primary factors

Challenges



- Induced Currents: milliwatts and not a problem
- Induced oscillations: 7 hour natural frequency couples poorly with moon and sun, active damping with anchor
- Radiation: carbon fiber composites good for 1000 years in Earth orbit (LDEF)
- Atomic oxygen: <25 micron Nickel coating between 60 and 800 km (LDEF)
- Environmental Impact: Ionosphere discharging not an issue
- Malfunctioning climbers: up to 3000 km reel in the cable, above 2600 km send up an empty climber to retrieve the first
- Lightning, wind, clouds: avoid through proper anchor location selection
- Meteors: ribbon design allows for 200 year probability-based life
- LEOs: active avoidance requires movement every 14 hours on average to avoid debris down to 1 cm
- Health hazards: under investigation but initial tests indicate minimal problem
- Damaged or severed ribbons: collatoral damage is minimal due to mass and distribution

Technical Budget

Component	Cost Estimate (US$)
Launch costs to GEO	1.0B
Ribbon production	400M
Spacecraft	500M
Climbers	370M
Power beaming stations	1.5B
Anchor station	600M
Tracking facility	500M
Other	430M
Contingency (30%)	1.6B
TOTAL	~6.9B

Costs are based on operational systems or detailed engineering studies.

Additional expenses will be incurred on legal and regulatory issues. Total construction should be around US$10B.

Recommend construction of a second system for redundancy: US$3B

SE Operating Budget

Annual Operating Budget per year in US$M

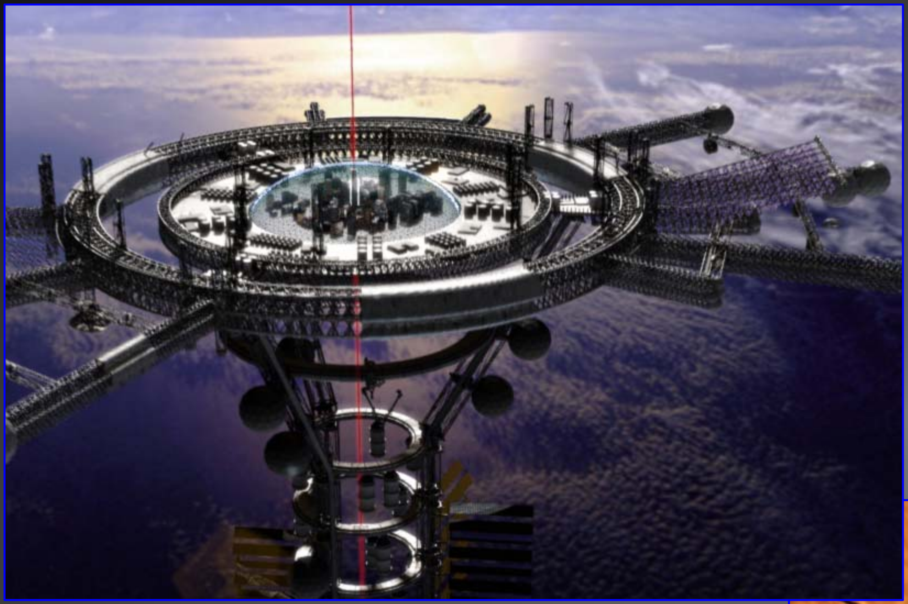
Climbers	0.2 - 2 each
Tracking system	10
Anchor station	10
Administration	10
Anchor maintenance	5
Laser maintenance	20
Other	30
TOTAL (50 launches)	135

This is ~US$250/kg operating costs to any destination.

Advantages

- Low operations costs - US$250/kg to LEO, GEO, Moon, Mars, Venus or the asteroid belts
- No payload envelope restrictions
- No launch vibrations
- Safe access to space - no explosive propellants or dangerous launch or re-entry forces
- Easily expandable to large systems or multiple systems
- Easily implemented at many solar system locations

Applications



- Solar power satellites - economical, clean power for use on Earth
- Solar System Exploration - colonization and full development of the moon, Mars and Earth orbit
- Telecommunications - enables extremely high performance systems

Next Steps

- Material development efforts are underway by private industry
- Space elevator climber competition will demonstrate basic concept—no winner this year!
- Engineering development centers in the U.S., Spain and Netherlands are under development
- Technical conferences continuing
- Greater public awareness
- Increased financial support being sought

Diving into the Details

- I have focused on the details of the first construction climber
- I don't do rocket science, but I recognize an electric car when I see one
  - At 900 kg, the first climber is in the weight and power range of an electric car
- I proposed an alternative design to the Edwards climber based on my work on fatigue and tribology
- Slides that follow are from previous SE talks

