Plans for Using Geant4 in Space Elevator Research

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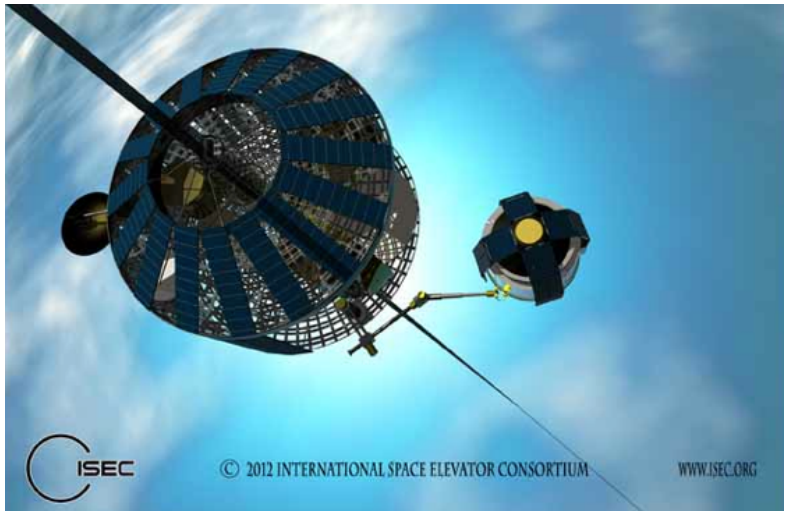
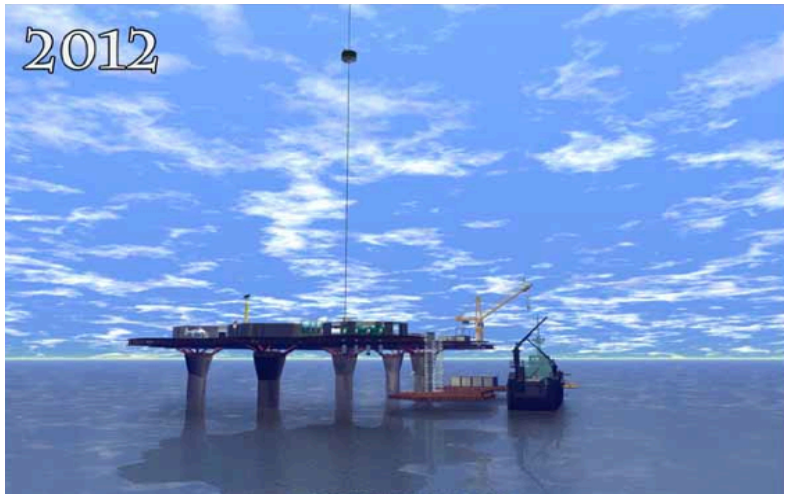
Outline

- A space elevator primer
- Critical technologies
- The research program
- A space elevator simulator
- Conclusion

