Assessment of the Technological Feasibility and Challenges of the Space Elevator Concept

A Cosmic Study for the International Academy of Astronautics
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Subject: Cosmic Study Status Report September 2011

By Whom: Dr. Peter Swan, Co-Chair of Study

Major Topics: Overview, Outline, Schedule, Meetings Achieved, Near-term Meetings, General Summary, Individual Chapter Abstracts & Questions

Overview: The Space Elevator Community has made great progress in the last six months which is significantly assisting the IAA Cosmic Study. The big events that did contribute to individual chapters are:

- International Space Elevator Conference (Aug 2011, Redmond Washington, USA) – Focus day on carbon nano-tubes for tension strength. [yearly event with Cosmic study meetings held]
- International Space Elevator Consortium Study Report Published entitled; *"Space Elevator Survivability, Space Debris Mitigation,"* Lulu.com, Apr 2011.
- National Geographic Magazine [with over 100 million readers] featured two pages on Space Elevator in the July 2011 issue.

Outline:

Schedule: The study is on track for a Spring 2013 publishing date. The study schedule is as follows:

Date	Action	Type	Location	Host
Oct 10	Study Approved by IAA	Written	Paris	IAA
Oct 10	Kick off study	Mtg	Prague	IAA
Mar 11	Outline Due	Mtg	Paris	IAA
Aug 11	Annotated outline/major questions	Mtg	Seattle	ISEC
9 Sept 11	Draft Chapters Due	Written	To Website	team
Oct 11	Discuss Chapter inputs	Mtg	Cape Town	IAA
9 Jan 12	Feedback Chapters – all review	Written	On website	team
9 Mar 12	Draft Chapters resubmitted	Written	On website	team
Mar 12	Chapters discussed in detail	Mtg	Paris	IAA
9 July 12	Final Chapters submitted	Written	On website	Team
Aug 12	Chapter overlap review	Mtg	Seattle	ISEC
Oct 12	Final review chapters/feedback	Mtg	Naples	IAA/ISEC
1 Dec 12	Final Chapters submitted	Written	On website	Team
Mar 13	Peer Review 1 Dec – 15 March	Written	From website	Team
9 Apr 13	Corrections accomplished – final	Written	From website	Team
9 Jun 13	Final Approval from ISEC & IAA	Written	From website	Team

Meetings Achieved: The study group met in Paris in March 2011 to finalize the outline and to ensure the participants were “kicked-off.” Indeed the study has been aggressively initiated and the members are participating and contributing. The August meeting was held at the International Space Elevator Conference and was conducted as a two hour brainstorming session within the conference. Many good ideas surfaced and the summary has been sent to the participants.

Near-term Meetings: the next two meetings will be critical. The one in Cape Town will pull together the various chapter inputs and hopefully will have a good start at a report. After that, the Paris March meeting will try to refine the chapters and pull together the various thrusts of the study into a common aiming point.

General Summary: the status of the study group is fine. We are progressing and hopefully making progress. The real indicator is the excellent set of chapter abstracts and basic questions for the study. They are shown in the following section. The study is on schedule and should make the April 2013 date.

Individual Chapter Abstracts & Questions:

Chapter 1: Introduction

1.1.2 Abstract: This first chapter establishes Brad Edwards’ space elevator baseline in 2000 and sets the stage for the rest of the study to grow from this historic baseline. In addition, the chapter describes “why a space elevator,” suggests a comprehensive vision, and describes the IAA’s approach for their cosmic studies. The last part of the introduction chapter lays out the book’s structure with a set of chapter abstracts and major questions to be discussed within the chapter.

Major Questions:

- Why build a space elevator?
- What is being addressed in the cosmic study?
- How is the cosmic study organized?
- What is an operational view and how does it “set up” a space system architecture?

1.0 General Background

1.1 Why a space elevator

1.2 Cosmic Study Approach

1.2.1 Technological Maturity (TRL’s)

1.2.2 Risk Matrix Chart

1.3 Conceptual Architecture

1.3.1 OV-1

1.3.2 Schedule

1.3.3 What are the Elements of a Space Elevator

1.3.4 Global Vision –

1.3.4.1 Population: The Earth may not be able to support the increasing number of humans.

1.3.4.2 Energy: We are running out of the fossil fuels that are the cornerstone of modern society.

1.3.4.3 Pollution: Our various activities are affecting the Earth and affecting climate change.

1.3.4.4 Local and Global Catastrophe: An asteroid hitting the Earth could be a small disaster, a city killer, or a global transformation.

