Bryan Laubscher
Black Line Ascension/Los Alamos National Laboratory

Bryan E. Laubscher received his Ph.D. in physics in 1994 from the University of New Mexico with a concentration in astrophysics. He is currently on entrepreneurial leave from Los Alamos National Laboratory where he is a project leader and he has worked in various capacities for 16 years. His past projects include LANL's portion of the Sloan Digital Sky Survey , Magdalena Ridge Observatory and a project developing concepts and technologies for space situational awareness. Over the years Bryan has participated in research in astronomy, lidar, non-linear optics, space mission design, space-borne instrumentation design and construction, spacecraft design, novel electromagnetic detection concepts and technologies, detector/receiver system development, spectrometer development, interferometry and participated in many field experiments. Bryan led space elevator development at LANL until going on entrepreneurial leave in 2006. On entrepreneurial leave, Bryan is starting a company to build the strongest materials ever created. These materials are based upon carbon nanotubes – the strongest structures known in nature and the first material identified with sufficient strength-to-weight properties to build a space elevator.

The Space Elevator and Its Promise for Next Generation Exploration

Bryan Laubscher
Black Line Ascension / Los Alamos National Laboratory

August 17, 2006

Next Generation Exploration Conference

NASA Ames Research Center

Acknowledgements

- Brad Edwards
- Anders Jorgensen
- Steve Patamia
- Mervyn Kellum
- Black Line Ascension
- Los Alamos National Laboratory
- Institute for Scientific Research
- NASA

Support for Visionaries

- "The flying machine which will really fly might be evolved by the combined and continuous efforts of mathematicians and mechanicians in from one million to ten million years"
  - The New York Times
    - 9 October 1903

(Source: DARPA)

- "We started assembly today"
  - Orville Wright's Diary
    - 9 October 1903

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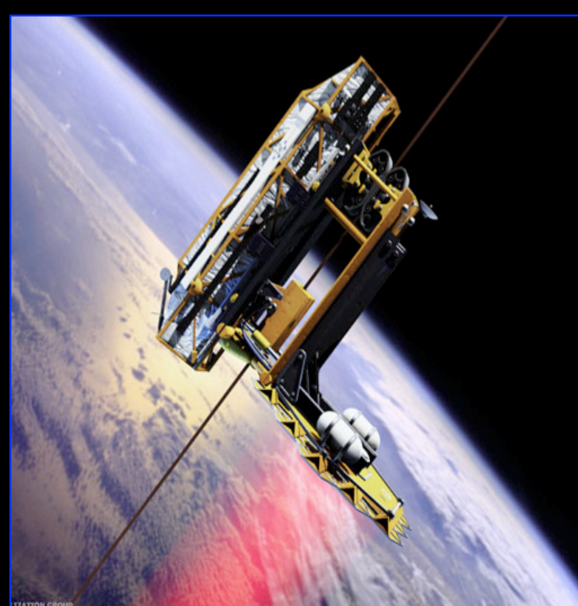
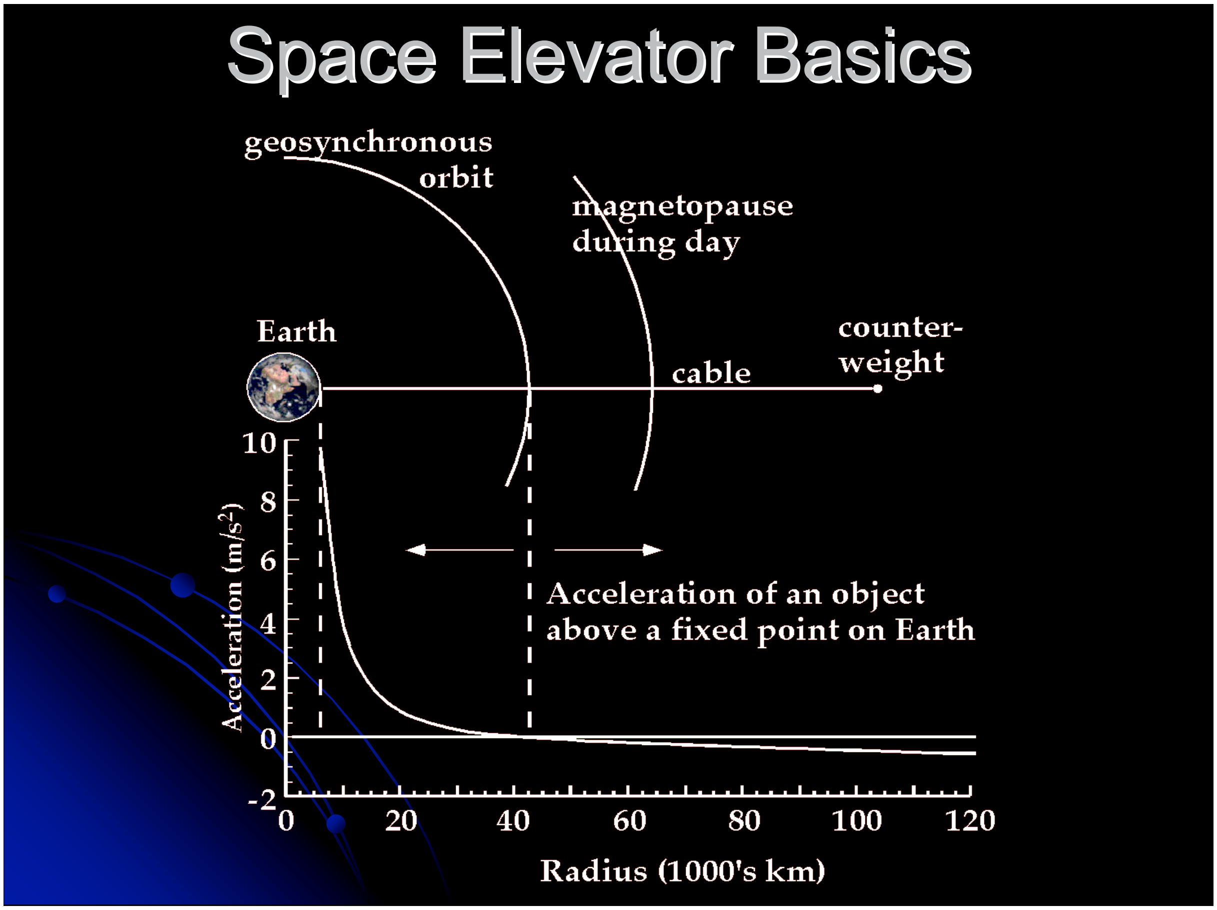
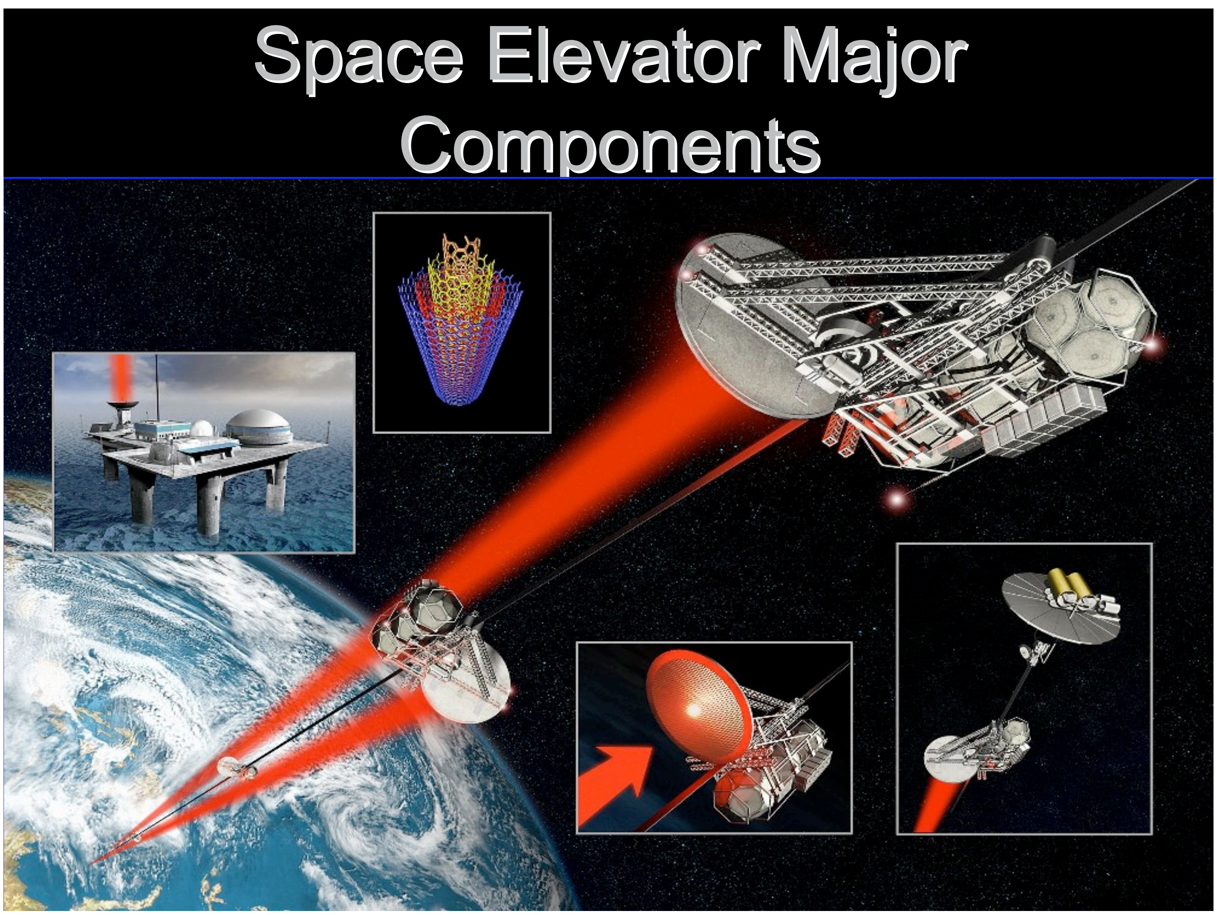
- Space Exploration
- Conferences and Events
- Philosophy
- Conclusion




