

International Academy of Astronautics (IAA)  
Agenda of meeting - Study Group 3.24 "Road to Space Elevator Era"  
5th meeting in Paris, France on March 21<sup>st</sup>, 2016



Date: Monday, March 21<sup>st</sup>, 2016

Time: 08:30 – 10:00

Place: IAA Meeting room (when you go in IAA building, you can find exact place)

International Academy of Astronautics

6 rue Galilee 75116 Paris, France

Chair: Akira Tsuchida (CM2), Co-chair: Peter Swan, Ph.D. (M4), David Raitt, Ph.D. (M4)

Secretary: Ms. Sakurako Takahashi

Agenda:

1. E-18M Activity Report: SG3.24 "Road to Space Elevator Era" Sakurako Takahashi
  - The first review of the Space Elevator Mission Definition Document (SEMDD) and the Space Elevator System Requirement Document (SESRD) was completed as the first step to define the Space Elevator Prediction Feasibility Index (SEPMFI).
  - A summary chart was drafted to show relationships between "Mission Definition", "System Requirement", "Critical Technologies" and "Verification". Reviews and comments from each SG3.24 member are requested.
  - For more detail, refer to the appendix 1.
  
2. Mission Definition comments review and Study Report (Draft 1 - template) of Study Group 3.24 "Road to Space Elevator Era" Sakurako Takahashi
  - Chair, Co-chair, and Secretary greatly appreciate the comments made to the draft of the SEMDD. The comments we have received were listed in the appendix 2.
  - The comments were reflected to the SEMDD, which is included in the first draft of our group's Study Report as Chapter 2.
  - The draft of the Study Report is shown in the appendix 3.

Contact Information:

Mr. Akira Tsuchida (CM2/IAA) [tsuchida.akira@gmail.com](mailto:tsuchida.akira@gmail.com)

Ms. Sakurako Takahashi [takahashi.sakurako@jamss.co.jp](mailto:takahashi.sakurako@jamss.co.jp)



3. New Design for the Space Elevator

John Knapman

- Dr. Knapman is working on a research if it is possible to build a space elevator with currently available materials. The advantage of this idea is there is no need to wait for super-strong materials and the construction of a space elevator might be started much earlier than the current estimation.
- His presentation is attached as appendix 4.

4. Next Meeting Schedule

- The next meetings will be held in Seattle/USA in August and in Guadalajara/Mexico in September.



# E-18M Activity Report: SG3.24 “Road to Space Elevator Era”








As a preparation of Space Elevator  
Permanent Committee creation in IAA

Akira Tsuchida,  
Chair, IAA Study Group 3.24 “Road to Space Elevator Era”

# SG3.24 “Road to Space Elevator Era”

## - 1. Status Report Overview



2014/9	2015/3	2015/9	2016/3	2016/9	2017/3	2017/9
Toronto	Paris	Jerusalem	Paris	Guadalajara	Paris	Adelaide
						E-0 
					E-6 	
				E-12 		
5 <sup>th</sup> meeting in Paris			E-18 	Kick off Critical Technology & Research Plan		
1 <sup>st</sup> Carbon Nanotube Exp 3 <sup>rd</sup> SG meeting in Seattle 4 <sup>th</sup> SG meeting in Jerusalem		E-24 	Mission Definition/System Requirement development			
2 <sup>nd</sup> meeting in Paris	E-30 	Kick off Mission Definition and System Requirements development to define “critical technologies”				
E-36 	Established SG3.24, 1 <sup>st</sup> meeting, formed 5 sub-groups					



## SG3.24 “Road to Space Elevator Era”

### - 2. Final Products and Intermediate Goals

- ❑ New IAA Study Group “Road to Space Elevator Era” provides the following results as **intermediate goals**:
  - Review the advancement of critical technologies required to implement the Space Elevator. This will include carbon nano-tubes, control dynamics, etc.
  - Define the Space Elevator Prediction Feasibility Index (SEPMI) based upon the critical technologies identified
  - Publish the yearly Space Elevator Feasibility Status Assessment
  - Conduct IAA sponsored SSpace Elevator Challenge (SPEC) and conference in the world
  - Making presentations in countries and organizations throughout the world, especially in developing countries and countries just beginning their involvement in space activities.
  - Making space elevator infrastructure concepts an integral part of university science and engineering curricula.

E-36  
Through  
E-12

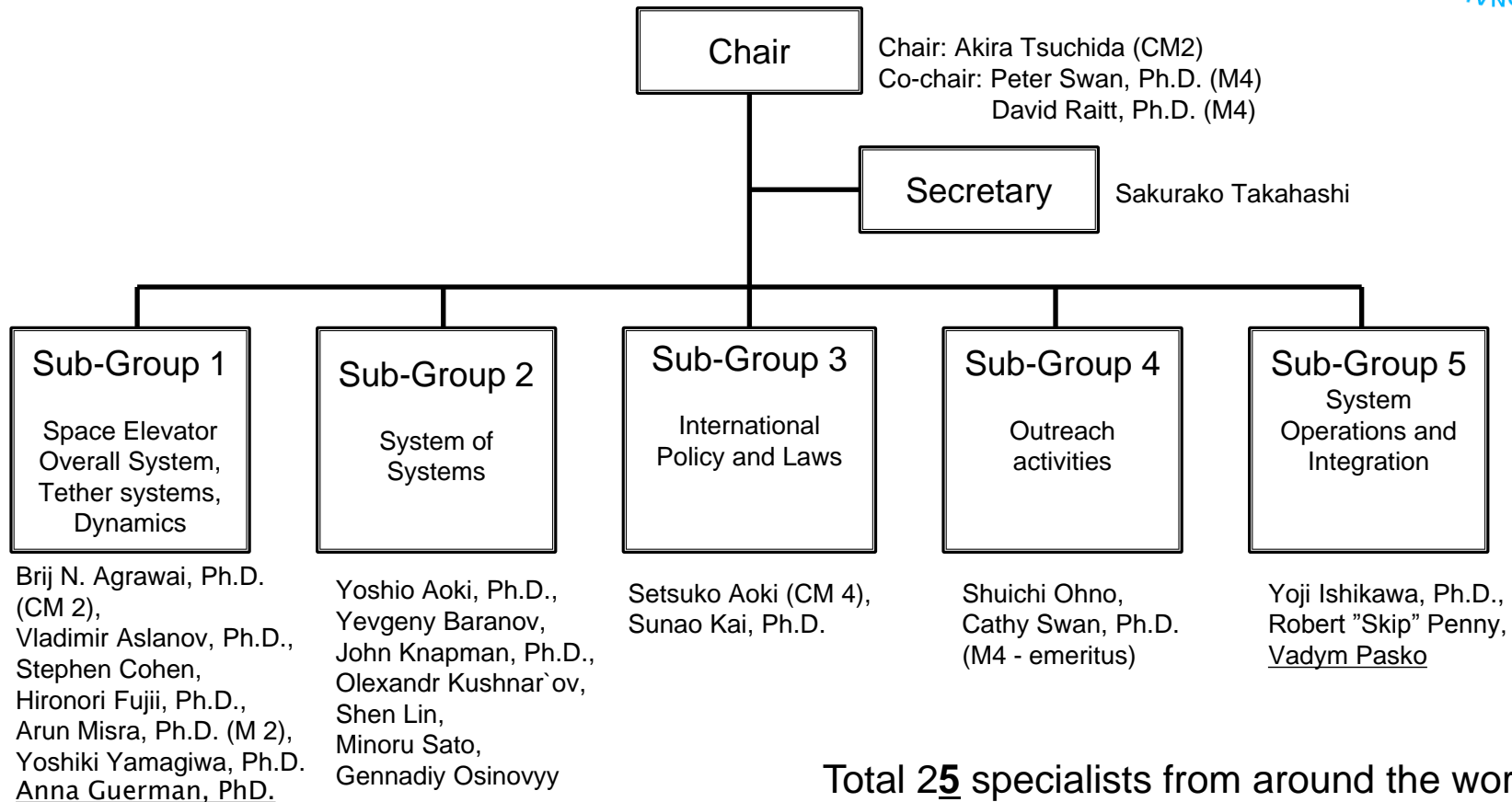
#### ❑ **Final Products:**

- IAA Report on the Road to Space Elevator Era
  - ✓ Space Elevator Prediction Feasibility Index (SEPMI)
  - ✓ Pilot project proposal with first level system engineering details