A Simple Vision: We have an inspiring goal. A suggested simple vision that can change the world:

The Space Elevator gives us the road
to limitless opportunities while opening up the Solar System.

1.4 Feasibility Condition

1.5 Layout of the Cosmic Study Report

Part I – Major Elements

Chapter 2: Tether Material

Abstract: The tether must be made of a material that can withstand its environment and operational stresses. This would include all of the threats to the system as well as tensile strength necessary to support itself. It turns out that if the tether can support 45 [or Ben is this greater or smaller] MYuri { or GPa} of tension, a space elevator can not only support itself, but five major tether riders (at 10 tons each plus 10 tons payload) at a time. Materials currently being tested in the laboratory have surpassed that level and promise a tether that can withstand the environmental and operational stresses necessary. Will it be carbon nanotubes, or boron nitrite materials, or something else?

Major Questions – Tether:
Te #1 – What are the basic requirements for developing the tether materials?
Te #2 – What is the basic materials development approach?
Te #3 – Is a metre wide, paper thin tether the optimum configuration?
Te #4 -- What are the acceptable stress levels expected to accomplish the space elevator?

2.0 Estimated strength material,
2.1 Feasibility condition,
2.2 Carbon nano-tube status,
2.3 Single or dual walled,
2.4 Strength projections vs. time,
2.5 Reliability,
2.6 Robustness,
2.7 Environmental survival,
2.8 Parallel material,
2.9 Projection of suitable material

Chapter 3: Tether Riders

Abstract: The variety of climbers will surprise even the early believers in a space elevator. There will be tether weavers, repairers, safety inspectors along with logistical trams, commercial climbers, human rated climbers, hotels, launch ports, etc. However, key to their success will be the requirement to have an open standard so that all manner of climbers can work on the space elevator. The analogy would be the railroad's standard width of its rails. Anyone can put a train on the rails if they adopt the standards. A similar approach must be used to ensure compatibility between tether and climbers. The complexity of the tether interface has driven the design of tether riders and keeps its maturity level between technological development and engineering applicability.

Major Questions – Tether Rider:
TR #1 – What are the basic requirements for developing a tether rider?
TR #2 – What is the basic systems approach?
TR #3 – Is there a need for "sidings" so that different types of climbers can pass or be parked?
TR #4 -- Are there permanent locations, ie. Hotels?

3.0 Basic needs,
3.1 Mass goals,
3.2 Major components [structure, motor, power source, drive wheels, tether connection, communications, environment],
3.3 Deployment scheme,
3.4 Re-use?
3.5 General summary

Chapter 4: Power for the System

Abstract: Power will be supplied through various mechanisms leading to electrical motors that move the climbers. Ideas range from laser and radio frequency energy from the ground, to solar or nuclear power for a non-interruptible supply. Design trades will lay out options and systems engineers will move toward proposed solutions. The current concept is to launch at dawn using solar energy all day, lasers through the first night, and then solar energy the rest of the trip with short eclipses.

Baseline Power Concept

- solar energy propulsion from dawn to first night
- then laser energy from dusk till dawn
- then solar energy to the top with minimum interuptions from short eclipses

Major Questions – Energy Sources:
ES #1 – What are the basic requirements for developing an energy source?
ES #2 – What is the basic systems approach?
ES #3 – Could paper-thin flexible batteries be built into the ribbon at intervals?
ES #4 -- What are the engineering challenges, such as pointing solar arrays?