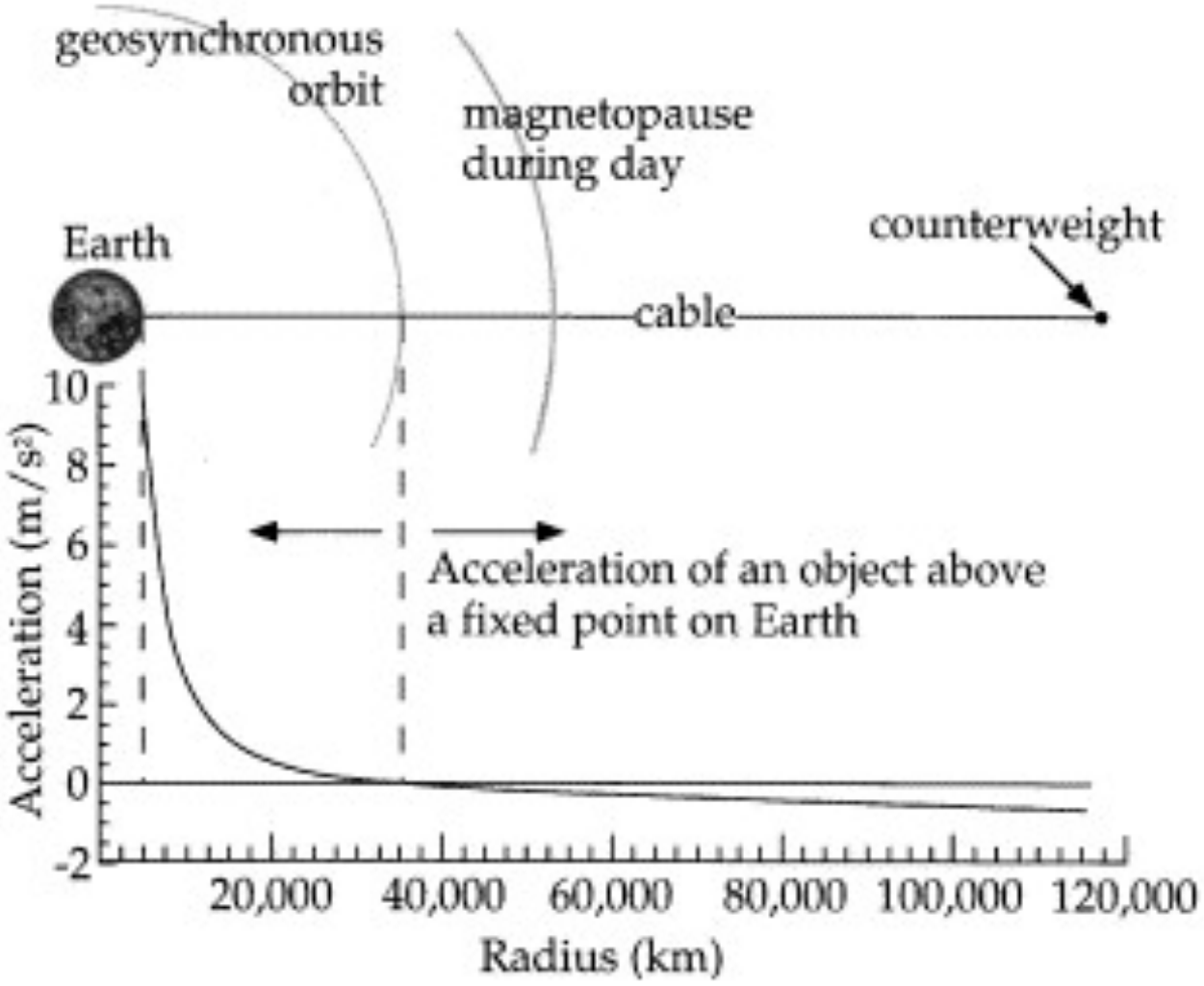
The Modern Space Elevator

- First scientific concept:
  - Tsiolkovsky, 1895
  - compressive tower
- Modern space elevator a tether, not a tower
  - tensile structure, gravitationally stabilized
- DARPA study (Edwards, 1983)
  - SE is feasible with strong materials
- Discovery of CNTs (Iijima, 1991)



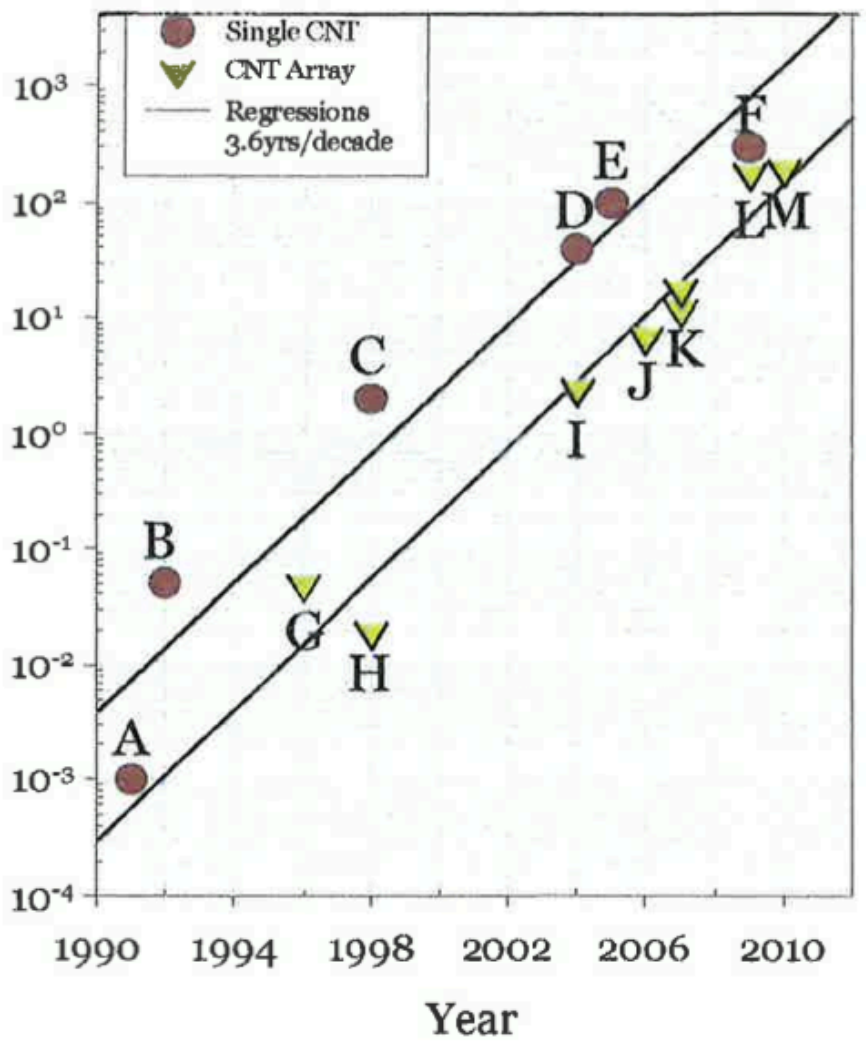


Balancing the Forces



Strong Materials

- Carbon nanotubes
  - strong enough
  - long enough ?
- Single crystal graphene
  - 200 x steel strength
  - 1 m long sample produced
  - continuous production being studied
- Other materials
  - boron nitride
  - some already strong enough to build lunar elevator