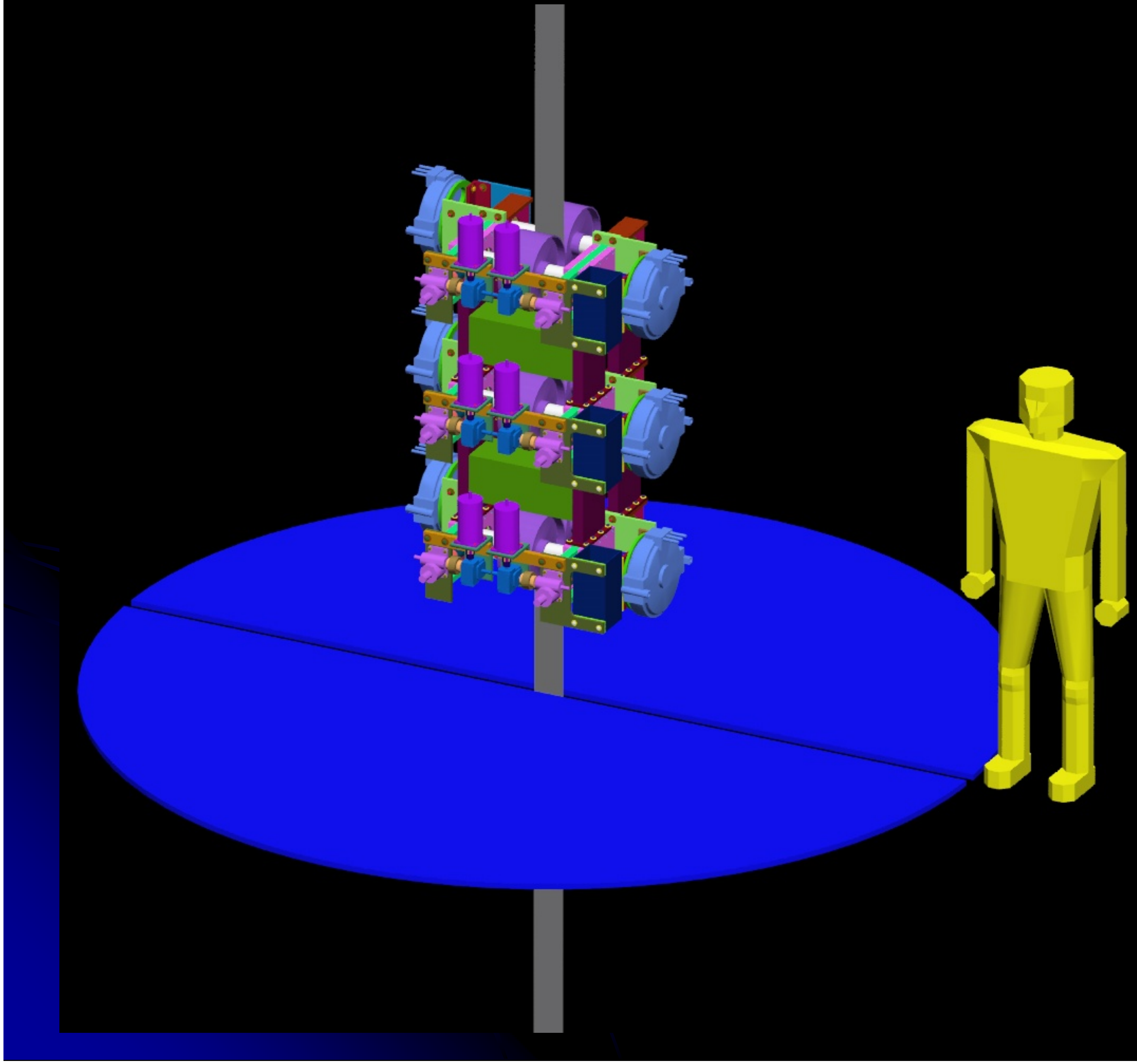
The Goal:

- To design 230 construction climbers to increase the load capacity of the pilot ribbon to 20 tonnes in the least amount of time
- The first construction climber is limited to 900 kg
  - The drive train must weigh less than 233 kg
  - Climbers end their lives as counterweights for the ribbon

To be covered here:

- Propose a design for the first construction climber
- Identify a critical Ribbon material property necessary to do a real design
  - Discuss friction and fatigue
- Describe the challenge of the motors
- Describe the mass budget challenge

Proposed alternative design



Pinched wheel design with no track

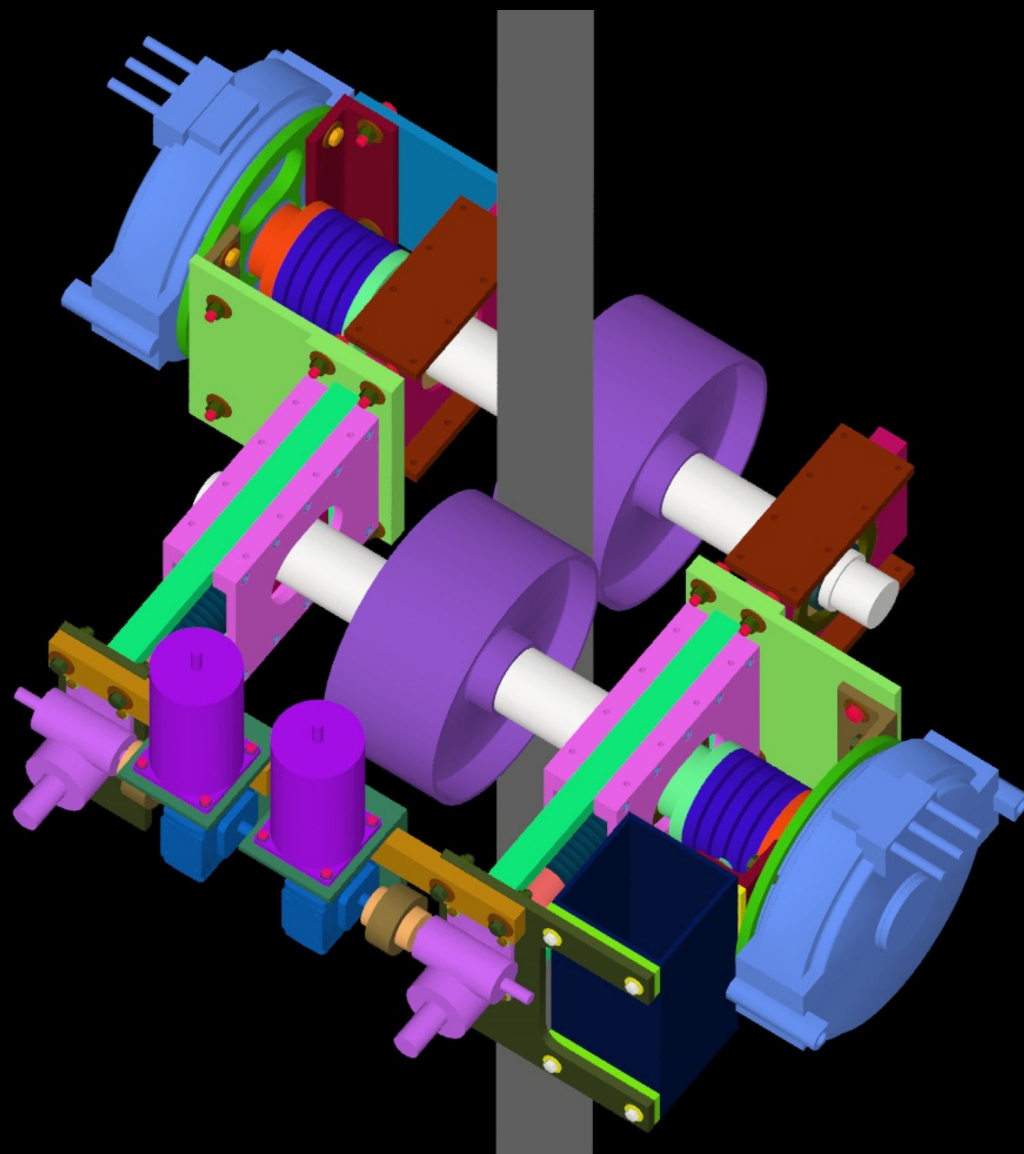
This is an incomplete scale model of the first climber. The PV array (blue disk) is 4 m in diameter