Space Elevator Basics
geosynchronous
orbit
magnetopause
during day
Earth
cable
counter-
weight
Acceleration of an object
above a fixed point on Earth
Acceleration (m/s²)
10
8
6
4
2
0
-2
0
20
40
60
80
100
120
Radius (1000's km)


Space Elevator Major
Components

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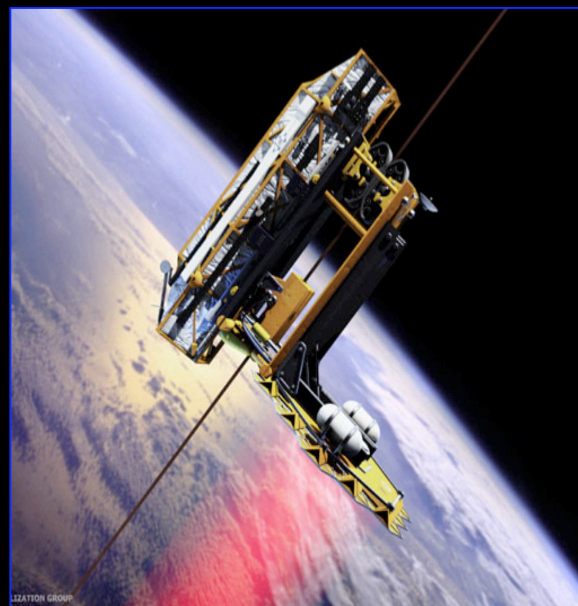


Launch Costs

Launch System	Launch Cost ($/kg)
Delta/Atlas to GEO	80,000
Space Shuttle to LEO	64,000
Ariane 5G	23,285
Delta/Atlas to LEO	10,000

(From D. Raitt, ESA/ESTEC., Proc. IAC 2004, Vancouver, Canada)

Rocket (In)Efficiency

- The rocket equation explains the efficiency of rocket propulsion:

$$\Delta V = V_p \ln(M_i/M_f)$$

$$\exp[\Delta V/ V_p] = M_i/M_f$$

- Large amounts of fuel are needed to accelerate fuel and payload to speed so that the accelerated fuel can be used to accelerate the payload (and remaining fuel) to even greater speed, etc.
- Fuel is lifted to high altitudes before it is burned

Earth's Gravity Well And other ΔVs

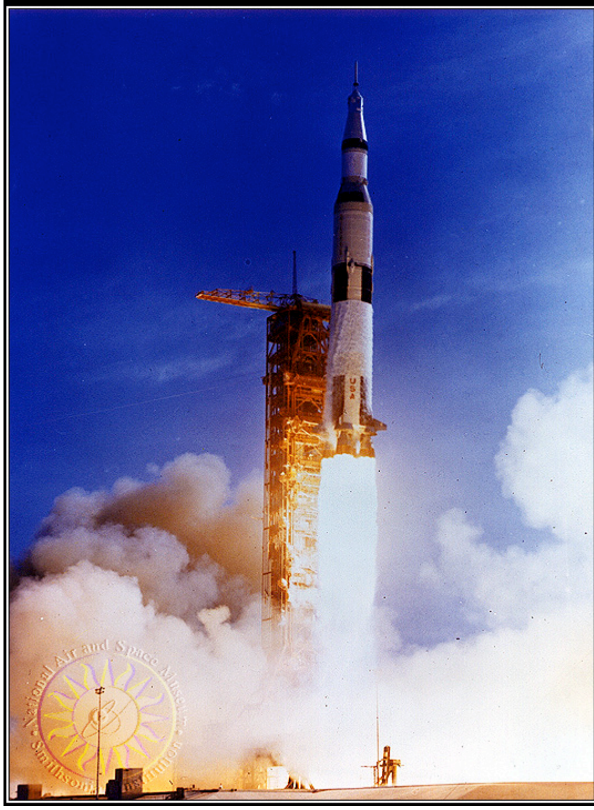
- Earth's gravity well is so deep that we can barely escape it with chemical rockets. Once you are at LEO, you are "most of the way" to anywhere.