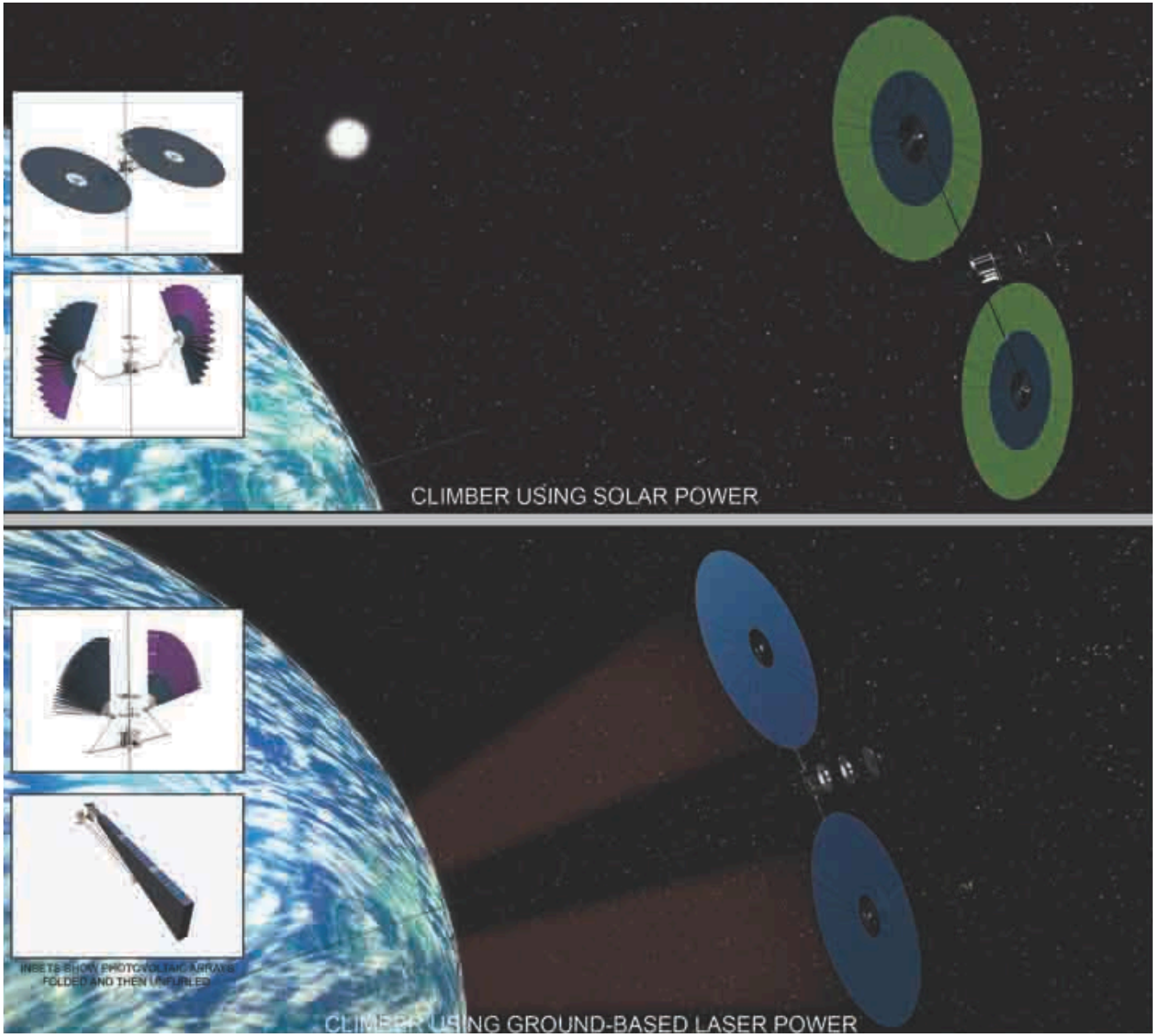
Climbers

- Estimated speed 200 km/h
  - determined from likely power available
  - will arrive at GEO in 7 days
- Mass of first climber: 20 tons (14 ton payload)
  - later climbers will be bigger
- Crawlers
  - grip the tether with rollers and pull themselves up
  - problems: tether material may be slippery, large number of bearing revolutions required for a single journey to GEO, heat dissipation
- Maglev/linear induction motors
  - use tether to carry current, set up magnetic field (graphene ?)

Power Transmission to Climber

- Solar power
  - for medium and high altitudes
  - should be more than adequate
- Beamed power
  - ground-based lasers or microwaves for low altitude
  - more problematic
    - deep in gravity well
    - atmosphere
- Tether as transmission line
  - could be configured as coax cable, or single strand with AC power