E-6: Start  
E-0: Conclude

# SG3.24 “Road to Space Elevator Era”

## - 3. SG Structure



Total **25** specialists from around the world:  
Japan [10], with Canada [2], China [1],  
Finland [1], Russia [1], UK [2],  
Ukraine [3->**4**], USA [3], and Portugal [1]

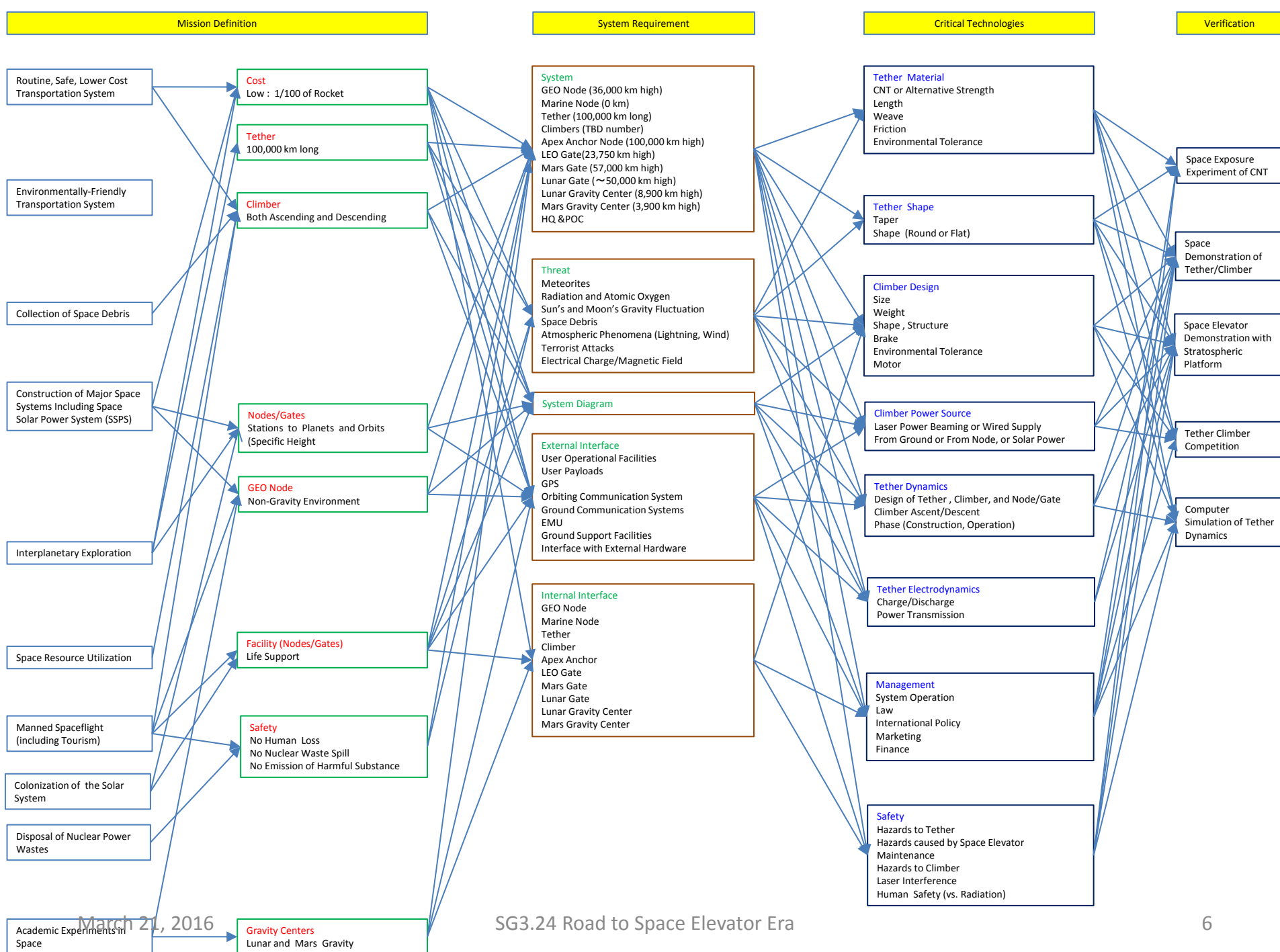


## SG3.24 “Road to Space Elevator Era”

### - 3. Specific Activities in past 12 months

- ▣ “Mission Definition”, “System Requirement”, “Critical Technologies”, and “Verification” relationship discussion
  - To identify critical technologies, required to implement the Space Elevator, with all study group members have on the same page, relationship of these process/documents are drafted.
  - Our study progress is relatively slow but it is the important to discuss at this point.
  - SG3.24 members should review and make comments on this chart.









## SG3.24 “Road to Space Elevator Era”

### - 3. Specific Activities in past 12 month (Continued)

- Start drafting of “International Academy of Astronautics (IAA) Study Report (Draft 1 - template) of Study Group 3.24 Road to Space Elevator Era”
  - Table of contents of first draft 1 is as shown below:

Chapter 1 Introduction – purpose of this study  
Chapter 2 Space Elevator Mission Definition  
Chapter 3 Space Elevator System Requirements  
Chapter 4 Critical technologies required implementing the Space Elevator  
Chapter 5 Space Elevator Prediction Feasibility Index (SEPMI)  
Chapter 6 Recommendation of on-orbit verification/demonstration experiment  
Acknowledgement  
Appendixes  
Appendix-1 Contributor List  
Appendix-2 Acronyms and Common Terminology  
Appendix-3 Research Topics List

## SG3.24 “Road to Space Elevator Era”

### - 3. Specific Activities in past 12 month (Continued)



#### ▣ Acronyms and Common Terminology

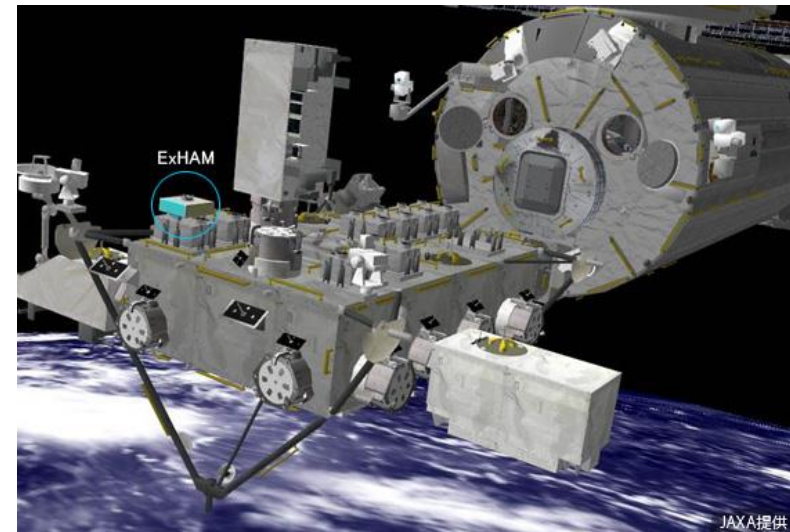
- Because we have new study group members since last IAA study group report, IAA study group #3-24 met in Seattle in August of 2015. The team agreed to use, as much as possible, consistent terminology for this study group report.