$$\Delta v_{\text{Earth to LEO}} = 9.7 \text{ km/sec}$$

$$\Delta v_{\text{LEO to MoonSurf}} = 5.5 \text{ km/sec}$$

$$\Delta v_{\text{LEO to MarsVic}} = 3.8 \text{ km/sec}$$

Saturn V



- Built in 1960's for Apollo Program
- Chemical Propulsion
- 5% of mass to LEO
- 2.4% of mass to Trans Lunar Injection
- 1st stage, 94%mass ratio
- 2nd stage, 90%mass ratio
- 3rd stage, 86%mass ratio
- Most powerful rocket even flown
- No failures

Mars Mass and Cost with Chemical Rockets

- Test mass from Earth's surface to LEO
  - M_{ratio} = 20
- Test mass from LEO to Mars Transfer Orbit
  - M_{ratio} = 2.39
- Miscellaneous rocket and structure mass
  - M_{misc} = 6.9 % of the lifted fuel and payload
- Mass Expenditure to Mars
  - Mass Expenditure = (1 kg x 20 + 2.39 kg x 20) x 1.069 = 72.5 kg
- Total cost for 1 kg to Mars
  - Cost to LEO $10,000 / kg x 72.5 kg = $725,000
  - Good to a factor of 3!
  - Brought to you by the rocket equation and Earth's gravity well and 40 years of experience with the cost of rockets!
- NOTE: These calculations are for cargo that doesn't respirate, drink or eat on the way to Mars. For humans the mass that must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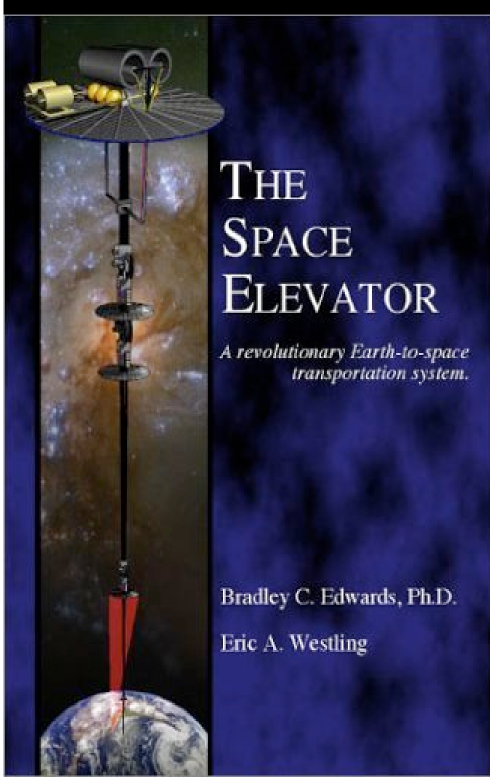
Space Elevator Early History
Konstantin Tsiolkovsky 1895
Sir Arthur C. Clarke 1945
John McCarthy early 1950s
Y. N. Artsutanov 1960
Isaacs, Vine, Bradner, Bachus, 1966
Jerome Pearson, 1975
К.Э. ЦИОЛКОВСКИЙ
ГРЕЗЫ О ЗЕМЛЕ И НЕБЕ

1999 Space Elevator Concept

- Carbon nanotubes discovered in 1991
- 1999 NASA Space Elevator Conference
- Reported in press that we would build an elevator in “300 years”
- Piqued Brad Edwards’ interest

Space Elevator Recent History



- 2000 Bradley C. Edwards
- 2002 *The Space Elevator* book published
- 1st (2002), 2nd (2003) and 3rd (2004) Annual International Space Elevator Conference
- Space Exploration2005 – 2nd Biennial SE Workshop
- 55th & 56th International Astronautical Congresses

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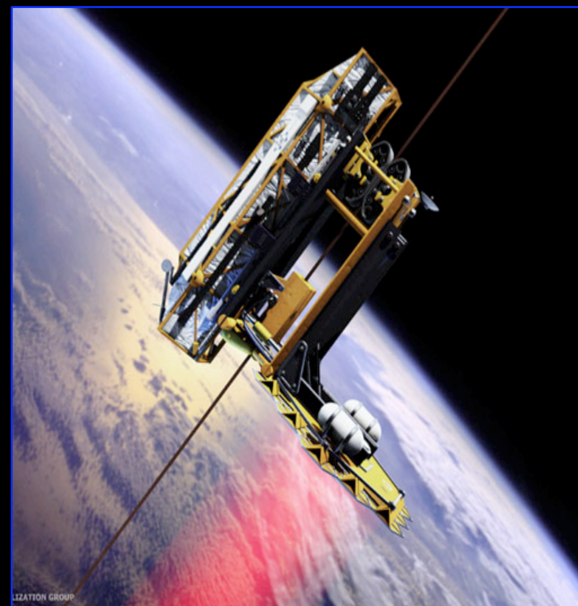
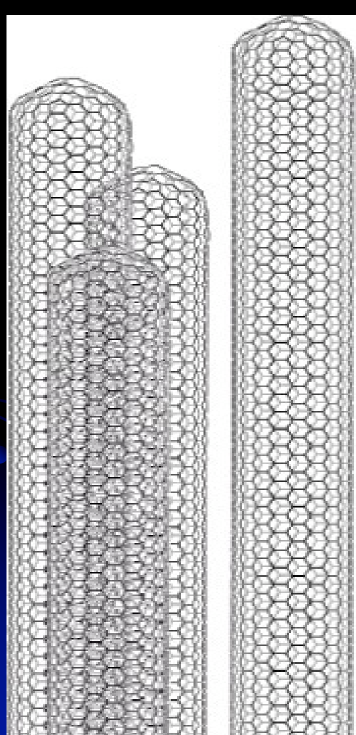
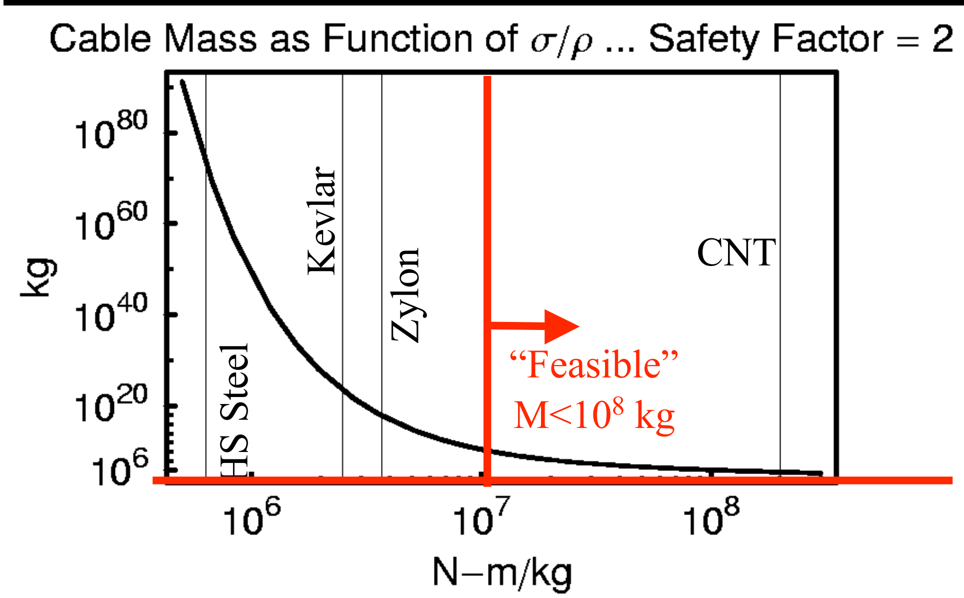