Solar and Ground-based Laser

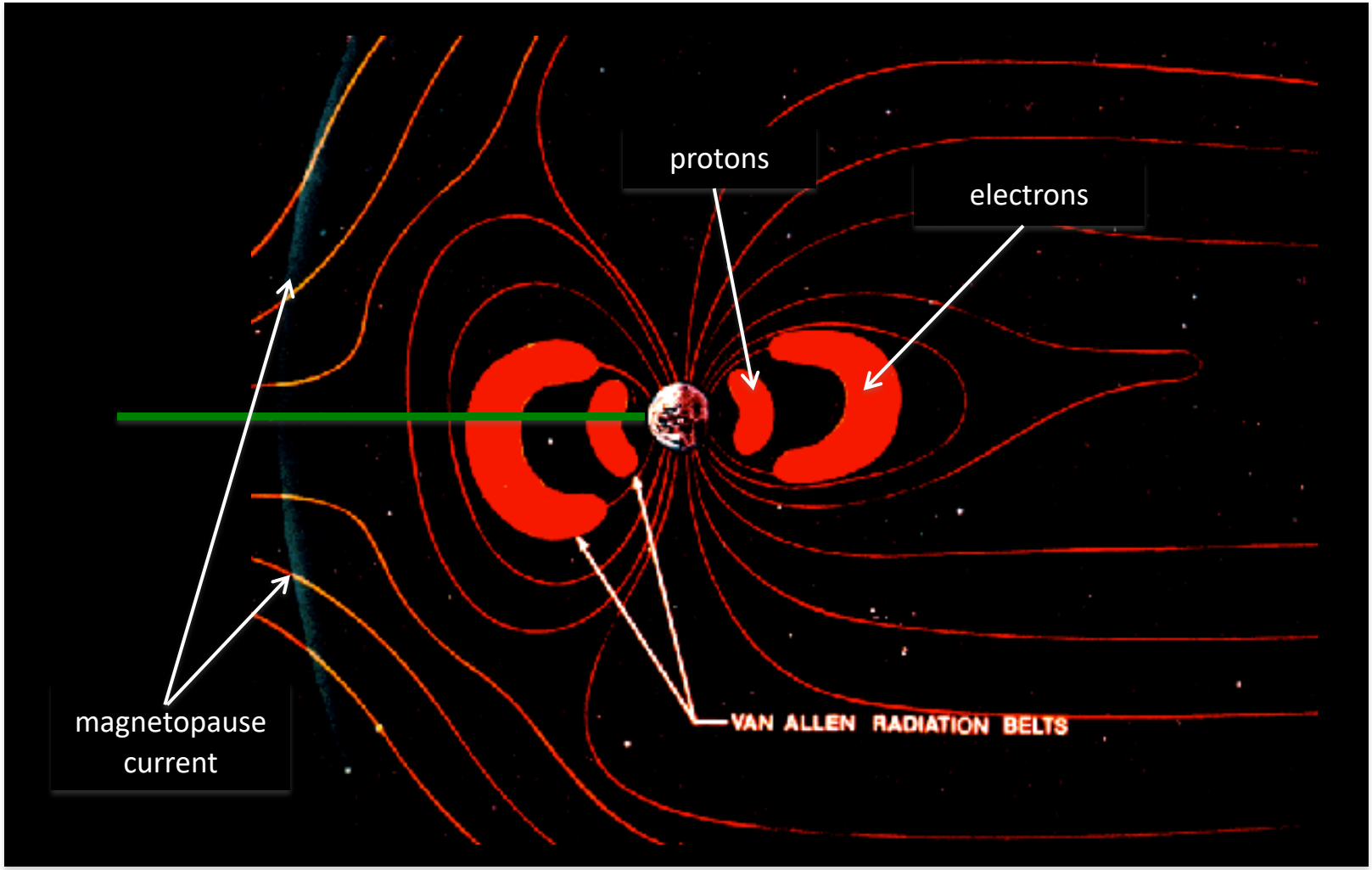


Simulating the Electromagnetic and Radiation Environment

- Need models of magnetic and electric fields from Earth's surface to 100,000 km altitude
  - Tsyganenko magnetic model best so far
    - Laurent Desorgher's implementation of this used in Geant4 application Planetocosmics
  - several electric field models available
    - some in database form, some as potentials

- Need particle fluxes and types
  - AE9 database latest for electrons
  - AP9 database latest for protons
  - other particle types?