Not all components shown are space-worthy

Development of the CAD model

- Goals for the model:
  - to identify all the features of the drive train and associate real components with them even if they were just placeholders
  - to see if reasonable components would fit within the mass budget
  - to address assembly considerations
  - to minimize structural mass by placing material primarily in the load paths

Two wheels clamped onto the ribbon

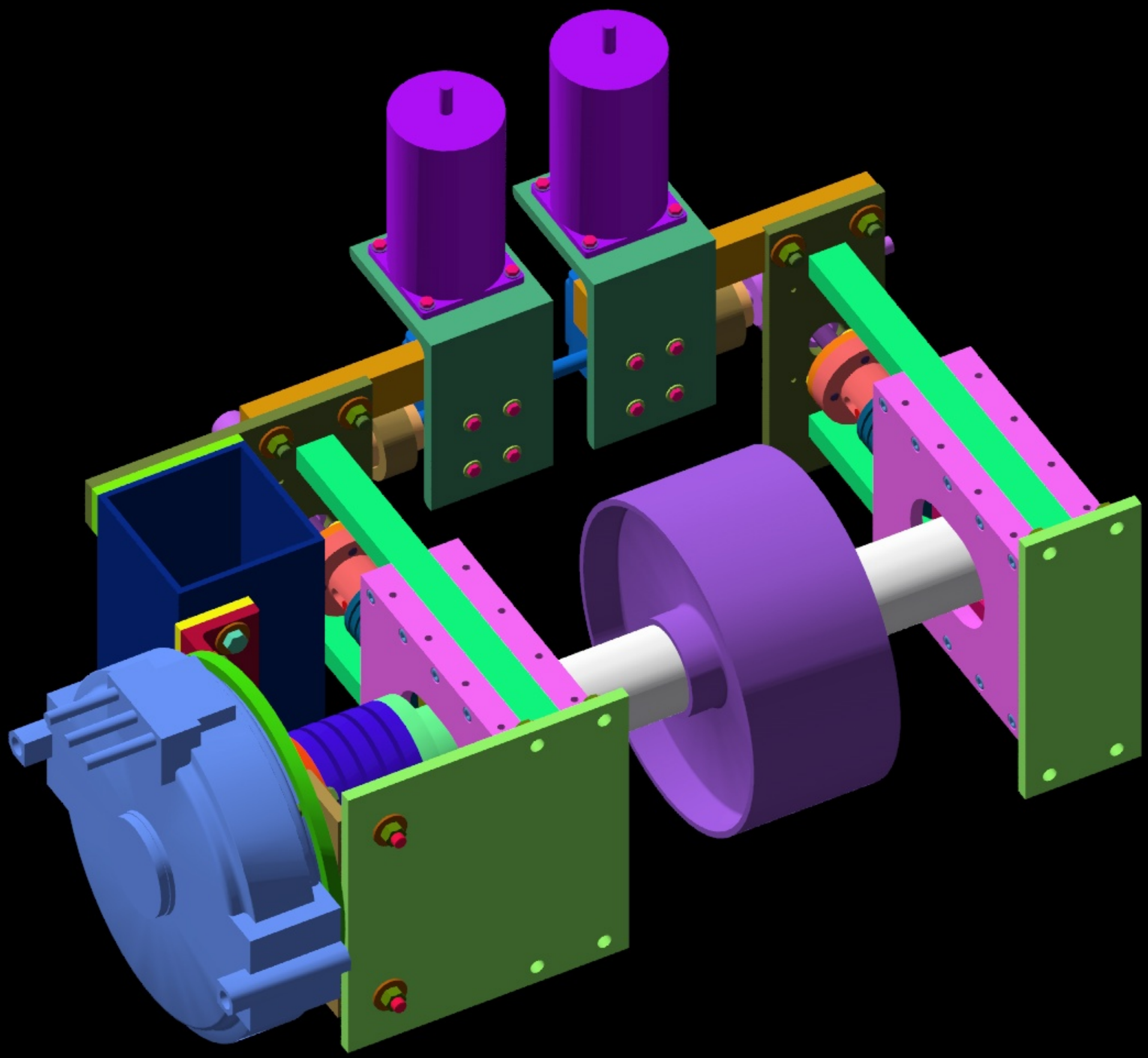


The axle on the far side of the ribbon is fixed to the frame of the climber through self-aligning bearings.

On the near side of the ribbon, the axle is mounted on a linear slide so the wheel can be pressed against the ribbon or retracted away from it.

Motors are connected to the axles by Schmidt couplings to absorb any angular or lateral offsets.