## SG3.24 “Road to Space Elevator Era”

### - 3. Specific Activities in past 12 month (Continued)

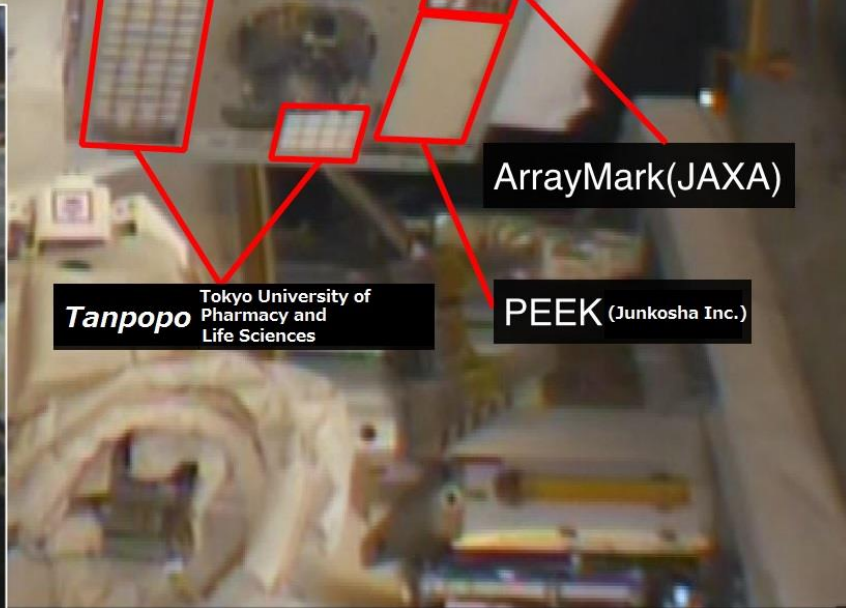
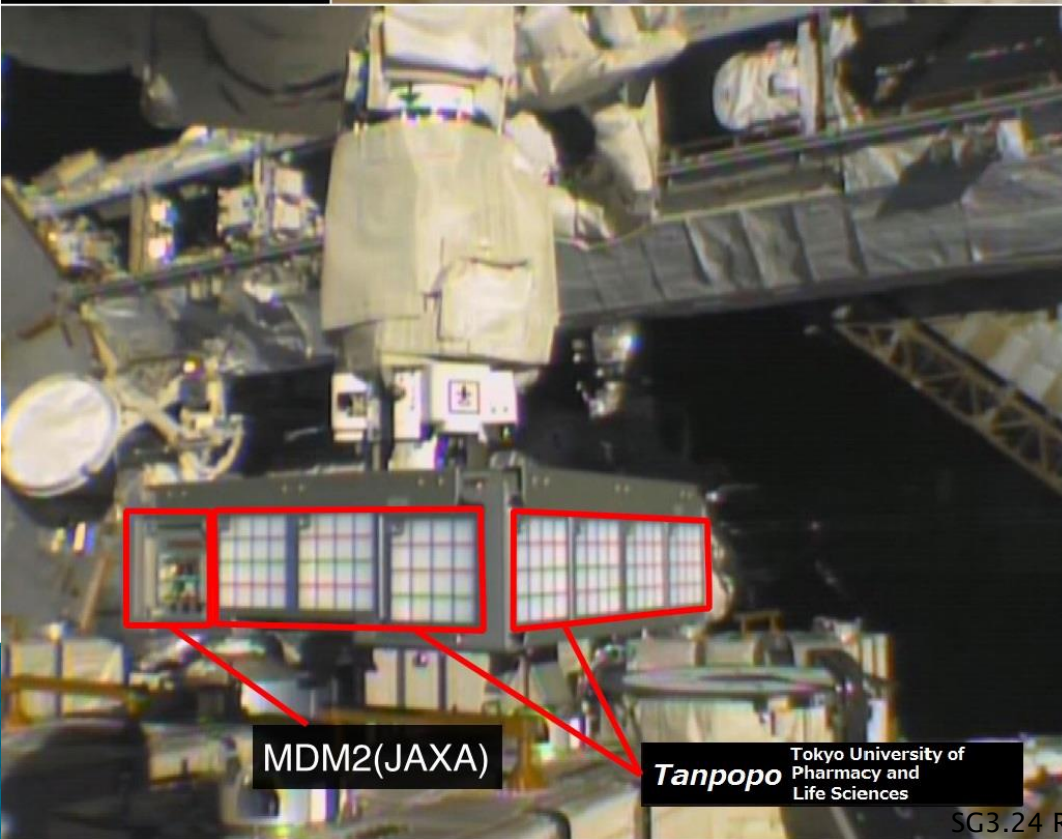
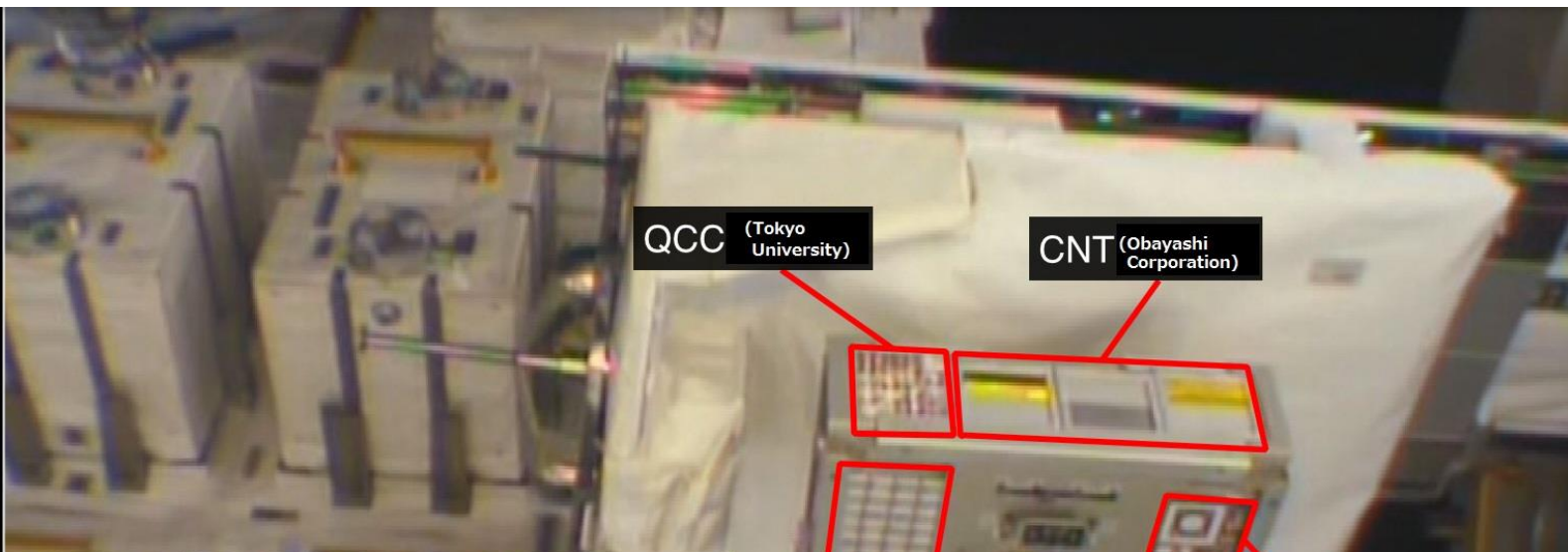
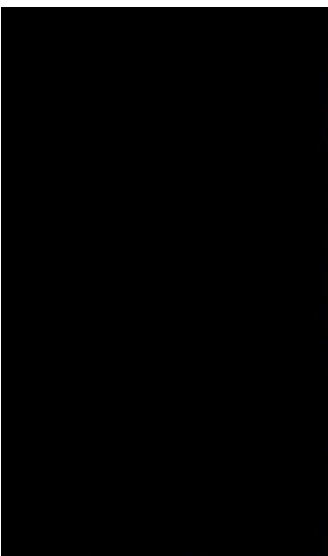
- ❑ One of Final Products – as a part of pilot project with first level system engineering test is just started:
  - ✓ On May 26, 2015, the first experiment using JAXA's new experiment device, the Experiment Handrail Attachment Mechanism (ExHAM) started.
  - ✓ Space Environment Exposure Experiment of Carbon Nanotube Material for Space Application (CNT)