Carbon Nanotubes



- 1985 Smalley and Curl discover Buckyballs, C_{60}
- 1991 Iijima discovers Carbon Nanotubes
- 1 to many nanometers wide
- As of 2004, 4cm length
- Up to 300 GPa depending on purity (high strength steel – 4GPa)
- 130 GPa required for SE (with safety factor of two)

Importance of Tensile Strength/Density



WTC: 10^9 kg

Earth: 6×10^{24} kg

Sun: 2×10^{30} kg

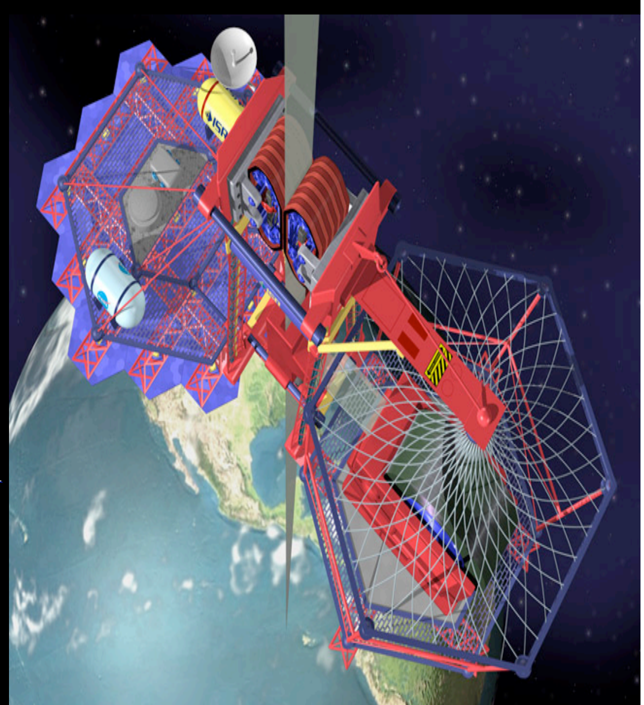
Galaxy: 10^{41} kg?

Universe: 10^{52} kg?

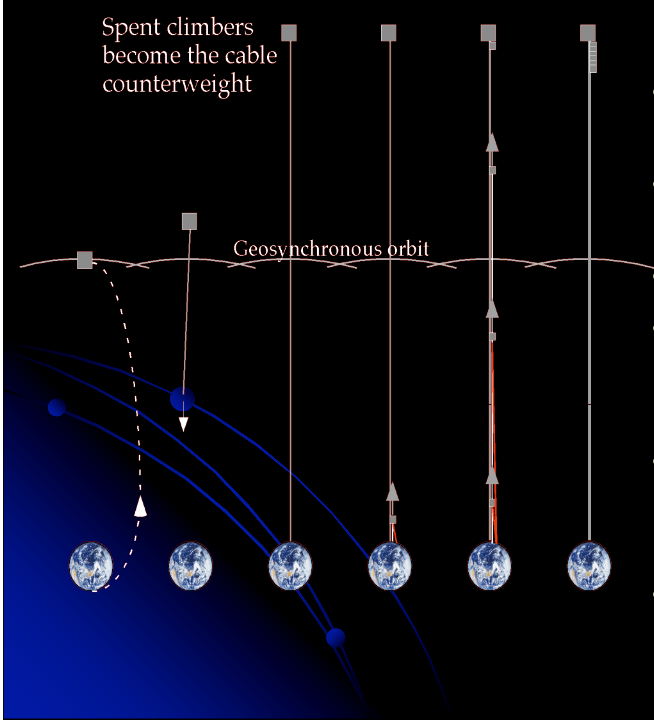
(Designed tension half of tensile strength) (S. E. Patamia, LANL)

Initial Space Elevator Parameters

- 100,000 km long (36,000 km GEO orbit)
- 1 meter wide, curved cross section
- Thinner than a sheet of paper
- 20 metric ton capacity
- 650 metric ton ribbon, 800 metric ton counterweight
- 7 metric ton climber, 13 metric ton payload
- Power beamed to climbers from lasers coupled to 10-meter telescopes on Earth
- 7 day trip to geosynchronous
- Launch costs
  - 1st Elevator - $3000 / kg
  - 5th Elevator - $300 / kg



Deployment Scenario



- Pilot ribbon
  - 22 – 40 metric tons
  - ~15 cm wide
  - 100,000 km long
- Assemble spacecraft in LEO
- Boost to GEO above ground station
- Deploy ribbon downward
- Thrust to keep rising spacecraft over ground station
- Build up final ribbon by sending up small climbers that attach new ribbon
- 1st space elevator finished after two years of assembly

Economics: Elevators and Launch Cost

Bryan's Estimates

- Shatters the paradigm of the rocket equation!
- $1.5 B of research and development
- 1st elevator costs $18 B
- 2nd elevator costs $6.9 B
- 3rd elevator costs $4.2 B
- 4th elevator costs $2.4 B
- Economy of scale is operating in a space elevator infrastructure

Ribbons	Launch Cost ($/kg)
1x20T	3000
2x20T	300
2x20&200T	150
2x20,200, 500T	30
Space Shuttle	64,000

Transcontinental Railroad Analogy

- Planning began in the 1850's
- Built from 1863-1869 in a "wilderness"
- The Union was fighting the Civil War when it began this project
- Huge initial cost to build the line from Omaha, Nebraska to Sacramento, California
- Built the railroad line as well as infrastructure such as coaling stations and water sources for the steam locomotives
- Created towns in the middle of nowhere
- Unified the United States across the continent and opened the west
- America's greatest engineering feat of the 19th century
- New York to San Francisco travel fell from 6 months to 7 days and $1000 to $70
- Owners became the some of the richest men in America

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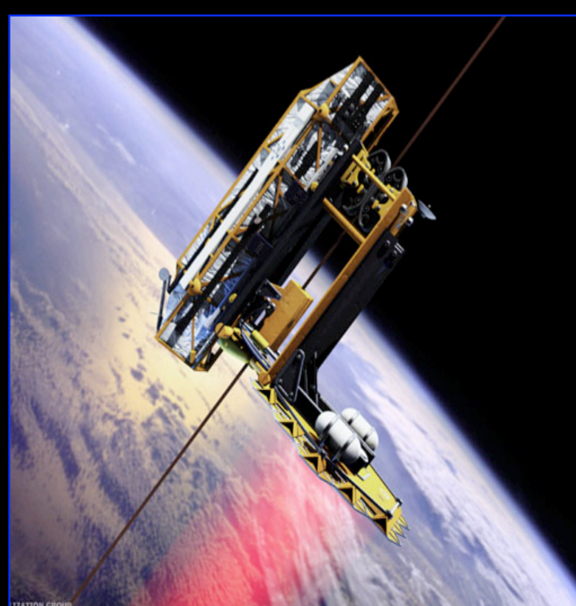
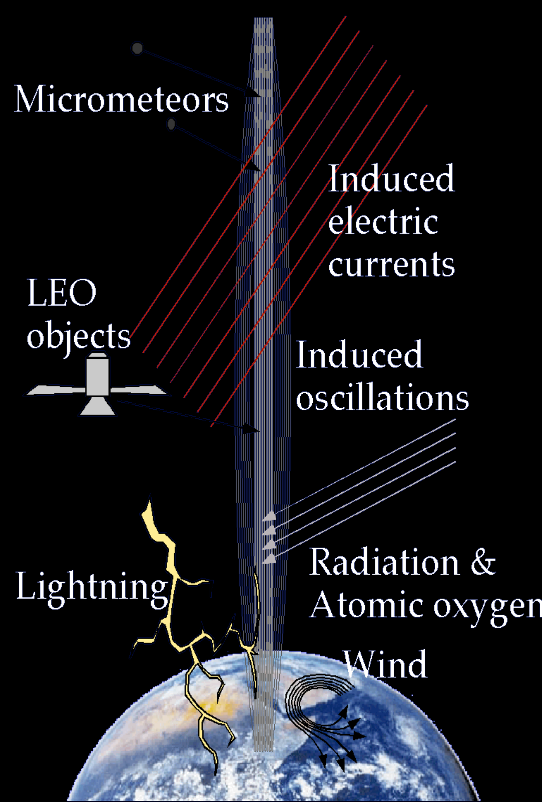