4.0 Introduction with requirements,
4.1 Types of power needed,
4.2 Delivery alternatives,
4.3 Power (Solar) arrays for laser and solar,
4.4 Systems design,
4.5 Projected improvements in materials and power generation

Chapter 5: End Station Infrastructures (Base Station & Apex Anchor)

Abstract: The two ends of a space elevator have many possible engineering paths. It turns out that one of the biggest issues is location of the base station. The trades for the Earth's attachment reach across political, investment, engineering, weather, and operational issues. A simple solution could be that a heavy ship(s) would act as a base for operations as well as to move the tether out of harms way by initiating a resonance motion. Much more will be discussed during the chapter on location and technologies. In addition, the benefits of elevating the base station to a high altitude will be discussed with a new technology that can provide that capability. Trades will be presented to show the reason for elevating the base station to an altitude out of the atmosphere. The counterweight, or apex anchor, will be the mechanism that allows the tether to maintain tension and perceived rigidity. The makeup of the apex anchor and its components must be discussed to ensure a consistent design with simple engineering solution

Major Questions – Base Station and Counter Weight (CW):
Te #1 – What are the basic requirements for the base station and apex anchor?
Te #2 – What is the basic systems approach to develop the two end points of the space elevator?
Te #3 – Should the base station be at altitude? What height?

5.0 Introduction
5.1 Counterweight Description [Apex Anchor]
[alternative sources of mass, schedule of enhancement, distance]
5.2 Earth Based Anchor
5.2.1`Base Stations:
Trades: base legs vs. continuous space elevator?
Threats, Dangers, solutions
Feasibility, Development approach, testing

5.2.1 Surface Stations

Location:Terrestrial vs. Ocean
Suggested Locations, and why
Description of Anchor Stations
Community of Activities

5.2.3 Base Legs: Stations at Altitude

Advantages – Disadvantages
Challenges of Earth's Turbulent Atmosphere
The lowest 100 km
Options Considered
Simple Ribbon vs. Bolstered Ribbon
Development of the Launch Loop
Preferred design
Surface Stations
Transfer to Main Ribbon
Technology Summary
Forces and Structural Materials
Magnetic Levitation
Winds and Stabilization
Initial Erection
Open Questions

5.3 Systems Recommendation [ground, sea, at altitude]

Note: I am using the term Base Legs as when I was thinking of the problem -- I just ran multiple carbon nanotubes ribbons down from some location... I like your use of launch loops to take the stress off the lower portion of the space elevator and enable "free reigning commerce" to take place up the base legs... if you want to use other words than base legs, please suggest them...

Part II – Systems Approach

Chapter 6: Systems of Systems Design

Systems of Systems Design: No one has made an elevator that moves along a tether for 100,000 km against gravity. The design factors inherent in this challenge are new and must be addressed by the design team. There is no reason to believe that this cannot be achieved with solid engineering processes leading to materials production and assembly in a timely manner. A systematic design process must be applied to a family of systems that will yield an operational space elevator. This system of systems design will challenge the skills of systems architects and the systems engineers.

Major Questions – Systems Design:
SE #1 – What are the Customer Needs?
SE #2 – What are the basic requirements?
SE#3 – What is the basic systems operational concept?

6.0 Introduction: This chapter will address the following questions and resolve issues that are created.

SE #1 – What are the Customer's Needs?
SE #2 – What are the requirements?
SE#3 – What is the systems operational concept?
SE#4 – What Vision will drive the team?
SE#5 – What safety factor is optimum (factor of 2 or 4)?

6.1 Process Discipline: The development of a mega-project needs discipline, especially during the initial phases, to ensure the requirements are developed early and continually refined as the knowledge base expands. To successfully mature requirements from the initial phase to operations demands a process that understands complexity, leaps of faith, commitment, passion and focus.

- Discipline & Process
- Why
- Needs

6.2 Approach: The systems engineering mission is to "Assure the fully integrated development and realization of products which meet stakeholders' expectations within cost, schedule and risk constraints." [1] The bottom line is that when the approach is properly applied to a systems-of-systems project, strong systems engineering will lead to an outstanding product.

6.3 Systems Engineering Process Tasks The basic tasks derived from the systems engineering process can be presented.

- Define the System Objectives
- Establish the Functionality
- Establish Performance Requirements
- Evolve Design and Operations Concepts
- Select a Baseline
- Verify the Baseline meets Requirements
- Iterate the Process through Lower Level Trades

[1] *SEPrimerAIAA-INCOSE_1997-08, p 3.*

6.4 Global Needs Lead to Four Basic Requirements: Global problems require large-scale solutions. There are four remarkable motivational drivers.