(Purpose of this experiment is for All Space Application, not specifically for space elevator)



Ref: [http://iss.jaxa.jp/en/kiboexp/news/150608\\_exham-1\\_started.html](http://iss.jaxa.jp/en/kiboexp/news/150608_exham-1_started.html)







## SG3.24 “Road to Space Elevator Era”

### - 4. Next 6 months plan

- ❑ Kick off Critical Technology & Research Plan development based on discussion of past 12 months.
- ❑ Continue work with the following missions:
  - ✓ Conduct IAA sponsored SSpace Elevator Challenge (SPEC) and conference in the world
  - ✓ Making presentations in countries and organizations throughout the world, especially in developing countries and countries just beginning their involvement in space activities.
- ❑ Next meetings in 2016 will be held in Seattle/USA in August and in Guadalajara/Mexico in September 2016

# Appendix–1



- ▶ Proposal presentation in Toronto (Sep. 2014)

# New IAA SG 3.24 “Road to Space Elevator Era” Background



## ► Background

- ✓ After successful completion of IAA Study Group 3–13 “Assessment of the Technological Feasibility and Challenges of the Space Elevator Concept” activity, we originally wanted to create Permanent Committee (SEPC) in IAA.
- ✓ Proposer and co-authors determined that it is more practical to suggest to create new study group for now so that IAA can be ready to create SEPC in the future.



# New IAA SG3.24 “Road to Space Elevator Era”

## Table of contents



	Title
1	Where are we?
2	Primary Mission
3	Participants
4	Things to be researched
5	Conclusion
Backup	Several on-going projects in the world

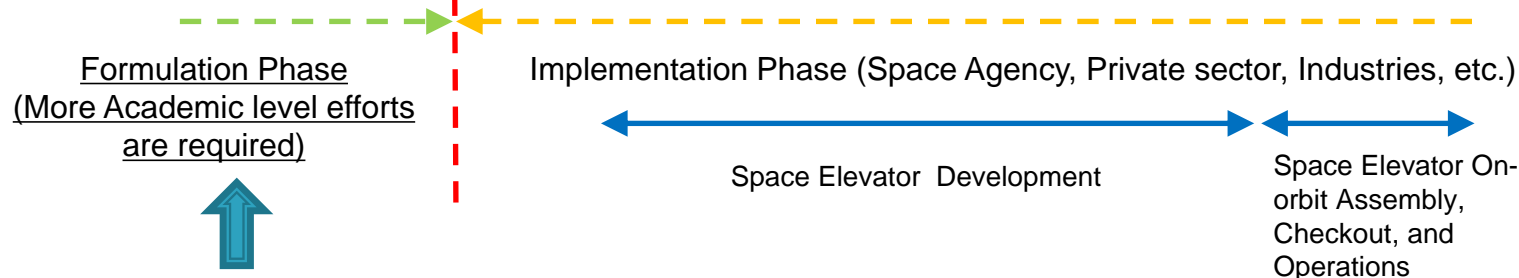
# New IAA SG3.24 “Road to Space Elevator Era”

## - 1. Where are we?



### Typical Project Life Cycle Phases

Project Life Cycle Phases	Pre Phase A: Concept Study	Phase A: Concept & Technology Development	Phase B: Preliminary Design and Technology Completion	Phase C: Final Design & Fabrication	Phase D: System Assembly, Integration & Test, Launch	Phase E: Operations & Sustainment	Phase F: Closeout
Reviews -Mission		MCR MDR					
Reviews -System		SRR SDR	PDR	CDR	ORR FRR		



**We are still here.**

#### <Notes>

MCR: Mission Concept Review, MDR: Mission Definition Review, SRR: System Requirements Review, SDR: System Definition Review, PDR: Preliminary Design Review, CDR: Critical Design Review, ORR: Operational Readiness Review, FRR: Flight Readiness Review  
(Ref: NPR7123.1A NASA Systems Engineering Processes and Requirements w/Change 1 (11/04/09))

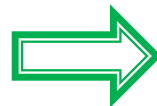
# SG3.24 “Road to Space Elevator Era”

## - 2. Primary Mission



2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
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**IAA Study Group 3.13**  
(2010/4-2013/3)  
“Assessment of the Technological Feasibility and Challenges of the Space Elevator Concept”



**IAA Study Group 3.24**  
(2014/10-2017/9)  
“Road to Space Elevator Era”



**IAA Permanent Committee?**  
(2018/3-)  
“Space Elevator (TBD)”

Primary Mission:  
Technical Feasibility Assessment

Primary Mission:

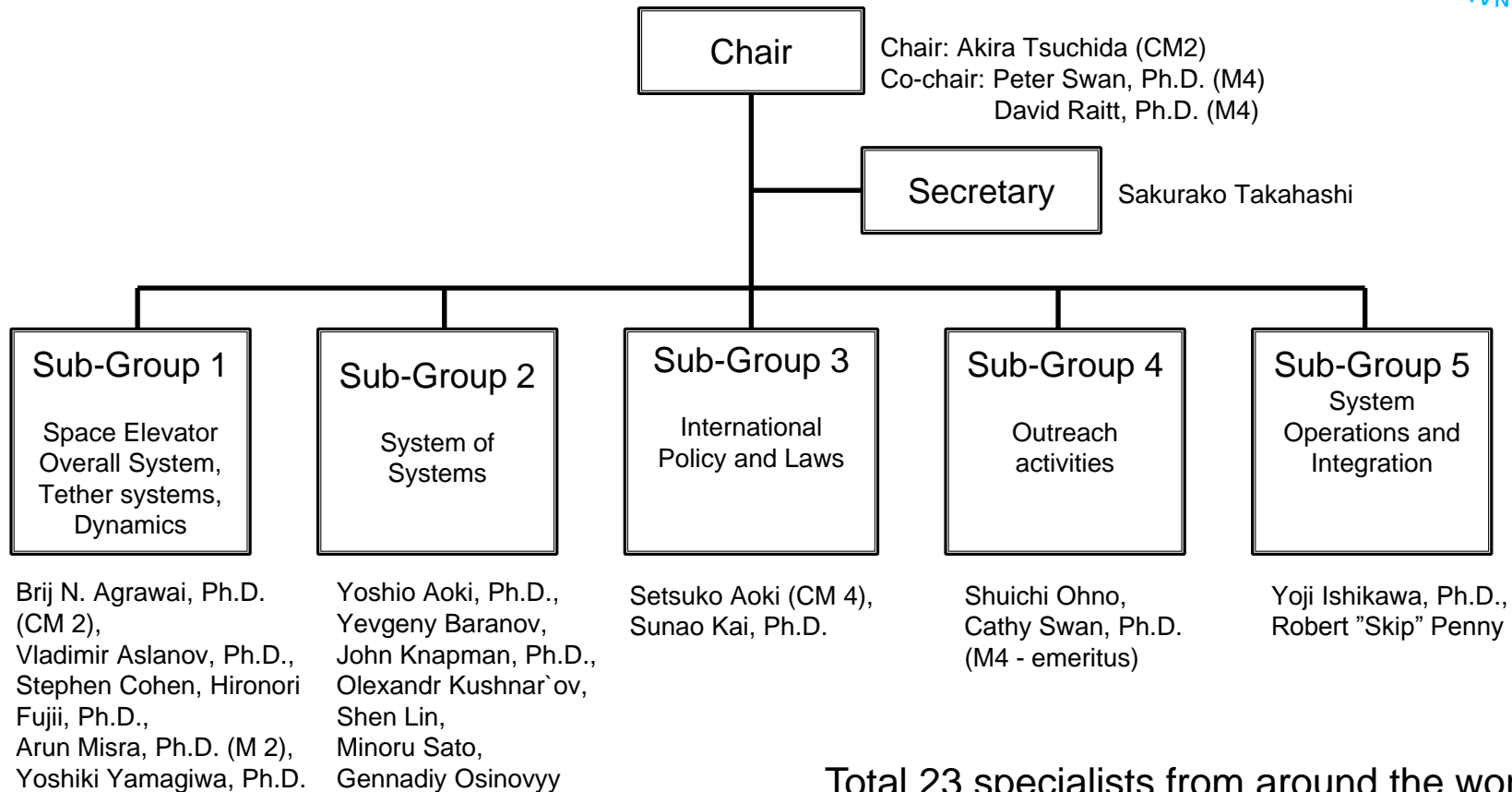
1. Review the advancement of critical technologies required to implement the Space Elevator
2. Define the Space Elevator Prediction Feasibility Index (SEPFI) including pilot project proposal (on-orbit demo) with first level system engineering details
3. Progress consideration of non-technological area such as international policy and law.
4. Increase more involvement from non-space area, developing countries

Primary Mission:

1. (IAA leads to) show options of the next generation transport infrastructure in space.
2. (IAA) creates recommended Mission Definition and/or System Requirement of the Space Elevator.

# SG3.24 “Road to Space Elevator Era”

## - 3. SG Structure



Total 23 specialists from around the world:  
Japan [10], with Canada [2], China [1], Finland [1], Russia [1], UK [2], Ukraine [3], and USA [3]

# SG3.24 “Road to Space Elevator Era”

## - 4. Things to be researched

▣ There are several topics (Candidates) to be researched:

Primary Mission	Things	Pre-cursor missions as a preparation of Space Elevator achievement	Primary group in this Study Group	Related Study Group (SG), Permanent Committee (PC) of IAA
1. Review the advancement of critical technologies required to implement the Space Elevator	Tether Dynamics	1. Simulation 2. On orbit verification of Dynamics of Flexible Space Tether	Group 1	2. Small Satellite PC
	Tether materials development, testing and manufacture	1. Material exposure experiment in space	Group 1, 5	
	Hazards to the tether and to tether climbers	1.Space Debris 2. Rates of wear and erosion	Group 1, 2	1. Space Debris PC
	Hazards caused by the space elevator	1. Risks to other spacecraft of collision with high-strength tether 2. Laser interference with existing operational satellites	Secretary, Group 2, 3, 5	
	Marine Node, High Stage one	System requirements development in addition to existing Marine launch system	Group 2	
	Tether Climber Design	1. Heat Management 2. Light weight structure 3. Energy transmission 4. Radiation Protection	Group 2, 5	

<Notes> These candidates are mainly suggested by ISEC, Space Elevator’s research topics.

# SG3.24 “Road to Space Elevator Era”

## - 4. Things to be researched

▣ There are several topics (Candidates) to be researched: (Continued)

Primary Mission	Things	Pre-cursor missions	Primary group	Related Study Group (SG), Permanent Committee (PC) of IAA
2. Define the Space Elevator Prediction Feasibility Index (SEPFI)	Maintain Developmental Roadmaps of Space Elevator and TRL (Technology Readiness Level)	N/A	Secretary, Group5	
3. Progress consideration of non-technological area such as international policy and law.	1. Evaluate the issues to be addressed at the international level. 2. Develop concept of legal approach to the entities responsible for Terrestrial [both land and sea], Aeronautical, and Space Laws.	N/A	Group 3	
4. Increase more involvement from non-space area, developing countries	1. Making presentations in countries and organizations throughout the world, especially in developing countries and countries just beginning their involvement in space activities. 2. Demonstrated event such as Space Elevator Challenge in developing countries	N/A	Group 4	SG5-11 Comparative Assessment of Regional Cooperation in Space: Policies, Governance and Legal Tools.  SG1-14 Promoting Global Space Knowledge and Expertise in Developing Countries
	Disposal of Radiation Waste	N/A	Group 2	SG3-21 Space Disposal of Radioactive Waste

<Notes> These candidates are mainly suggested by ISEC, Space Elevator’s research topics.