Magnetic and Radiation Environment

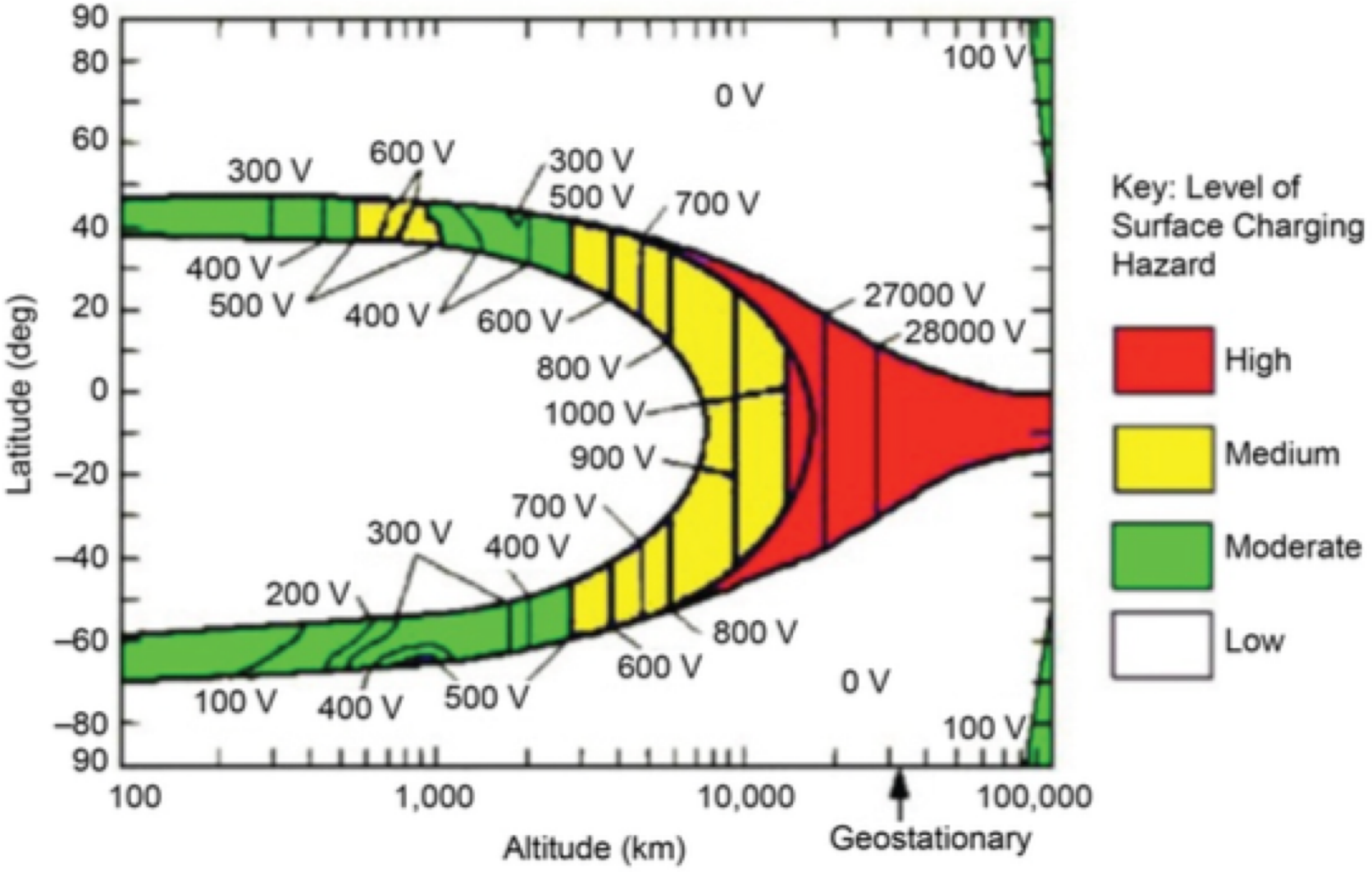


Charging

- Spacecraft accumulate charge from space environment
  - charging can be severe, especially if there are loose ends, sharp edges
  - discharge could be strong enough to destroy SE tether material
    - what kind of mitigation should be planned?
  - formerly a Geant4 advanced example: cosmic ray charging for LISA
    - discontinued after G4 9.2
    - but can be extended for space elevator studies

- Use magnetosphere models and AE9, AP9 databases to get particle type and flux
- Use Geant4 EM processes to do interactions throughout SE length