Technology Development

- Carbon Nanotubes
  - Woven ribbon
  - Composite ribbon
  - Lower cost
  - Manufacturability
- Climbers
  - Compression or pressure on ribbon without damage
  - High reliability
  - Operate in multiple environments
  - Reusable
- Power Beaming
  - Each component has been demonstrated but an integrated system has not been operated
- Human travel on space elevators above LEO requires shielding development
- Deployment Spacecraft
  - Must be launched to LEO in pieces and then assembled
  - Deployment mechanism
  - Power for thrusting and deployment
- At the current, conceptual level of our understanding of the space elevator systems, no “show stoppers” have been identified
- The devil is in the details

Hazards

- Magnetosphere
- Induced oscillations
- Radiation
- Atomic oxygen in Earth’s upper atmosphere
- Environmental Impact: Ionosphere
- Malfunctioning climbers
- Lightning, wind, clouds
- Meteors and space debris
- Satellites
- Health considerations

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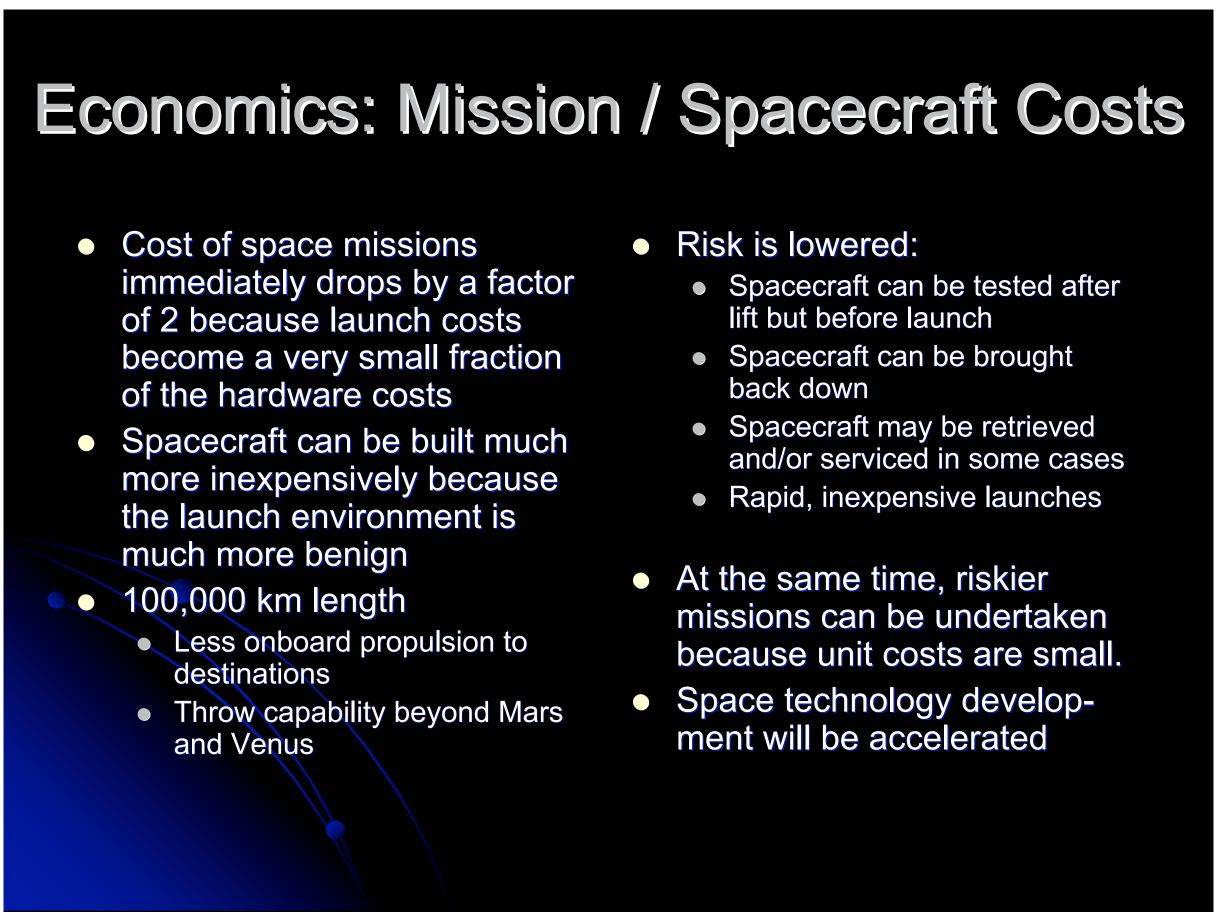

Economics: Mission / Spacecraft Costs
Cost of space missions immediately drops by a factor of 2 because launch costs become a very small fraction of the hardware costs
Spacecraft can be built much more inexpensively because the launch environment is much more benign
100,000 km length
Less onboard propulsion to destinations
Throw capability beyond Mars and Venus
Risk is lowered:
Spacecraft can be tested after lift but before launch
Spacecraft can be brought back down
Spacecraft may be retrieved and/or serviced in some cases
Rapid, inexpensive launches
At the same time, riskier missions can be undertaken because unit costs are small.
Space technology development will be accelerated