## SG3.24 “Road to Space Elevator Era”

### - 5. Conclusion

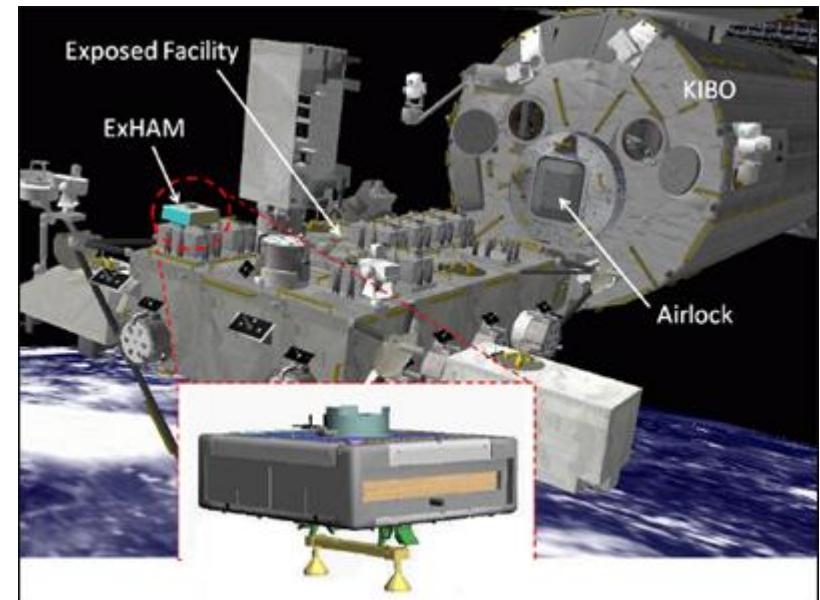
- New IAA Study Group “Road to Space Elevator Era” provides the following results as intermediate goals:
  - Review the advancement of critical technologies required to implement the Space Elevator. This will include carbon nano-tubes, control dynamics, etc.
  - Define the Space Elevator Prediction Feasibility Index (SEPFI) based upon the critical technologies identified
  - Publish the yearly Space Elevator Feasibility Status Assessment
  - Conduct IAA sponsored SSpace Elevator Challenge (SPEC) and conference in the world
  - Making presentations in countries and organizations throughout the world, especially in developing countries and countries just beginning their involvement in space activities.
  - Making space elevator infrastructure concepts an integral part of university science and engineering curricula.
- Final Products:
  - IAA Report on the Road to Space Elevator Era
    - ✓ Space Elevator Prediction Feasibility Index (SEPFI)
    - ✓ Pilot project proposal with first level system engineering details



## SG3.24 “Road to Space Elevator Era”

- Back-up chart, several on-going projects in the world

- ❑ Japan Society for Aeronautical and Space Science made committee for SE feasibility study.
- ❑ "Science Council of Japan" defined Space Elevator project as one of master plan for large research projects - 2014. It is the first step of starting very small research but recognized Space Elevator as "National Project".
- ❑ JAXA started ExHAM, material exposure experiment in space service using Japanese experiment module of the International Space Station.



<Credit> JAXA (<http://iss.jaxa.jp/en/kiboexp/ef/exham/>)

# SG3.24 “Road to Space Elevator Era”

- Back-up chart, several on-going projects in the world

- ❑ Encouraging young student, future engineers and scientists are the most important things. Space Elevator Challenges are now held in worldwide. (US, Japan, Europe, and Israel).



SPEC in Japan  
Aug 2014  
(Alt 1200m)  
(45 sec video is available.)

# SG3.24 “Road to Space Elevator Era”

- Back-up chart, several on-going projects in the world



Robo Climb: a robotic climber competition between student teams around the region of Seattle, USA. Aug, 2014

- ❑ “Physics of Space Elevator” is published in Japan. This book is actually a textbook to learn physics for high school student level.



Physics of Space Elevator



Number	Paragraph	Comments	Name	Response from Chairman	Status	Remarks
1	All	Most of the Version 1.0 is deleted in the Version 1.2. Why? Unless there are justifiable reasons, the later Versions should be drafted on the basis of the Version 1.0.	ISHIKAWA, Yoji	Appology not to explain well before change, to be clear, I would like to go back to Rev 1.0J (Sep 1, 2015) and modify by myself. I asked SG members to review V1.2, however some miss-communication and/or miss-understanding happened between V1.0J and V1.2. I should make sure that everybody is ready before sending V1.2.	In work	
2	All	A Mission Definition Document (MDD) is in principle to provide common definitions for the missions. The Version 1.2 contains so many specific definitions which have not determined yet and therefore is inappropriate for an MDD. The Version 1.2 should be reexamined and redrafted from this perspective.	ISHIKAWA, Yoji	Agree, I will update based on this comments. As I explained at the begining of this study, both Mission Definition Document and System Requirement Document should be developped in pararel, uncertine numbers should be descirved in System Requirement document with TBD.	In work	
3	All	The detailed specifications of the IOC/FOC have been neither agreed nor approved yet by the Study Group, and should not be described as Our Destinations. The detailed specifications are just some of case examples at this stage.	ISHIKAWA, Yoji	There are three space elevator construction concept in the past (Edwards, IAA, and Obayashi). I would like to appreciate all three team, at this point, I want to try to list up these three in MDD as example.	In work	
4	Forward	The contents in the Forward are inappropriate for an MDD. For example, the poem should be deleted.	ISHIKAWA, Yoji	When IAA approved this new (2nd) space elevator study as IAA activities, it was expected to focus to cooperate with industries and to practical space eperimental area. Based on this expectation, I should agree with this comments.	In work	
5	2 Mission Description	The "every day" in "Routine: Space will become routine with lift-offs occurring every day with massive tether climbers." has not been agreed yet, and should not be described in the MDD.	ISHIKAWA, Yoji	Recommend to change wording from "everyday" to "periodically". Otherwise rewording entire sentence.	In work	N/A
6	2 Mission Description	The "below \$100/kg" in "The price for a payload to be delivered to GEO will be below \$100/kg." has not been agreed yet, and should not be described in the MDD.	ISHIKAWA, Yoji	Based on my study what we should write down on Mission Definition Document as written #31 below, these kind of number should be evaluated if it should written in mission definition or in system requirement.	In work	N/A
7	2 Mission Description	The "\$100/kg to GEO," "14 and 70 metric tons each," "within a week" have not been agreed yet, and should not be described in the MDD.	ISHIKAWA, Yoji	Same response as #6 above.	In work	N/A
8	2 Mission Description	The "24/7/365/50 yrs." needs some explanation.	ISHIKAWA, Yoji	Same response as #6 above.	In work	N/A
9	3 System Description	Most of the sentences in this section describe systems, which should be dealt with in the System Requirement Document.	ISHIKAWA, Yoji	Same response as #2 above.	In work	
10	Mission Requirement Document	Mission Requirement Document(MRD) is not necessray. The contents of MRD should be merged in the System Requirement Document(SRD) and MDD. Section 2 and 4 of MRD should be moved to MDD and section 3 should be moved to SRD.	HOSHIKAWA, Riki	Agree, start drafting system requirement documents as high level description. No need to descrive in detail yet.	In work	