Charging Hazard vs. Altitude



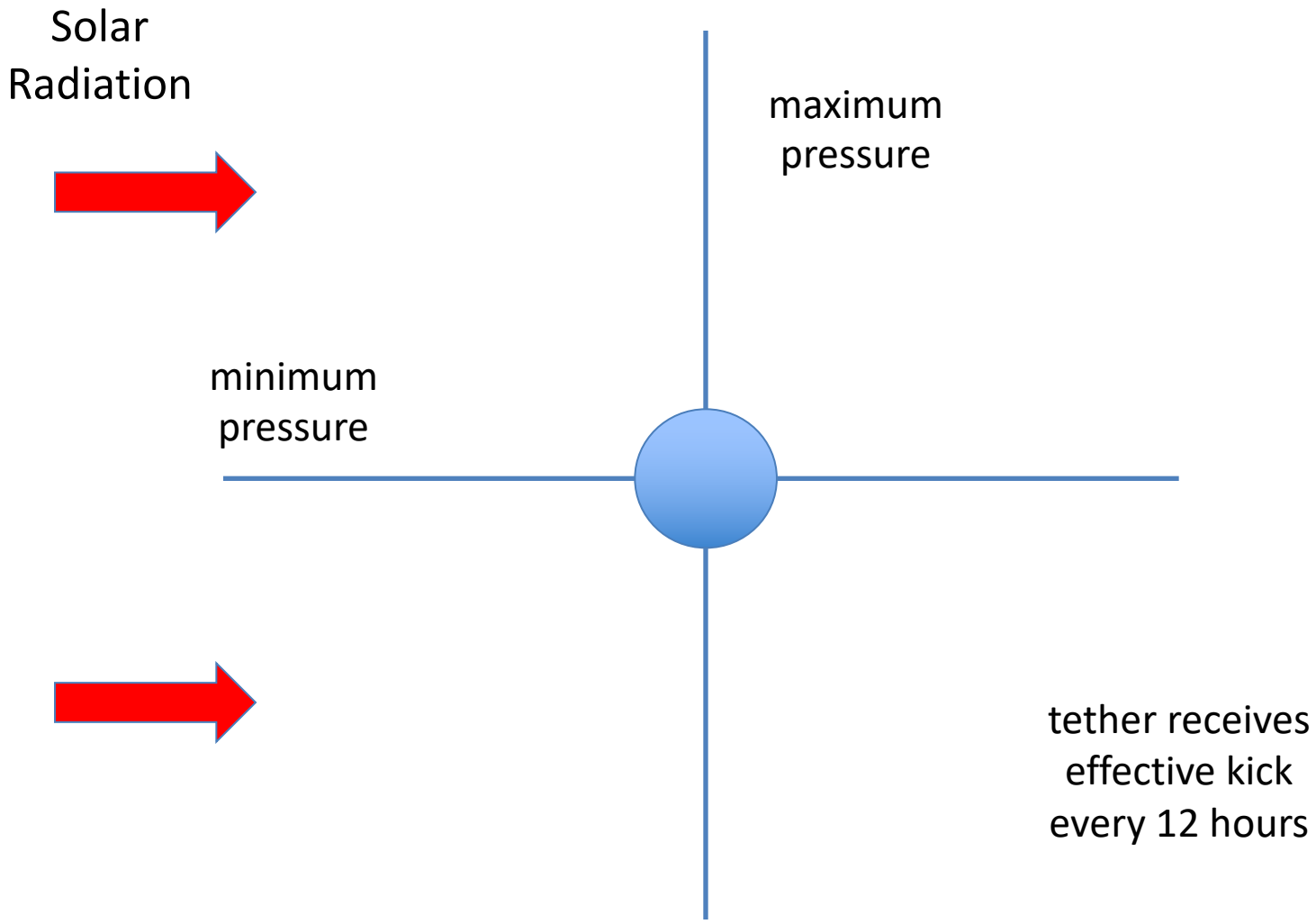
Radiation Pressure

- Space elevator tether typically 1 m wide, 10^8 m long
  - huge solar sail (10 km square)

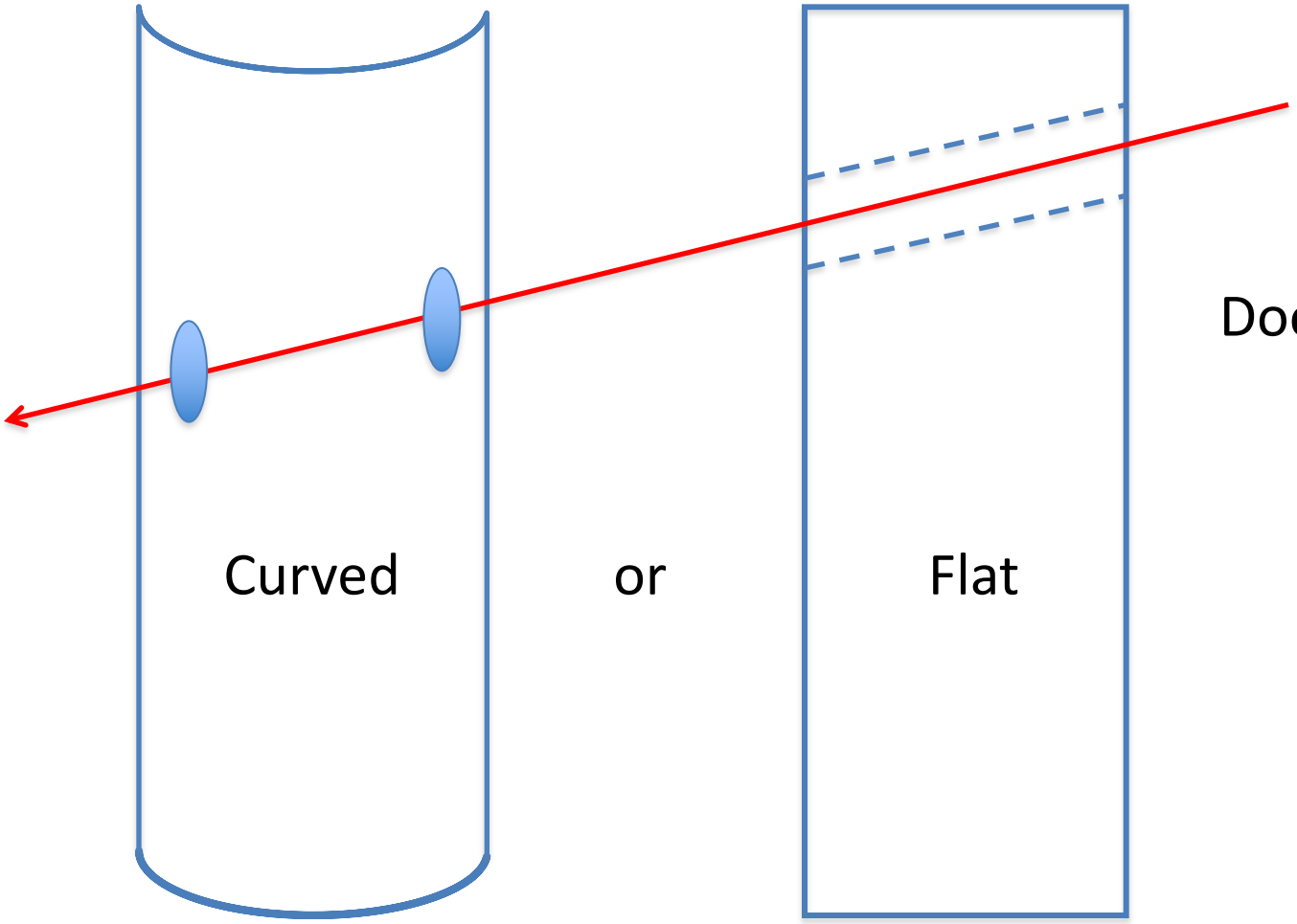
- Need to calculate momentum transfer of Compton scattering, photo-electric effect, solar wind
  - with large area facing sun, macroscopic forces will result (~800 N)
  - periodic driving force could result in resonant motion
  - or amplify normal transverse modes of space elevator tether (6.2 days, 10.1 hours, 5.3 hours, 3.6 hours, ….)