Floating axle traction module



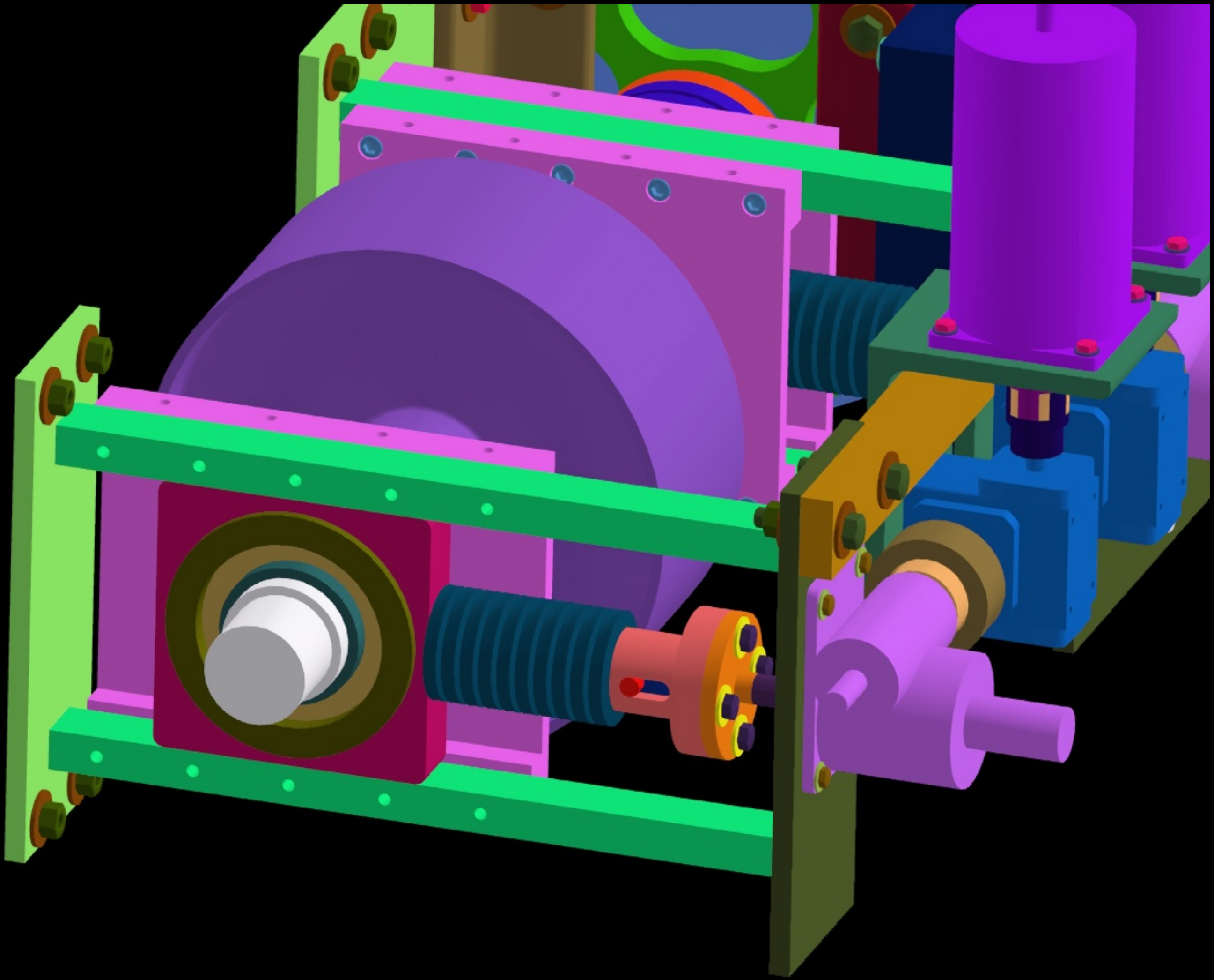
The two sides of this module are not stable to torsion without the interface structures between modules

Wheel pinch forces are transmitted through the light green plates on either side of the wheel.

Forces coming from the rest of the climber are connected through the bearing housing slides

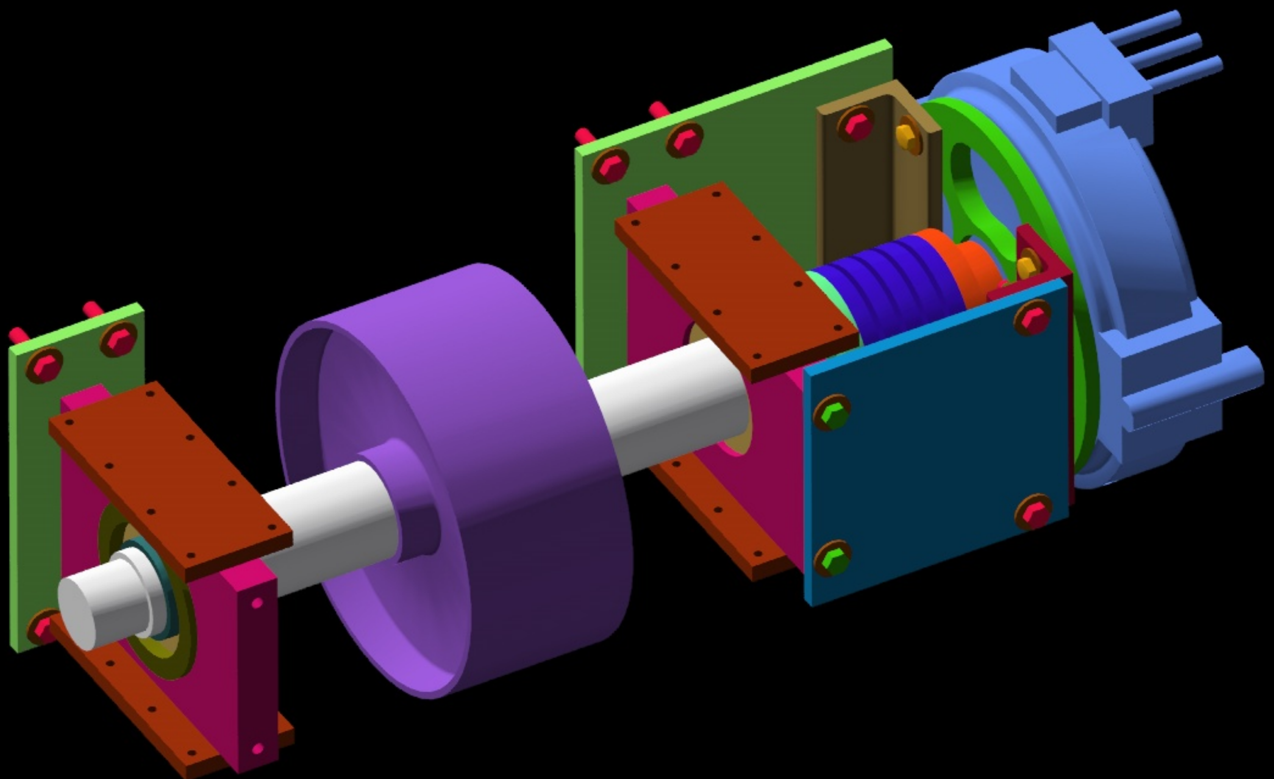
Every wheel is motorized.