Number	Paragraph	Comments	Name	Response from Chairman	Status	Remarks
11	Add section:	3.1.8 Lunar Gravity Center and Mars Gravity Center  表紙の図には見られるのに記述が本文中にないため、追加すべきと考えます。文言は考えますので、もうしばしお待ちください。	TAKAHASHI, Sakurako	Agree. (Element shown in figure should have explanation in main sentence.)	In work	Sentences added
12	pg 3	"dreamt" is not a word	Cohen, Stephen	Reword to "dreamed"	In work	N/A
13	pg 3	two consecutive commas in middle of pg ', ,'	Cohen, Stephen	Agree	In work	N/A
14	2.6	two consecutive periods ' . '	Cohen, Stephen	Agree	In work	N/A
	2. MISSION DESCRIPTION	Add to the list of enabled missions:	Olexandr Kushnarov, Evgeniy Baranov, Gennadiy Osinovyv,			
15		<b>Progress in space tourism:</b> As a space travel will become accessible so the number of space visitors will dramatically increase.		After re-structuring paragraph based on comments #1-#4, #32, this comment should be considered to be written clearly.	In work	A sentence added
16		<b>Academic experiments in space:</b> Chip and safe access to space will enable carrying out numerous experiments in space that are not feasible now.		After re-structuring paragraph based on comments #1-#4, #32, this comment should be considered to be written clearly.	In work	A section added
17		<b>Space mining support:</b> delivery of space-mined minerals to the Earth's surface will become much chipper and safe.		After re-structuring paragraph based on comments #1-#4, #32, this comment should be considered to be written clearly.	In work	A sentence added
	2.5 Interplanetary Exploration	Add new paragraph:	Olexandr Kushnarov, Evgeniy Baranov, Gennadiy Osinovyv,			
18		Space Elevator will enable construction of future interplanetary spaceships with artificial gravity and closed ecosystems, capable of long-term mission support to the outer planets of the Solar System. Such spaceships with ability to contain not only the crew but a large number of scientists, tourists and colonists with total amount of more than 100 people can significantly increase efficiency of missions to outer planets.		This idea is "new" approach for interplanetary exploration compared with recent research. Although it is slight different interest from our study group's purpose, lets talk about this via Skype meeting in near future (If Yuzhnoye SDO agrees)	In work	
	2.8 Colonization of the Solar System	Add to the bottom:	Olexandr Kushnarov, Evgeniy Baranov, Gennadiy Osinovyv,			
19		Space colonies can be built not only on the Moon and Mars, but on other celestial bodies like moons of outer planets or in artificial worlds. All these ventures will become possible with construction of the space elevator network on our home planet.		We would like to get intention of Yuzhnoye's this comments via Skype meeting. (If Yuzhnoye SDO agrees)	In work	
	Add section:	2.11 Support of other strategic technologies.	Olexandr Kushnarov, Evgeniy Baranov, Gennadiy Osinovyv,			
20		Many Earth-based technologies will be affected by new possibilities of operations in space. The dreams of chip energy can become a reality when space-based resources will become accessible.		This comment might be related to comment #18 above. Let's take via Skype.	In work	chip→ cheap?
21		The abundance of He <sup>3</sup> in the lunar regolith can turn the Moon into a main pit of nuclear fuel for future fusion reactors. This unique stock is inaccessible yet, but Space Elevator can turn things up.		This comment might be related to comment #18 above. Let's take via Skype.	In work	
	Add section:	2.12 Disposal of nuclear wastes	Olexandr Kushnarov, Evgeniy Baranov, Gennadiy Osinovyv,			

Number	Paragraph	Comments	Name	Response from Chairman	Status	Remarks
22		<i>Sending nuclear wastes out of planet with chemical rockets is extremely expensive and risky task. Space Elevator can make it safer and significantly cheaper.</i>		Same kind of description is exists para 2.9. After re-structuring paragraph based on comments #1-#4, #32, this comment should be considered to be written clearly.	In work	Sentences added
	3. System Description. 3.1.1 Tether	Last sentence in the first paragraph states that tether is one meter wide and few mils thick at the bottom. In the atmosphere tether's cross section must be round in order to reduce wind drag. Tether taper ratio is probably specified for the altitude of GEO, but not for the very top point of the space elevator.	Olexandr Kushnarov, Evgeniy Baranov, Gennadiy Osinovy, Vydm Pasko			
23		Rephrase the mentioned sentence to:				
24		<i>The cross section of the carbon nanotube fiber is about several square centimeters at the bottom and increases by the factor of 6 at the altitude of the geostationary orbit. Afterwards tether's cross section decreases up to the altitude of the counterweight placed in 100,000 kilometers from the Earth's surface.</i>		After re-structuring paragraph based on comments #1-#4, #32, this comment should be considered to be written.	In work	Sentences added
25	3.1.2 Climber	As the climber powering is still an open issue the first sentence can be complemented with an alternative scheme like power beaming (preferably with the use of a space-based laser).	Olexandr Kushnarov, Evgeniy Baranov, Gennadiy Osinovy, Vydm Pasko	After re-structuring paragraph based on comments #1-#4, #32, this comment should be considered to be written.	In work	Sentences added
26		More information on climber cargo types must be specified, for example: number of passengers for a civil climber; maximal volume of a climber; list of possible goods (construction materials, life support materials) and their possible amount as a payload for climber; and so on.		After re-structuring paragraph based on comments #1-#4, #32, this comment should be considered to be written.	In work	Sentences added
27		Such detailed info can be used to estimate the time of a future spaceships construction process in orbit with the use of a space elevator to deliver construction materials to space.		After re-structuring paragraph based on comments #1-#4, #32, this comment should be considered to be written.	In work	Sentences added
	3.1.3 GEO Node	Add a couple of sentences or a paragraph:	Olexandr Kushnarov, Evgeniy Baranov, Gennadiy Osinovy,			
28		<i>As GEO Node will be the most populated station of the space elevator, an inhabited module with artificial gravity will be attached to the station. This module will provide 1g acceleration field to support health of the crew and guests of the GEO Node.</i>		This idea is "new" approach for interplanetary exploration compared with recent research. Although it is slight different interest from our study group's purpose, lets talk about this via Skype meeting in near future (If Yuzhnoye SDO agrees)	In work	
	3.1.4 Apex Anchor	Uncover the nature of the Apex Anchor – what it is made of.	Olexandr Kushnarov, Evgeniy Baranov, Gennadiy Osinovy,			
29		<i>Apex Anchor is one of the most important components of the Space Elevator as it serves as a counterweight. Major part of its mass probably would be formed by out-of-service climbers and/or initially collected space debris. Apex Anchor can also be used as the space port for interplanetary spacecraft and space laboratory.</i>		We would like to get intention of Yuzhnoye's this comments via Skype meeting. (If Yuzhnoye SDO agrees)	In work	
	3.1.5 Earth Port	Add sentence to the very end of the section:	Olexandr Kushnarov, Evgeniy Baranov, Gennadiy Osinovy,			
30		<i>On contrary, electric powering of atmospheric climbers with electric current running in tether can be used. In this case Earth Port will include transformer node that will feed tether (two or three parallel lines) with alternating current, while power plant can be based on land. This scheme will allow climbers to reach 40...50-km altitude by using Earth-based power source.</i>		Agree, after re-structuring paragraph based on comments #1-#4, #32, this comment should be considered to be written.	In work	Sentenses added
	Appendix A.1 Acronyms	Add:	Olexandr Kushnarov, Evgeniy Baranov, Gennadiy Osinovy,			

Number	Paragraph	Comments	Name	Response from Chairman	Status	Remarks
31		<i>SSPS – Space Solar Power System</i>		Agree	In work	Addeed
32	Table of contents	<p>There is no good template of mission definition documents. This is the big difERENCE to make system requirements documents. (System Requirments documsnts have many good example and template are exists.) To have common understanding, I should take an action to research "what is mission definition".</p> <p>I have several information as follows: example 1: European Committy Galileo program example 2: ESA Marcopolo mission example 3: Mission Definition Template from other area (ex: U.S. Department of Health &amp; Human Services)</p> <p>Then I should make additional comments to improve our products.</p>	Akira Tsuchida	---	In work	





International Academy of Astronautics (IAA)  
  
Study Report (Draft 1 - template)  
  
of  
  
Study Group 3.24 “Road to Space Elevator Era”



February 21, 2015

IAA Study Group 3.24 “Road to Space Elevator Era”



## Abstract

This Study Group named as "Road to Space Elevator Era" of the International Academy of Astronautics (IAA) is the 2<sup>nd</sup> study group related to space elevator study, followed-up of the SG3.13 "Assessment of the Technological Feasibility and Challenges of the Space Elevator Concept".