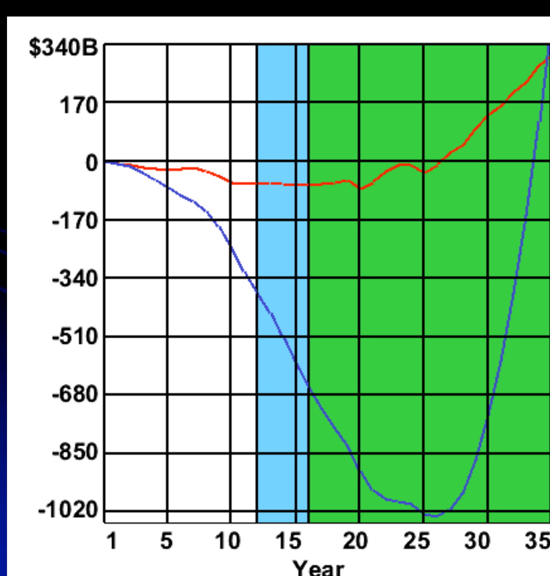
Space Solar Power

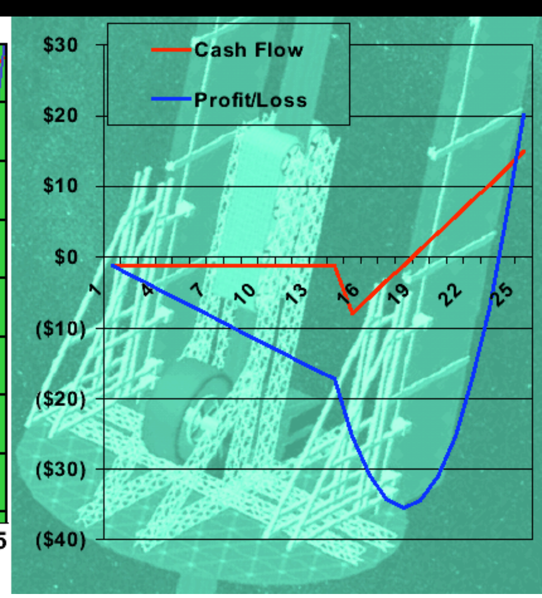
- SSP is possibly the second major commercial use of space
- Photovoltaic cells convert sunlight to electricity, then this energy is converted to microwaves and beamed to Earth
- On Earth these receiver arrays convert microwave power to electrical energy
- SSP promises clean energy for Earth
- Remote parts of Earth can have power beamed to a local ground station allowing economic growth
- High latitudes are problematic
- Constructing these huge structures at geosynchronous orbit will promote robotic technologies valuable to working in hostile environments

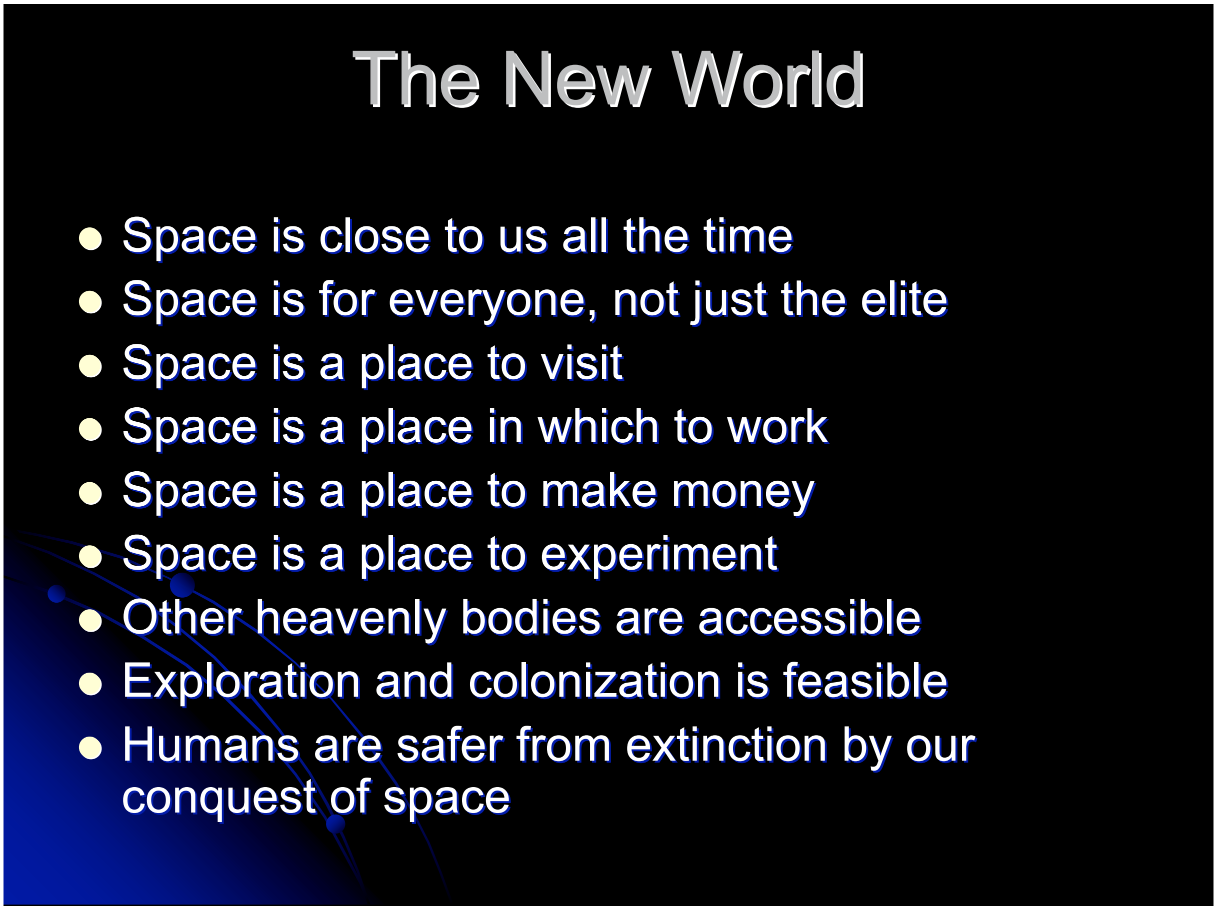
SSP Business Model

1975 NASA Study – Rockets
35 years to "breakeven"

2004 M. Kellum Study – Space Elevator
7 years to "breakeven"






The New World
Space is close to us all the time
Space is for everyone, not just the elite
Space is a place to visit
Space is a place in which to work
Space is a place to make money
Space is a place to experiment
Other heavenly bodies are accessible
Exploration and colonization is feasible
Humans are safer from extinction by our conquest of space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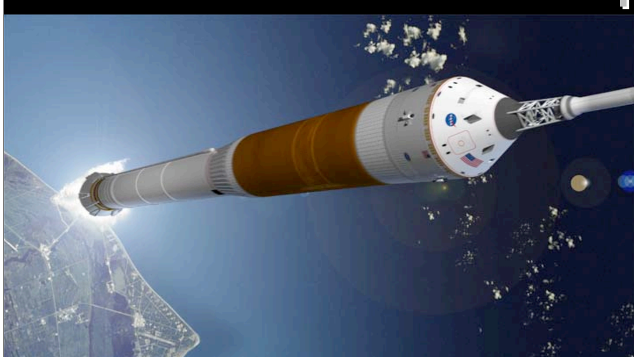
Lunar Exploration

- Apollo Program
  - 1962 – 1972
  - Precursor programs were Mercury and Gemini
  - Development missions to test technology
  - Lunar Orbit Rendezvous
  - 6 successful moon landings (last one in 1972)
  - 1 failed moon landing (Apollo 13) but crew returned safely
  - Saturn V, LEM, Command and Service modules developed
  - Cancelled prematurely by Nixon, 18, 19 & 20 never flew
  - Cost $135 B 2006 ($25.4B 1969)
- Space Exploration Initiative
  - 1989
  - ~$270 Billion (1989) for Lunar exploration and operations over 34 years
- Project Constellation
  - 2004 - ?
  - CLV & CEV being designed