The wheel compression mechanism



- One ton screw jacks compress a stack of belleville washers
- This concept allows great resolution in the application of force to the axle
- The components were all sized to take the loads but are not space-worthy. A concern is whether space-worthy components are even larger.

Fixed axle traction module

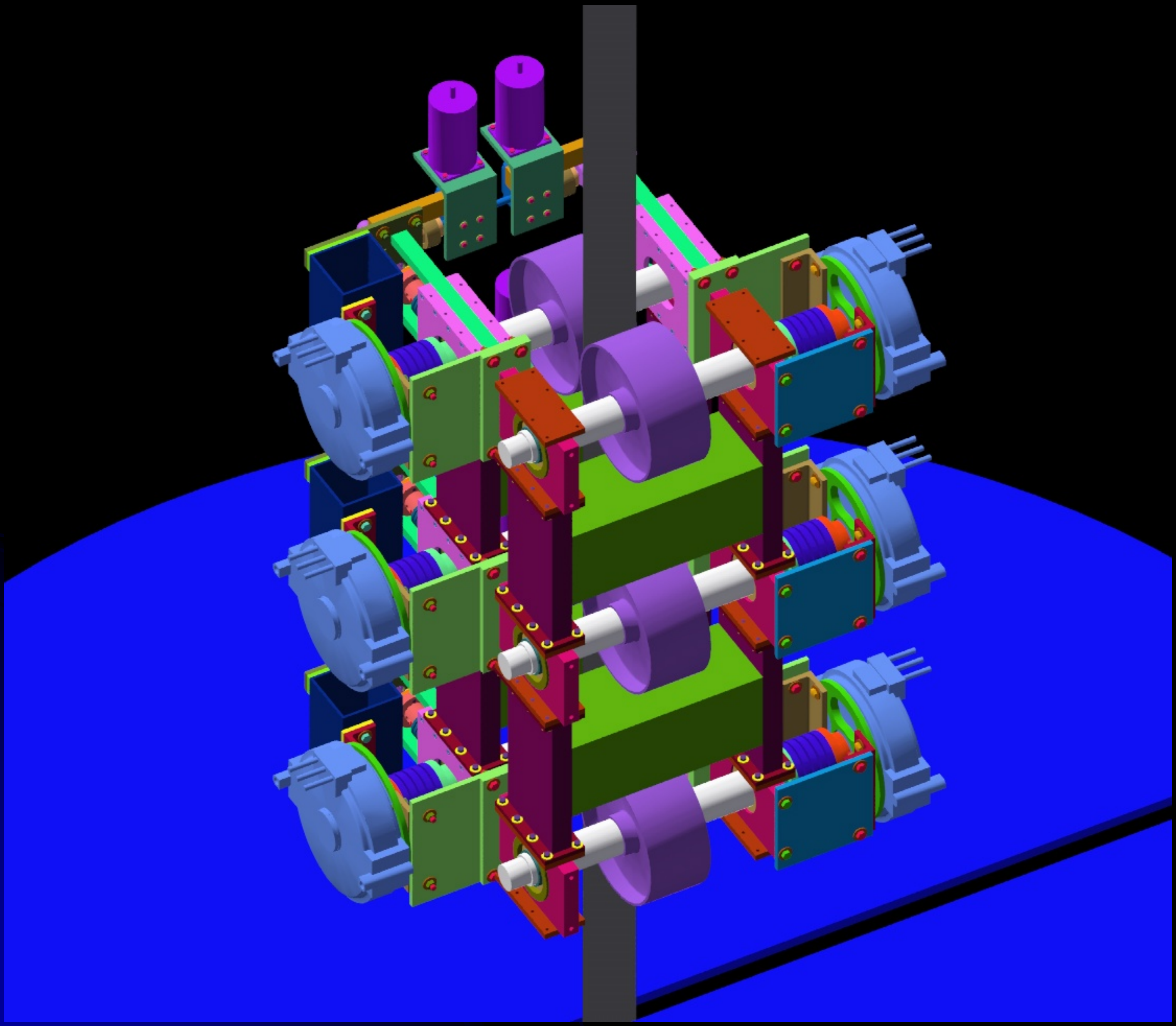


This module drives a wheel and absorbs the compressive force coming from the wheel on the other side of the ribbon.

This module is lighter than the one on the other side so balancing a climber to force the CG to lie within the ribbon is an issue.

Motors shown are 50kW axial gap models from Precision Magnetic Bearings.