- Need to study effects of
  - angle of incidence
  - orientation of tether face
  - radiation trajectories, ….

Radiation Pressure



Micrometeorite or Debris Damage



Does tether profile affect sever probability ?

Micrometeorite or Debris Damage

- Novel use of Geant4 to answer this question
  - shoot neutral Geantinos with known or expected distribution of trajectories using particle gun
  - make curved or flat volume for target
  - score hits with weight equal to geometric cross section of debris
  - flag a sever when sum of cross sections exceeds a threshold

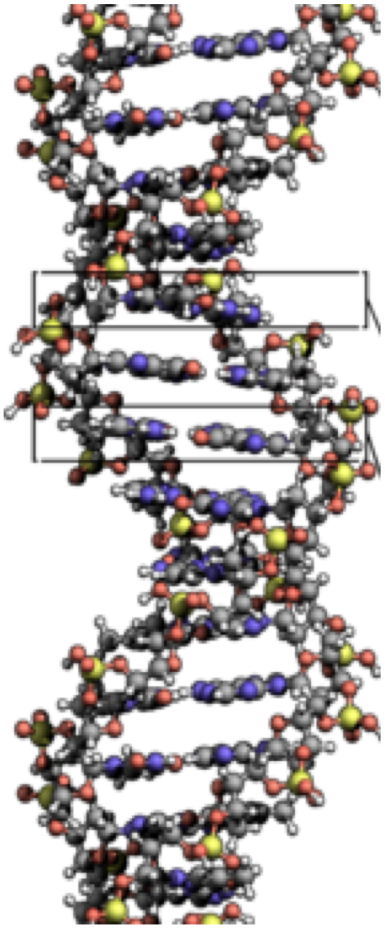
- Tether will move and flex over time
  - will this affect damage estimate?
  - can use time-dependent geometry

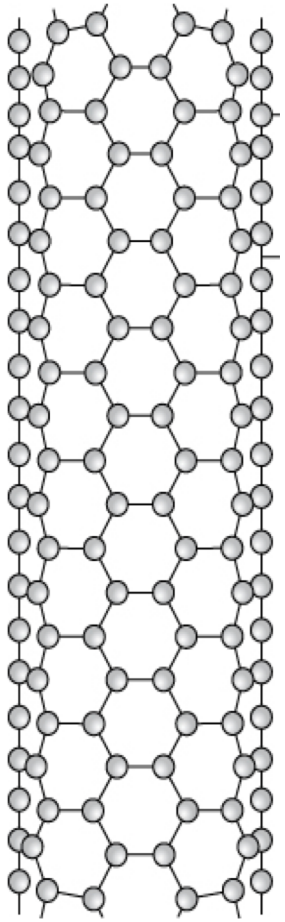
Radiation Damage

- Doses can be quite high
  - upper bound ~3 MRad/yr (30 kGy/yr) in radiation belts
  - trip to GEO takes 1 week → round trip up to 115 kRad
- More traditional use of Geant4
  - SEE in electronics of climber
  - protection of cargo
- Passengers
  - shielding makes climber heavy → active shielding?
  - Geant4 already being used in this area for space habitats
  - If problem not solved, space elevator will remain a freight elevator

Radiation (and chemical) Damage

- Damage to CNTs, graphene
  - Geant4 DNA physics already being applied to CNTs
  - much simpler geometry than DNA, simpler chemistry, too
  - at least one group working on this
  - monatomic oxygen in upper atmosphere – physical dynamics of 1 km/s impacts and chemical attacks on CNT structure





A Space Elevator Simulator

- Major goal for International Space Elevator Collaboration (ISEC): a software simulation tool for design and operation of a space elevator
  - everything mentioned above: dynamics, electrodynamics, radiation effects, etc.

- Need a software framework to accommodate
  - different types of tether dynamics code
  - radiation simulation
  - magnetosphere models
  - databases
  - visualization
  - user interfaces

A Space Elevator Simulator

- Year-long ISEC study completed in 2017 to specify use cases and overall design (https://isec.org/ ISEC Study Reports)
  - define its application areas
  - decide how it will be used
  - develop the outline of an object-oriented architecture
  - produce a blueprint for development to be given to a contractor

- Current idea is to build simulator around a math/physics engine like Mathematica or SageMath, and Geant4; they will provide:
  - differential equation solvers
  - finite element meshes
  - basic physics packages

Design Exercise

- Start with UML diagrams and listing of base classes
- Model base class
  - derived classes: dynamics models, field, tether models, …
- Tether class
  - derived classes: RigidRodTether, ContinuousTether, …
  - methods: AttachLoads(), MassProfile(), …
- Field class
  - derived classes: Gravitational, Electromagnetic, …
  - methods: GetField(), …

Conclusion

- Space elevator studies are underway in several places around the world
- The necessary technologies are advancing
- ISEC is taking the first steps to designing a space elevator simulator
- Many of the jobs in this simulator will be handled by Geant4
- Want to join?