- Low Cost Access to Space
- Special Location Capability
- Driving Space Innovation:
- Operationalize Space:

6.5 Wright-Flyer Basic Outline: **From the four overarching needs we can develop some basic requirements. The team must lay out basic requirements for the development of a space elevator.**

- Funding Started by….
- Preliminary Design Review by….
- Flight Readiness Review by…
- Deployment Initiated by…
- IOC capability by….
  - 20 ton payload capability
  - 5 climbers with payload at any instant (surface to GEO)
  - Climbers estimated at 20 tons each
  - $100 per kilogram (when multiple Wright-Flyers operate)
  - Reliability of elevator (777 jet engine exceeds 17,000 hours)[2]

6.7 Coalescing Thought: Risk Assessment

During the study, many factors relating to the space elevator were discussed. Two techniques will be used to summarize the status of the space elevator as of the spring of 2013.

- Technology readiness level ranking.
- Risk chart [Likelihood vs. Consequence].

Chapter 7: Dynamics of Operation Tether

Dynamics of Operational Tether: An operational tether will challenge the operator along many areas. A 100,000 km space elevator will have new and exciting dynamics that can only be predicted as there is no equivalent experimental model. Many of the traditional space issues [such as the influence of the Sun and the Moon] will exist with new ones surfacing as the study goes forward. .

Major Questions – Dynamics of Operational Tether:
DT #1 – What are the basic requirements for a stable space elevator?
DT #2 – What is the basic control approaches required?
DT #3 – How complex is the computer simulation to model the dynamics?
DT #4 -- Do we need knowledge of elements location separated by 1 km, 25 km or 100 kms?

7.1 Space Elevator Mechanics Modeling Issues

7.2 Static Equilibrium of the Space Elevator

7.2 Fundamentals of the Space Elevator Dynamics

7.2.1 Planar dynamics

7.2.2 Three-dimensional dynamics

7.2.3 Fixed vs. floating platform

7.3 Elastic Oscillations of the Space Elevator Ribbon

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[2] *Schmitt, Capt. John H., personal communications. 9/18/2003.*

7.3.1 Longitudinal oscillations

7.3.2 Transverse oscillations

7.4 Perturbations of the Space Elevator Dynamics

7.4.1 Effects of aerodynamic forces

7.4.2 Effects of the non-spherical shape of the earth

7.4.3 Luni-solar gravitational perturbations

7.5 Effects of Climbers on the Space Elevator Dynamics

7.5.1 Stationary climbers

7.5.2 Moving climbers

7.5.3 Climbing Schemes

7.6 Control of the Space Elevator Dynamics

7.6.1 Control of the pendular motion

7.6.2 Control of the elastic oscillations

Chapter 8: Tether Deployment Approaches

Tether Deployment Approaches: At the present time, there are two distinct and attractive approaches for the deployment of the space elevator. Each starts at GEO and deploys a single strand of tether to be built upon. Approaches vary at this point with one building from the ground up [Edwards approach] and the other lifts itself up from the counterweight reel [Gassend concept].

Major Questions – Tether Deployment:
TD #1 – What are the basic requirements for each approach?
TD #2 – What are the basic characteristics and strengths of each?
TD #3 – What modeling approaches are needed to predict and then monitor deployment?
TD #4 -- What testing approaches are required to prepare for initial deployment?

8.0 Introduction -,[Fujii and Misra]
Overview of Chap.2.7
8.1 Approach Choices – [MK]
Bootstrap vs. weaving vs.
History of deployment of space tether
Stable Condition,
Natural Dynamics
8.2 Deployment Dynamics during Phases - [NT]
[at GEO initial, short range, long tethers, approaching atmosphere, in atmosphere, attachment step]
Plans of space elevator construction
Dynamics of initial deployment
2.7.2.x Dynamics of a Partial Space Elevator [Mohammad Jalali Mashayekhi]
8.3 building the space elevator from simple first strand, [NT]
Momentum loss
Dynamics in building space elevator
8.4 testing of dynamics, [HAF and TW]
Methods to assure the reliability of tether deployment
Testing of deployment
1. On the ground or in space
2. Modeling of space environment (12 methods by YESII & T-Rex)
3. Design of the tether box(?) and deployment/ejection system

4. Synthesize of total system with such long length tether
5. Assessment of climber/elevator
6. Roles of numerical simulation