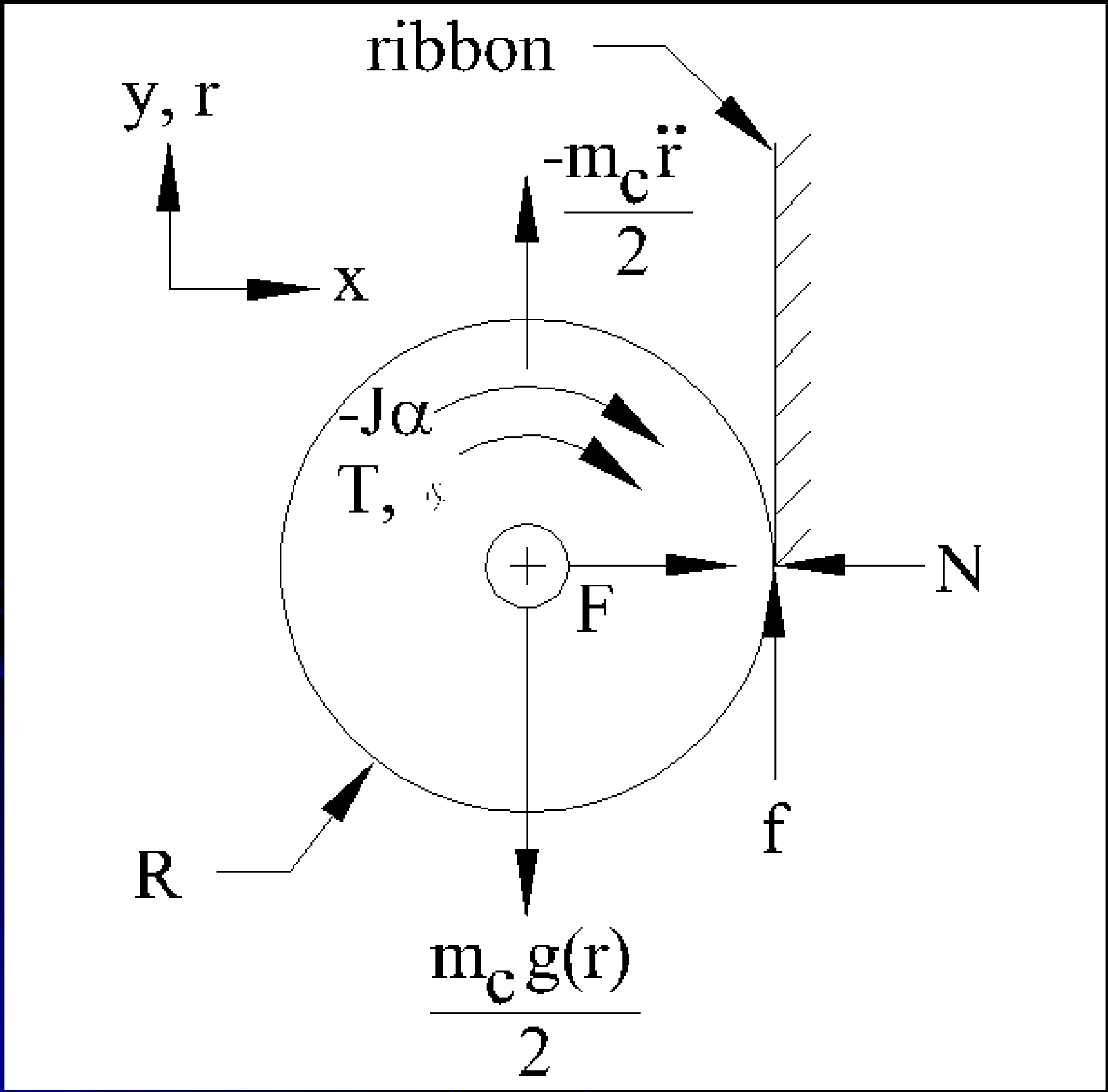
Interface structures



The structural modules in between the traction modules give torsional stiffness to the traction modules and allow loads from the rest of the climber to be coupled to the drive train.

This drive design (not including the PV arrays) weighs 1625 lbs, or 737 kg. This is about 3.16X the allowed 233 kg for the drive train. 20kW motors reduce it to 647 kg, or 2.77X.

Free Body Diagram of a Wheel



This picture models a single wheel on a climber with just two wheels

f = friction force from ribbon

F, N are compression and reaction forces pinching wheels on opposite sides of the ribbon together

This diagram allows us to write the equations of motion for the climber and determine all the forces acting on the climber