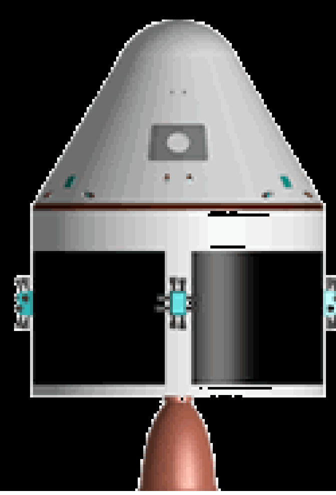
Lunar Exploration

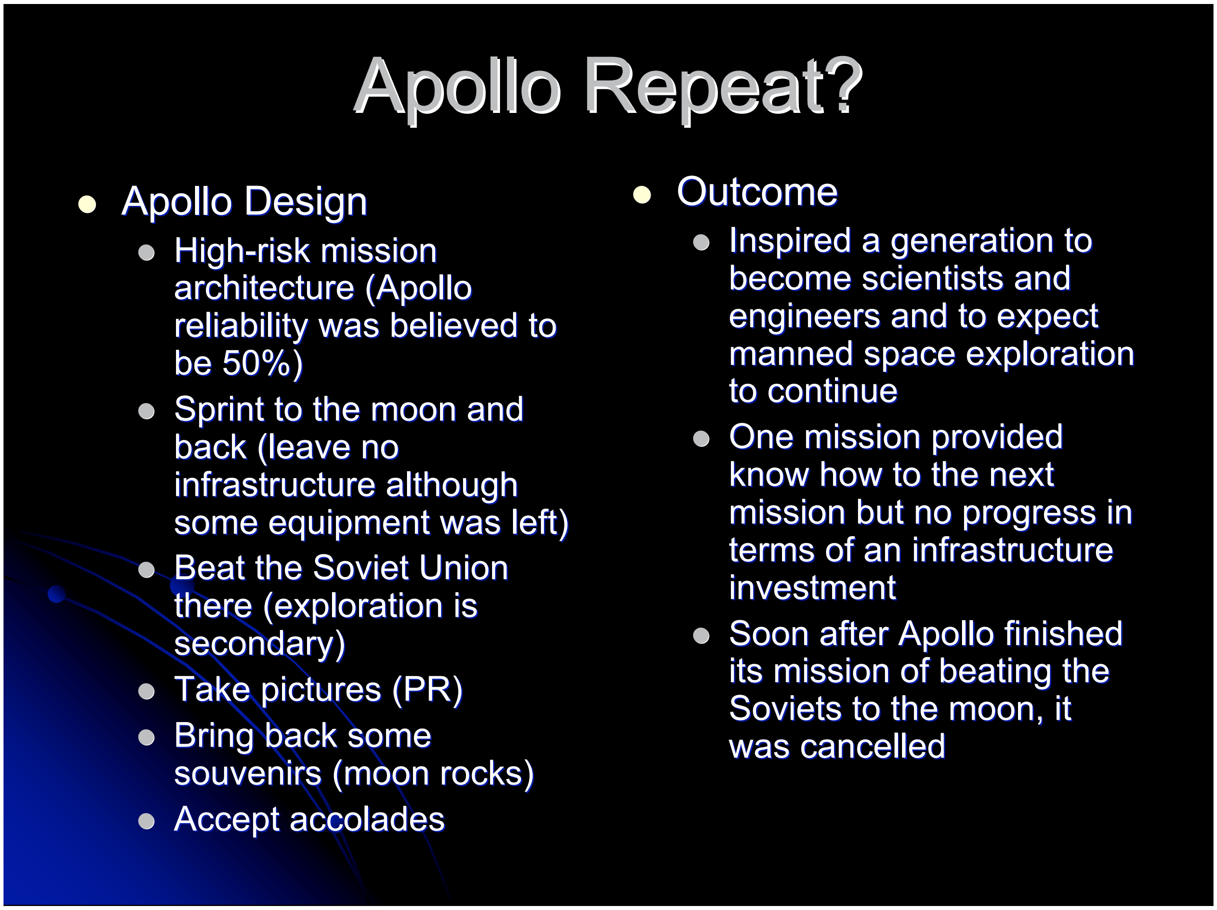


Project Constellation

Crew Launch Vehicle

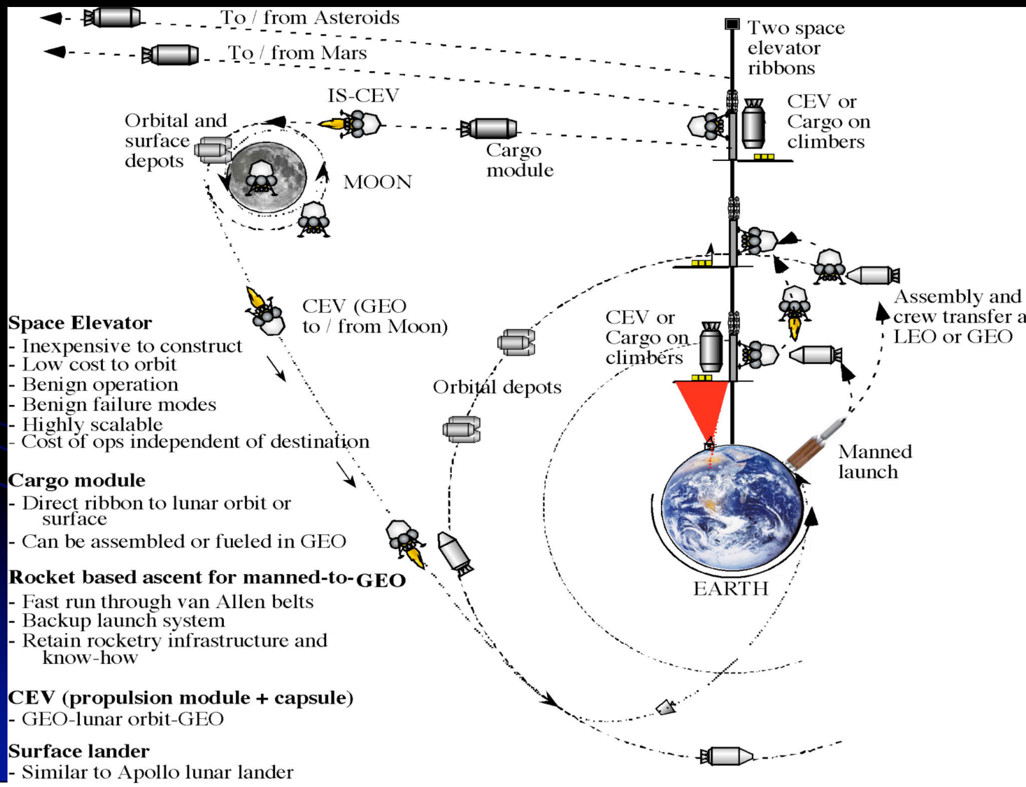
Crew Exploration Vehicle




Apollo Repeat?
Apollo Design
High-risk mission architecture (Apollo reliability was believed to be 50%)
Sprint to the moon and back (leave no infrastructure although some equipment was left)
Beat the Soviet Union there (exploration is secondary)
Take pictures (PR)
Bring back some souvenirs (moon rocks)
Accept accolades
Outcome
Inspired a generation to become scientists and engineers and to expect manned space exploration to continue
One mission provided know how to the next mission but no progress in terms of an infrastructure investment
Soon after Apollo finished its mission of beating the Soviets to the moon, it was cancelled