8.5 Cut Tether Dynamics, [PW]
Tether dynamics of severance in deployment phase
8.6 General Discussions, [All]

Major Questions to answer:
Major Topics: Stable Condition,
Natural Dynamics [Sun, Moon, resonances, etc],
Deployment
Dynamics during Phases [at GEO initial, short range, long tethers,
approaching atmosphere, in atmosphere, attachment step, building the space elevator from simple first strand, testing of dynamics]

Chapter 9: Systems Design for Environment

Systems Design for Environments: One complexity for the systems approach to a space elevator infrastructure is that it crosses so many environments. This chapter will address environments [except space debris – see next chapter] from the surface [ocean or terrestrial], the winds and storms of our atmosphere, multiple layers of complex particles, and magnetic fields for the first 100 kms, from the lower reaches of space, to GEO and beyond.

Major Questions – Environments:
DE #1 – What are the basic requirements across the multiple environments?
DE #2 – What is the basic systems approach for each?

Chapter 10: Systems Design for Space Debris

Systems Design for Space Debris: The International Space Elevator Consortium's recent study presented the issue of space debris, its probability of collision for the space elevator (with the debris density of April 2010), and mitigation techniques. This chapter will layout the systems design issues and recommended solutions for this problem and recommend operational, technical, and policy approaches..

Major Questions – Space Debris:
SD #1 – What is the threat? [densities, probabilities of collision, sizes]
SD #2 – What are the basic requirements for protecting against space debris?
SD #3 – What are the basic approaches recommended options?
SD #4 – What can the space elevator do to improve the situation?

10.1 General Background:
Descriptions of threats for various altitudes
10.2 Definition of the Problem:
History,
Description of Debris population,
knowledge of debris locations, and
knowledge of Elevator location
10.3 Probability of Impact:
Determining probability,
Density of Objects by altitude,
relative velocities,
Probability of Collision,
Risk to Space Elevator
10.4 Mitigation Techniques:
User needs,
user requirements,

potential solutions to space debris,
Systems approach for survival

10.5 Conclusions and Recommendations:
Density reduction,
Probability of Collision,
Significant questions,
Active Player actions

Chapter 11: Space Elevator Developmental Roadmaps

Developmental Roadmaps: Organizations which take on monumental tasks require a vision with some sort of roadmap that lays out the major thrusts, hurdles, and engineering paths. The roadmap has historically been a useful tool. It allows everyone involved to help layout the path for development of a mega-project such as the space elevator infrastructure. This chapter will present a baseline roadmap which can be matured towards operations.

Major Questions – Developmental Roadmaps:
DR #1 – What are the basic requirements for developing a roadmap, what is included?
DR #2 – What is the basic approach to develop a roadmap?
DR #3 – What is a baseline roadmap current as of 2012?

11.0 Historical View, Present Status, Various approaches , roadmap #1, roadmap #2, etc., major roadblocks
11.1 Various approaches
11.2 Road Map #1,
11.3 Road Map #2
11.4 Major Roadblocks

Chapter 12: Operations Concept

Operations Concept: Operations of the space elevator infrastructure will cross many traditional arenas to include: space operations, logistical support of remote locations, maritime delivery, personnel support for remote operations and future on-orbit operations. This chapter will discuss an operational view approach and propose an Operational View # 1 [OV 1].

Major Questions – Operations Concept:
OC #1 – What are the basic requirements for developing an ops concept?
OC #2 – What is the basic component of an ops concept?
OC #3 – What is the proposed OV 1?
OC #4 – How does the logistics of the Space Elevator tie with the customers?

12.1 Introduction:
Start with Operational View – 1 [OV-1]
12.2 Scope:
Describe Space Elevator Ops in classic bus and payload paradigm
12.2 Satellite Design
How does this impact the satellite industry and on-orbit capability
12.3 Operations View of Space Elevator
the Sec 3.2 stuff after cleanup from upcoming discussion.
12.3.1-x Elements and descriptions of each
12.x+1 Satellite Delivery Operations:
From factory to support base, to ribbon platform,
mating to climber and delivery to orbit

Part III – Future Considerations

Chapter 13: Legal Perspective

Legal Perspective: A significant aspect of the legal world is that this transportation infrastructure will cross four major disciplines of law; space, terrestrial, maritime, and aeronautical. Which will dominant? Who will own a space elevator and where will it be registered and located? These are major questions that must be considered early in the development. At least two legal regimes will be proposed for developing a future space elevator.