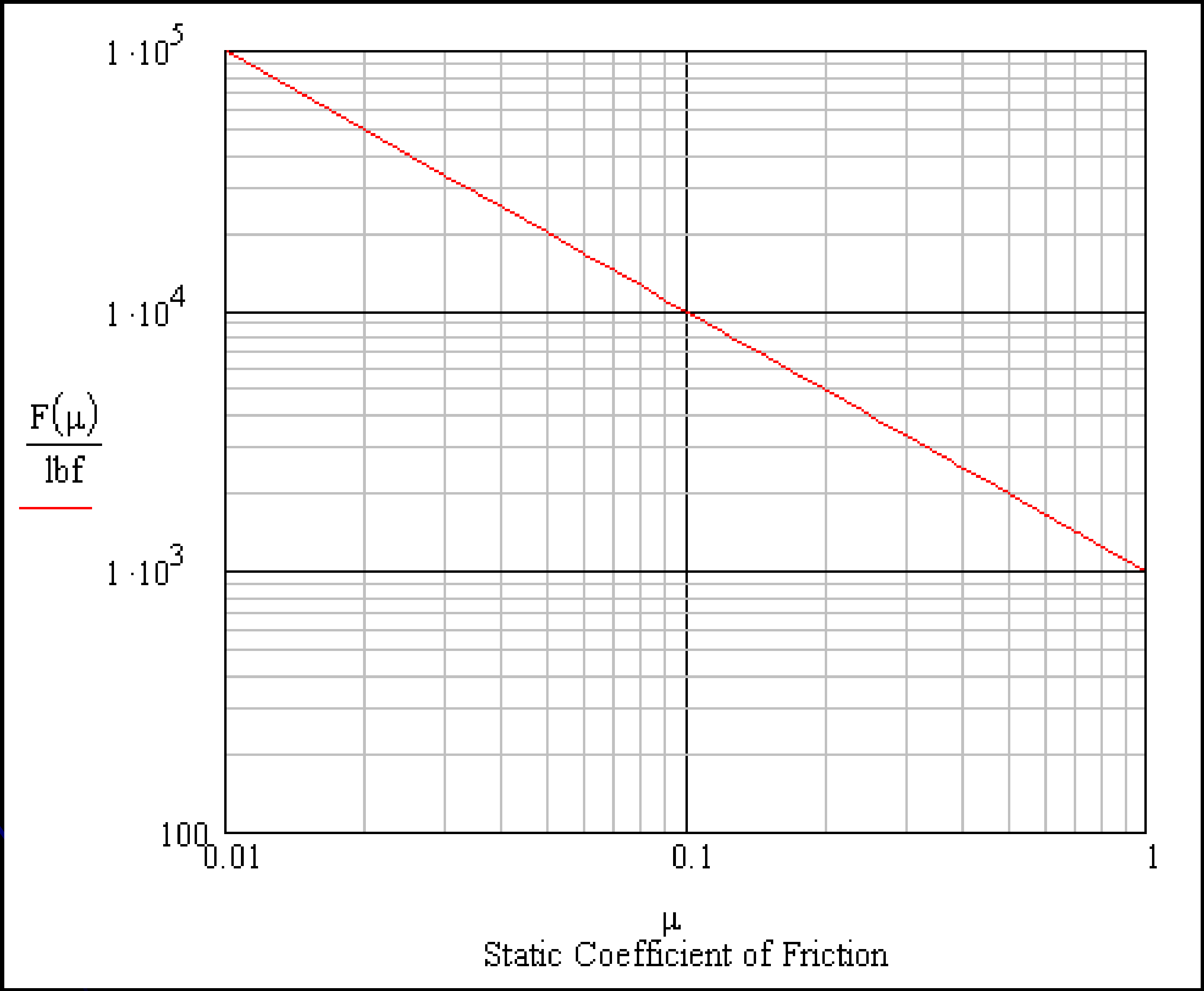
The big unknown material property

- The only thing holding the climber up and keeping it from sliding down the ribbon is **friction**
- To make the mathematical model work we need to know the coefficient of friction between the ribbon and the wheels
- The design of the ribbon is unknown now, so we cannot know this number. What to do?
  - Guess!

How does wheel pinch force vary with μ?

$$F(\mu) = \frac{m_c g(r)}{2\mu}$$

This graph and equation gives the total force required to pinch the wheels together around the ribbon to just keep a 900 kg climber from sliding down the ribbon



The implication of the last graph

- If the static coefficient of friction is as low as 0.1, wheels on a 900 kg climber must be compressed together with a total force of 10,000 lbs (5 tons)
- μ = .1 is right in the middle of the expected range for coefficient of friction
- Lower μ would make the ribbon too slippery for traction
  - μ < 0.1 is characteristic of sliding bearing materials

What is the relationship between friction and stress in the climber?

- The coefficient of friction between the wheels and ribbon determines the stress state in the whole drive mechanism
  - Lower coefficient of friction $\rightarrow$ harder the climber has to pinch the ribbon
  - The wheels and axles are in fully reversed contact or bending stress
- Fatigue failure is the result of cyclic stress
  - Fully reversed bending causes the worst material damage

Why is fatigue an issue?

- The space elevator is 100,000 km long
  - Construction climbers go the whole way
- A 20 inch diameter wheel must rotate almost 63 million times to get to the end of the ribbon—smaller wheel, more revs
- The climber gets traction by squeezing its wheels against the ribbon
  - The lower the coefficient of friction between the wheels and ribbon, the harder the climber must squeeze, forces and stresses are higher

What are fatigue failure modes of concern?

- Cracking a wheel axle
  - a disastrous failure for a climber
- Rolling fatigue causing spallation of sharp metal chunks from the rim of the wheel
  - A potential disaster for both ribbon and climber
- We need ~100% confidence that a climber will make it to the end of the ribbon
  - Fatigue allowables are always expressed at 50% confidence of failure
  - Allowable stresses are reduced to increase confidence

Conclusions from stress analysis

- Larger wheel diameters reduce contact stresses for fatigue
  - Larger wheels increase the climber's mass
- Adding wheel pairs lowers force on each pair, makes wheels smaller
  - Climber weighs less up to a point
- The maximum number of wheel sets is three and minimum wheel diameter is ~8.4 inches to rotate fewer than 150E6 revs
  - Fatigue allowable must be high to make small wheels

The motor problem

- Axial Gap electric motors in the 20kW range and up are not off-the-shelf items yet
- The climber design cannot be finished without a real motor design
  - This will take lots of money and time
- This design uses the CAD model from one vendor and mass information from another vendor
  - I couldn’t get a complete motor spec from one vendor

Where the motor info came from

- Rick Halstead of Empire Magnetics provided a spreadsheet with dimensions and masses of theoretical 20kW and 50kW axial gap electric motors
  - No torque-speed curve was available from these calculations—requires detailed design
- The CAD model came from Dantam Rao of Precision Magnetic Bearings
  - 50kW motor designed for electric cars
  - No torque-speed curve available
  - Never commercialized

Torque-speed curve

- The torque-speed curve of a motor gives the maximum torque the motor can deliver at zero speed, and how the torque declines at higher speeds
- Without this curve, you cannot calculate how the climber will accelerate up the ribbon
- You cannot calculate the power required by the traction drive

The mass budget constraint

- Why is the first climber limited to 900 kg?
  - Because the pilot ribbon is the largest that can fit in the Shuttle's cargo bay
  - The pilot ribbon can only support a 900 kg climber
  - If we can't build a 900 kg climber, then the pilot ribbon needs to be larger which means it can't be boosted to LEO with the Space Shuttle
  - Everything gets more expensive then
  - What can we boost the pilot ribbon with?

Climber Mass distribution from *The Space Elevator* by Edwards and Westling

Table 3.2: Mass Breakdown for the first climber

Component	Mass (kg)
Ribbon	520
Attitude Control	18
Command	18
Structure	64
Thermal Control	36
Ribbon Splicing	27
Power Control	27
Photovoltaic Arrays (12 m^2, 100 kW)	21
Motors (100 kW)	127
Track and Rollers	42
TOTAL	900

Design constraint of <233 kg comes from adding the red numbers in the table.

Not all of the structure can be dedicated to the drive system.

Mass Breakdown of proposed climber

Description of climber components:	Climber with six 20 kW motors	Climber with six 50 kW motors
Mass of 12 self-aligning bearings, kg	16	16
Mass of 6 axles, kg	32	32
Interface structural material, kg	51	51
Mass of 6 wheels, kg	53	53
Mass of 6 Schmidt couplings	63	63
Mass of structure in 3 fixed axle modules, kg	71	71
Mass of 6 motors, kg	84	174
Mass of 3 pairs of compression mechanisms, kg	136	136
Mass of structure in 3 floating axle modules, kg	141	141
Total mass of climber traction drive only, kg:	647	737
Required drive system mass, kg:	<233	<233