Extras

Current Activity in the Field

- International Space Elevator Consortium (www.isec.org)
  - a non-profit (501(c)(3)) group of engineers, scientists, writers and artists
  - yearly studies covering single aspects of SE development
  - annual meeting every August in Seattle

- Japan Space Elevator Association (www.jsea.jp)
  - also a non-profit
  - sponsored Space Elevator Games 2009 (climber competition)

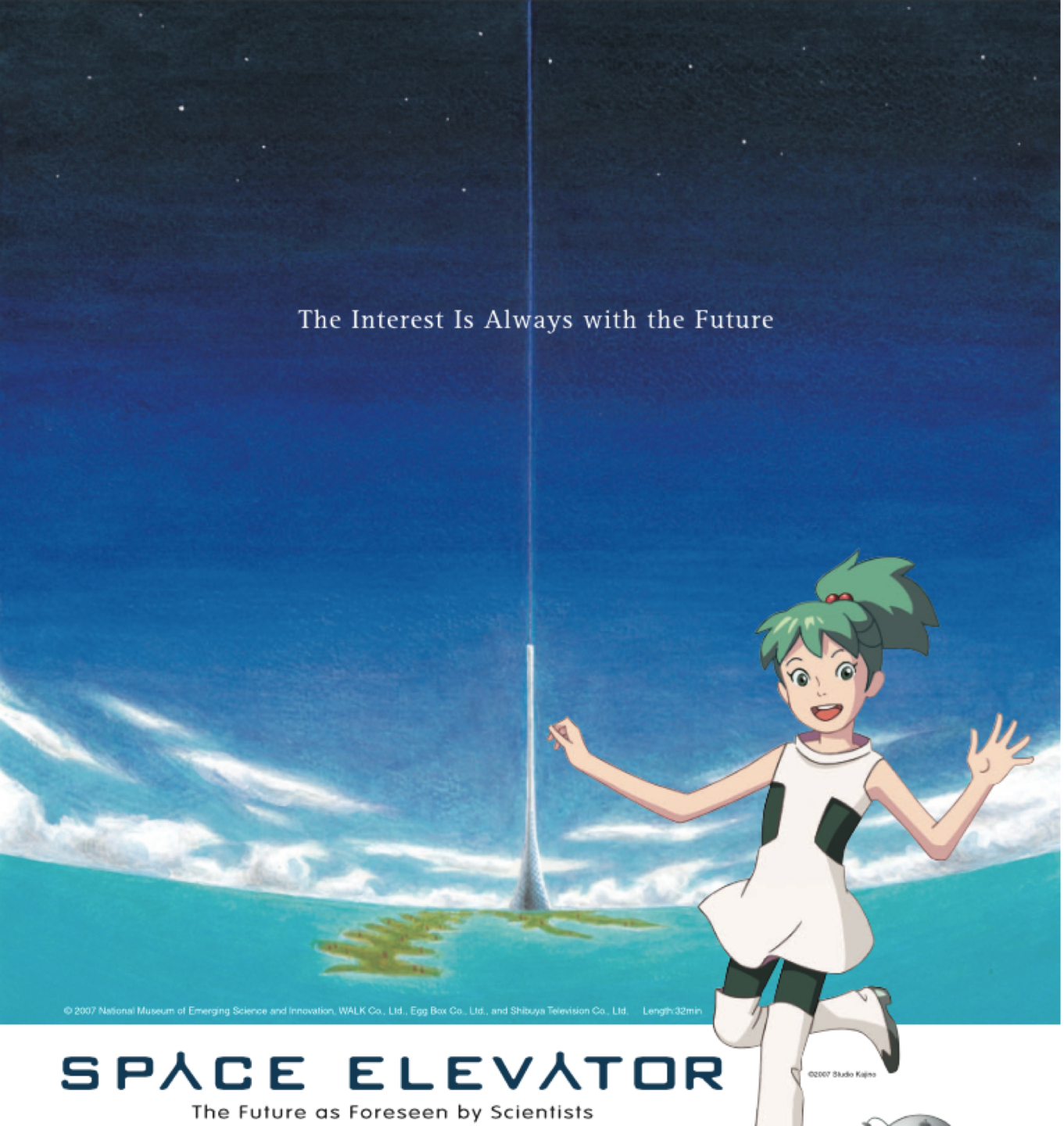
- Obayashi Corporation
  - large general contractor company (Tokyo)
  - currently working on linear motor climbers

Space Elevator News

- CNT global market estimated at $3.4 x 10^9 in 2022
  - current research budgets ~ $\$10^8$
  - IBM (2016) announced $3B research effort
- Science Council of Japan proposes (2017) to spend $200M over 10 years on space elevator research
- Survey of Japanese 9th graders showed 100% knew about space elevators
  - SE is or has been part of a kids' TV program for many years

Space Elevator News

- JAXA will soon fly a small (several meter) space elevator tether with climber
- Current Japanese plan: operational space elevator by 2050
- China announces (2018) plan to build space elevator by 2035
- Graphene Institute (UK) inaugurated 2018



Leaflet from Museum of Emerging Science and Innovation (Tokyo)