Major Questions – Legal Perspective:
LP #1 – What are the basic requirements for Legal Acceptance?
LP #2 – What are the basic systems approach issues that must be refined to ensure legal acceptance?
LP #3 – How to select between alternant legal regimes?

13.0 Historical View, Present Status,

In this field, we must explain three dimensions, i.e. law of the sea, law of the atmosphere and law of the outer space, because Space Elevator is such three dimension architecture.

13.01 Law of the Sea
13.02 Law of the Atmosphere
13.03 Law of the Outer Space

13.1 Laws/Policies Needed to succeed,

Main issue of law of the sea is United Nations Convention on the Law of the Sea.
Main issue of law of the atmosphere is Convention on International Civil Aviation(the Chicago Convention)
Main issue of law of the outer space is United Nations Outer Space Treaties.

13.11 Law of the Sea
13.12 Law of the Atmosphere
13.13 Law of the Outer Space

13.2 Laws/policies needed to be re-arranged,

These conventions are almost impossible to change for the space elevator under the current situation of global politics. So, we must search the way compatible with the conventions in order to establish and operate Space Elevator.

13.21 Law of the Sea
13.22 Law of the Atmosphere
13.23 Law of the Outer Space

13.3 Basic International Law direction to enable Space Elevator

In order to enable Space Elevator, we must establish the international organization for Space Elevator. In the near future, I can show you the draft of the treaty.

13.31 Law of the Sea
13.32 Law of the Atmosphere
13.33 Law of the Outer Space

or

13.0 Introduction
13.1 Three Applicable Legal Regions
Terrestrial [specifically Law of the Sea]
Atomspheric [specifically Law of Aeronautics]
Law of Outer Space
13.2 Two Approaches

Option A: International Approach – create parallel organization to INTELSAT and INMARSAT. First international government funding and operation, then transfers to commercial ownership and operations.

Option B: Country Sponsored – Commercially developed and operated

13.3 Road Forward to prepare legal landscape

Chapter 14: Financial Perspective

Financial Perspective: Numerous mega-projects throughout history have failed because of a lack of understanding of the financial environment surrounding them, as well as political maneuvering and competing jurisdictions, because a common goal is not pursued with clarity. This chapter will provide a detailed overview of the cost of construction, financing options, operational costs and resulting costs to consumers of a Space Elevator. In addition the returns on investment will be addressed. The reality of a space elevator systems development is that it will not occur until two things happen; 1) The tether material is proven out and 2) investors will finance the creation of an infrastructure to space. Current estimates of expense are reasonable when compared to other mega-projects with potential returns in the $10s of billions.

Major Questions – Financial Perspective:
FP #1 – What are the basic requirements for developing an investor group?
FP #2 – What is the approach that must be presented to them?
FP #3 – What are the recurring operating costs such as power and maintenance?
FP #4 -- What are the non-recurring start-up costs such as the building of a base station and the launching of the original tether?
FP #5 – How much will costs be reduced over time as multiple elevators are built?
FP #6 – What is the timeline for profitability?
FP #7 – What is the initial required investment and what are possible sources for that investment?
FP #8 – What is the final cost to consumers?
FP #9 – What will be the likely profit to investor?

14.1 Basic Theme of Chapter: Numerous mega-projects throughout history have failed because of a lack of understanding of the financial situation surrounding them. This chapter will provide a detailed overview of the cost of construction, financing options, operational costs and resulting cost to consumer for a Space Elevator.

14.2 Major Questions to Answer:

1. What are the non-recurring start-up costs such as the building of a base station and the launching of the original tether?
2. What are the continuous operating costs such as power and maintenance?
3. How much will costs be reduced over time as multiple elevators are built?
4. What is the initial required investment and what are possible sources for that investment?
5. What is the timeline for profitability?
6. What is the final cost to consumers?

14.3 Major Topics: Initial launch, material creation, climber costs, laser facilities, base station, crew, cargo logistics, financing, cash flow, return on investment.

Chapter 15: Study Conclusions
Chapter 16: Study Recommendations

Appendix: History of the Space Elevator Concept - Author Information – what is an IAA