A SPACE ELEVATOR BASED EXPLORATION PROGRAM
Principal Investigator:
Dr. Bradley C. Edwards
X Tech Corp.
Telephone: 304-669-9986
E-mail: brad_edwards@yahoo.com
Co-Investigators:
Dr. Hyam Benaroya
Rutgers University
Dr. Michael Duke
Colorado School of Mines
Dr. Hermann Koelle
Berlin Technical University
Dr. Bryan Laubscher
Los Alamos National Laboratory
Pam Luskin
Futron Corporation
Dr. David Raitt
European Space Agency - ESTEC
Ben Shelef
Spaceward Consulting
Dr. Paul Spudis
Spudis Lunar Resources
The Space Elevator Based Exploration Program will fully meet all of the goals set forth by President Bush and NASA Adminsitrator O'Keefe.
Concept: Well-studied lunar systems are combined with an innovative transportation system to produce an optimal exploration program.
• Lunar Base: Optimized designs for base and CEVs
• Transport system
- The Space Elevator: Low-cost, high-capacity, definable development risk. 3000 tons/yr @ $1B/yr operating cost
- CEV: Mature technology to limit risk and cost
• Evaluation Factors
- Safety : Efficient transportation allows for redundancy and overbuilt systems which provide safety
- Reliability: Few serious failure modes, failure mitigation quantifiable and achievable
- Affordability: 99% savings on transportation costs,
Total: $68B from 2005 through 2023 for large initial base
Peak: $5B in 2020
- Sustainability: Low-costs, high-performance, public, international and commercial support probable
- Extensibility/Evolvability: System is immediately applicable to extending human exploration across solar system
- Risk Assessment: small initial development risk and low overall program failure risk

Lunar Exploration

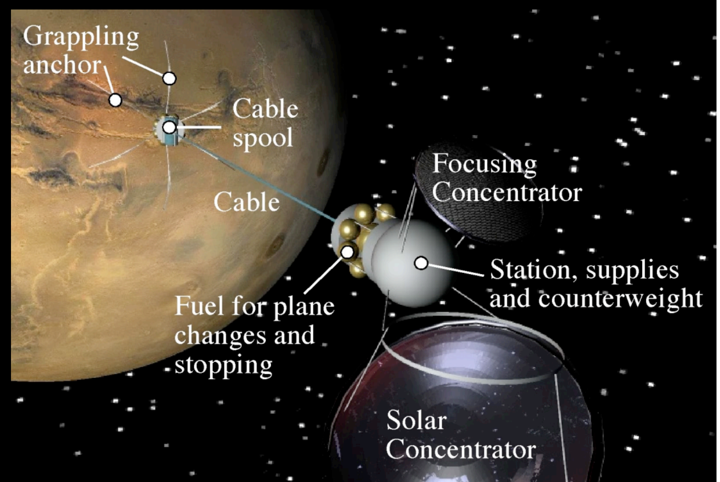


Mars Exploration Plans

- 1989 SEI Program - NASA
  - Slightly modified Apollo era design mission, exploration and base operations for 34 years
  - ~$270 Billion for lunar exploration
  - ~$270 Billion over for Martian exploration
  - 1000 ton Spacecraft to Mars
- Mars Direct – Martin Marietta
  - In-situ resource utilization (ISRU)
  - 1000 tons → 87 tons
  - $30 Billion
- 1993 Mars Design Reference Mission, NASA
  - Compromise between SEI and Mars Direct
  - $55 Billion
- 2004 Project Constellation, NASA
  - Crew Exploration Vehicle
  - Crew Launch Vehicle

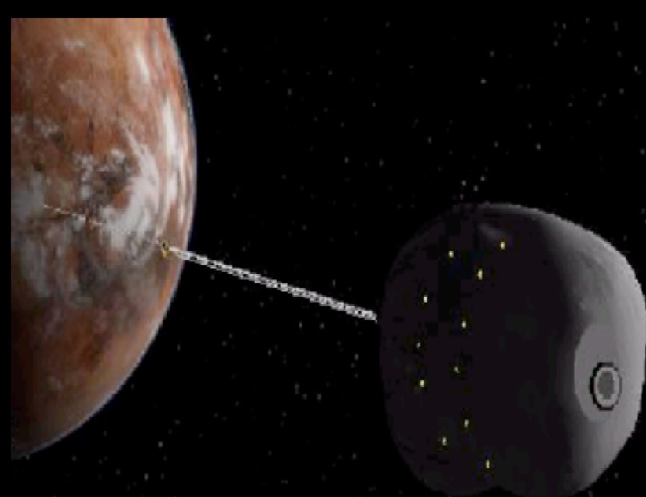
Mars Exploration / Earth Elevator

- Earth Elevator
  - Affordable, reliable robotic and manned exploration missions
  - High capacity, low cost launches to Mars
  - Possible to economically and reliably supply manned outposts and colonies
  - Earth elevator throws a Martian elevator to Mars orbit



Mars Exploration / Martian Elevator

- Martian Elevator
  - Less massive and shorter than Earth elevator
  - Deploys itself from orbit
  - Save on aerobraking and landing hardware using Martian elevator
  - Many interception altitudes are possible with a space elevator rendezvous
  - Enables recycling of hardware between Martian and Earth orbit
  - Enables capture of supplies from Earth and commerce from Mars to Earth



Mars Exploration Recap

- Rocket
  - 72.5 kg on Earth to get 1 kg on Mars (rocket equation)
  - That means $725,000 / kg of cargo to Mars (with aerobraking)
  - Everything must survive violent launch environment
- Space Elevator
  - $3000 / kg (economy of scale)
  - Benign launch environment, except for radiation
  - Higher velocity trip to Mars possible
  - Launch infrastructure that supports our ambitions in space

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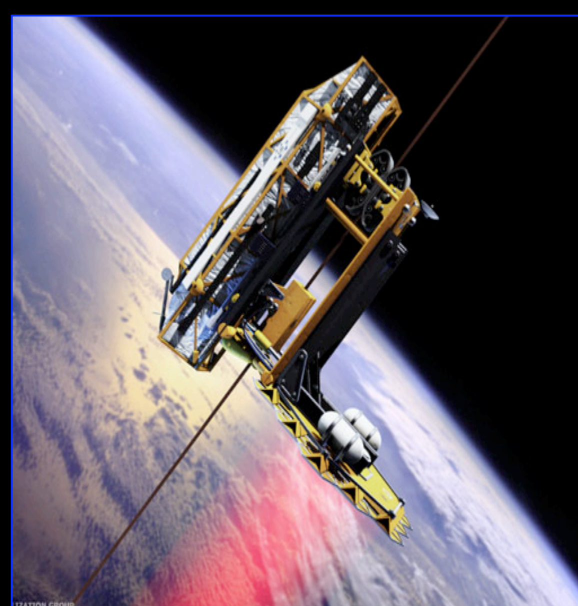

Future Conferences

57th International Astronautical Congress, Valencia, Spain, October 2 – 6, 2006: www.iac2006.com

Space Exploration 2007, 2nd Biennial Space Elevator Workshop, Albuquerque, NM March 25 – 28, 2007: www.sesinstitute.org