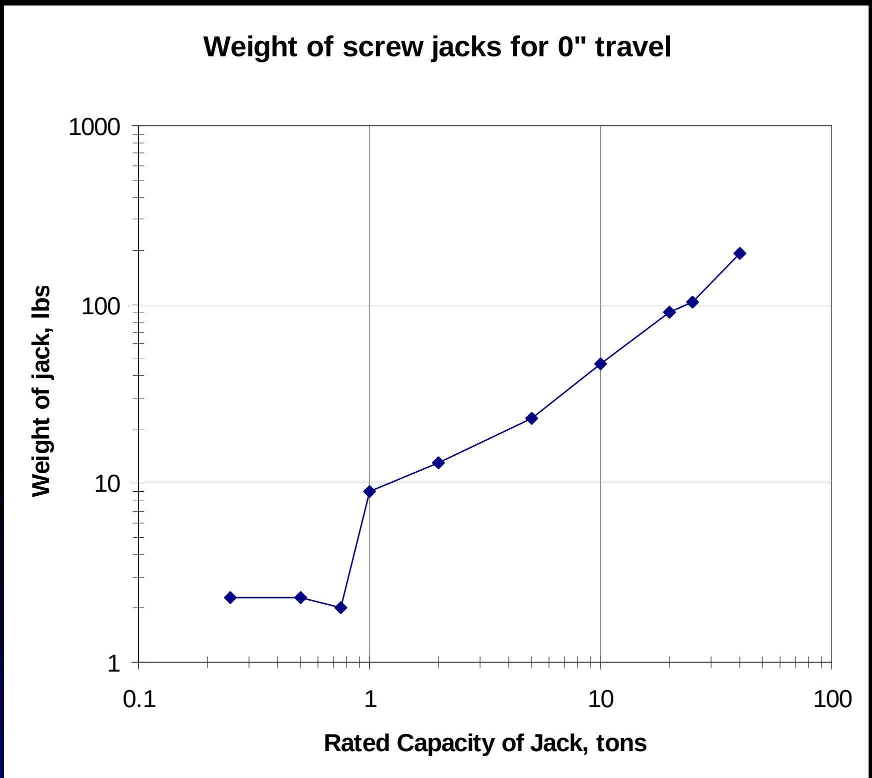
Motor masses courtesy of Rick Halstead, Empire Magnetics

The mass budget problem

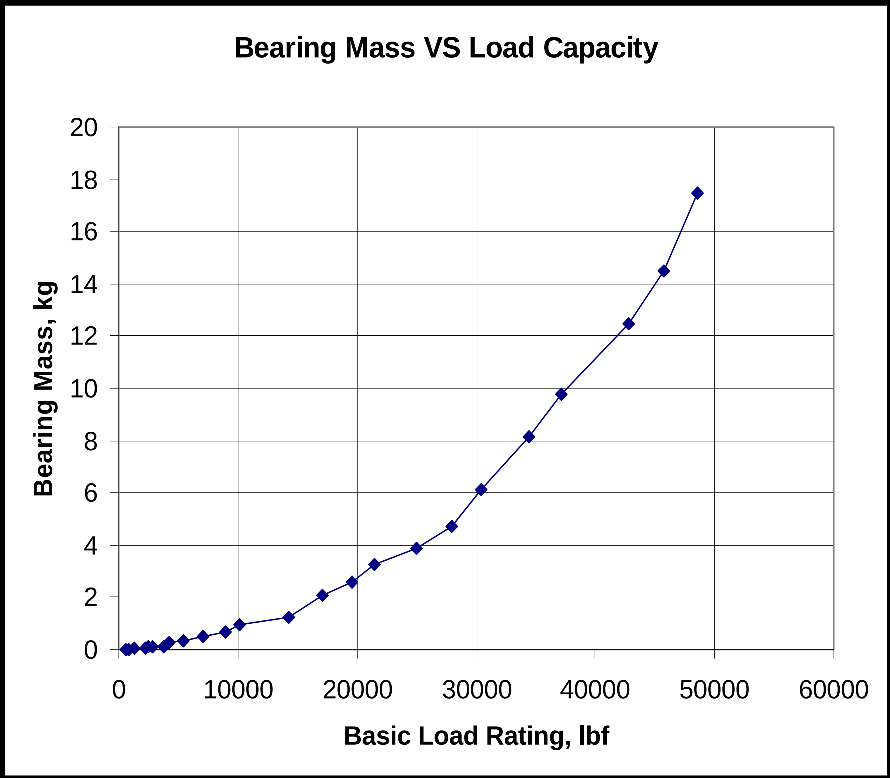
- Climber with six 20kW motors is 2.8X too heavy
- The Empire motor mass is less than the Edwards-Westling motor mass by 43 kg
  - Empire motor mass is 66% of baseline mass budget
  - This means the structural mass overage is even higher
- Can the structure be lightened by >3X?
  - Lots of analysis required to answer this

How components scale with capacity

Templeton-Kenly Uni-Lift Screw Jacks



SKF Self-Aligning Ball Bearings



The implication of these graphs is that there is a “threshold” mass for components at the low end of capacity and that mass increases rapidly with capacity

Conclusions

- The design shown is too heavy and needs to be made space-worthy
- Many components still need design:
  - thermal management system
  - brakes
  - power distribution/control hardware
  - batteries (?)
- Friction between the wheels and ribbon controls the stress in the whole drive train
- Fatigue is a killer issue requiring much analysis

Conclusions continued

- This design shows potential solutions for how to compress the wheels together and couple motors to the axles
- A possible solution to increase the coefficient of friction is to make the surface of the wheel out of CNTs

Is the SE feasible?

- I do think the engineering challenges can be overcome
- Once the ribbon fabric becomes available the race will be on
  - Whoever builds the first elevator **owns** space
- I see the SE as a cargo elevator
  - Too slow for humans (me, anyway)
  - Radiation shielding for the trip adds an onerous burden to the climber

Acknowledgements

- Dr. Bradley Edwards and Eric Westling
- Robert Wands, FNAL
- Rick Halstead, President of Empire Magnetics, Inc
- Dantam Rao, Precision Magnetic Bearing Systems, Inc.
- Metin Aydin, Caterpillar Inc

For more information:

- http://www.bartoszekeng.com/se_calcs/se.htm
- http://www.isr.us/research_es_se.asp
- http://www.spaceelevator.com/docs/
- http://www.elevator2010.org/site/primer.html
- http://www.gassend.com/
- http://www.sesinstitute.org/
- http://www.americanantigravity.com/highlift.html
- http://www.liftport.com/
- http://www.l5news.org/index.html