Main goal of this study group are:

(From proposition paper, Development of a unique space transportation system of the future, called a space elevator, should be accomplished with more international cooperation and should contribute to the overall development of space science and systems development. To accomplish these desires, projects are identified that can be accomplished in the near future leading to risk reduction and engineering enhancements. Specifically, the following practical on-orbit verification projects could be planned and promoted through this study group's activity.)

- 1) Promotion of ISS (International Space Station) utilization and leveraging of Small Satellite (Cube, Micro, etc.) concepts to accomplish on-orbit verification; such as, advanced material research (ex. material exposure experiment) and development while extending tether technology development.
- 2) Promotion of space technology spin-out into industrial application (and vice versa) by the collaboration with civil engineering, architectural engineering, and space engineering experts.
- 3) Plan and execute precursor missions, leveraging existing technology, to demonstrate prototype space elevator segments. (ex. Marine Node for sub-orbital rocket launch; tether satellites for dynamics of deployment; movement around Earth-space with low thrust, high efficiency rocket motors demonstrating start-up activities.)

To accomplish these goals, we made preliminary "Mission Definition", "System Requirement" first, and then listed up "Critical technologies required implementing the Space Elevator".

Space Elevator Prediction Feasibility Index (SEPFI) is also created to determine priority order of space elevator research topics and to show overall space elevator feasibility.



Chapter 1 Introduction – purpose of this study	
Chapter 2 Space Elevator Mission Definition	
Chapter 3 Space Elevator System Requirements	
Chapter 4 Critical technologies required implementing the Space Elevator	
Chapter 5 Space Elevator Prediction Feasibility Index (SEPMI)	
Chapter 6 Recommendation of on-orbit verification/demonstration experiment	
Acknowledgement	

Appendixes	
Appendix-1 Contributor List	
Appendix-2 Acronyms and Common Terminology	
Appendix-3 Research Topics List	
Appendix-4 TBD...	



## Chapter 1

### Introduction – purpose of this study





## Chapter 2

### Space Elevator Mission Definition



(High Level Mission definition should be described so that high level System Requirement can be determined as a result "Critical technologies required to implement the Space Elevator" can be defined. My (Akira's) intention is this mission definition shall define our expected cost target to ascend/descend payloads by space elevator. I think there is a fundamental conceptual problem on Space Elevator. In US, train system is not popular and air plane is more popular for transportation method in nationwide. On the other hand, why public ground transportation is popular in Japan but not Air plane. We should evaluate how much cost is required to build space elevator and how much cost is also required to maintain. Based on my experience of several big national projects, annual maintenance cost is usually 5% through 10% of initial required. If we want to maintain space elevator for 20 years, total cost of initial building cost and maintenance cost becomes 200% or 300% of initial cost is required.

We should put some assumption how many times and how much weight of payloads can be transported in space elevator life cycle. (we can include several income such as removing space debris, etc.)





# **Space Elevator Mission Definition Document**



### Change Record

<i>Version</i>	<i>Prepared or Revised by</i>	<i>Date</i>
<b>1.0</b>	<b>Yoji Ishikawa</b>	<b>June 26, 2015</b>
<b>1.0 P</b>	<b>Peter Swan</b>	<b>July 4, 2015</b>
<b>1.0J</b>	<b>JAMSS</b>	<b>Sep. 1, 2015</b>
<b>1.1</b>	<b>Skip Penny/Peter Swan</b>	<b>August 28, 2015</b>
<b>1.2</b>	<b>Skip Penny/Peter Swan (JAMSS update)</b>	<b>September 15, 2015</b>
<b>1.3</b>	<b>Akira Tsuchida</b> <b>(Re-Updated from 1.0J based on comments)</b>	<b>Feb 21, 2016</b>



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## **1. INTRODUCTION**

### **1.1. Scope**

TBD

### **1.2. Documentation**

#### **1.2.1. Applicable Documents**

[AD1] Elevator System Requirements Documents

#### **1.2.2. Reference Documents**

[RD1] Space Elevators: An Assessment of the Technological Feasibility and the Way Forward, Eds. Peter A. Swan, David I. Rait, Cathy W. Swan, Robert E. Penny, and John M. Knapman, The International Academy of Astronautics, 2013.

[RD2] The Space Elevator: A revolutionary Earth-to-space transportation system, Bradley C. Edwards and Eric A. Westling, Spaseo Inc., 2002.

[RD3] The Space Elevator Construction Concept (Obayashi Corporation), Yoji Ishikawa, Tatsuhito Tamura, Kiyotoshi Otsuka, Takaya Horiike, Takeo Iwaoka, Naoki Masui, Katsuya Hamachi, Satomi Katsuyama, and Yoshio Aoki, IAC-13-D4.3.6, 2013.

[ISEC2010] ISEC Study Report, Space Elevator Survivability, Space Debris Mitigation

[ISEC2012] ISEC Study Report, Space Elevator Operations Concept

[ISEC2013] ISEC Study Report, Space Elevator Tether Climbers

[ISEC2014] ISEC Study Report, Space Elevator Architecture and Roadmaps

[ISEC2015] ISEC Study Report, draft, Marine Node



## **2. MISSION OBJECTIVES and SIGNIFICANCE**

The goal of building a space elevator infrastructure is to provide safe, routine, inexpensive, daily transportation infrastructure to space, especially for GEO and beyond. It is no exaggeration to say that a Space Elevator is beneficial to all of humanity. Its objectives are multifold.

### **2.1. Routine, Safe, Lower Cost Transportation System**

It is estimated that the cost going up to space with the Space Elevator is two orders of magnitude lower than those of conventional methods, or rockets. Since a higher transportation cost is now the biggest obstacle for expansion of space activity, the lower transportation cost associated with the Space Elevator will allow all kinds of space business to flourish in the future.

### **2.2. Environmentally-Friendly Transportation System**

The Space Elevator is an environmentally-friendly transportation system. Mainly it uses electrical energy for the traction of the vehicles (called climbers). Solid fuel used for conventional propulsion system contains halogenated compounds, which have a harmful impact on the Earth environment and the ozone layer. Also, the Space Elevator, unlike the conventional rockets of which the bodies are disposed in the orbit around the Earth to become space debris, has almost nothing to be thrown away, producing no space debris. Instead, the Space Elevator can contribute to the collection of existing space debris (See below.).

### **2.3. Collection of Space Debris**

The Space Elevator is useful for the collection of space debris. Debris exists mostly at a Low Earth Orbit (LEO) and a Geosynchronous Earth Orbit (GEO). The tether of the Space Elevator, at the height of LEO, has high relative velocity with space debris because of the significant difference in the circling speed.

### **2.4. Construction, Inspace, of major space systems, especially the Space Solar Power System (SSPS)**



The Space Elevator will be able to facilitate the construction of major space systems at many creative locations [GEO Node, Apex Anchor, etc.]. The strength of this capability is remarkable as there would be no restrictions on size or mass of the resulting space capability. One example of this phenomenal capability would be the case of Space Solar Power System (SSPS). The technical bottleneck of SSPS is its transportation cost. The completion of one SSPS of several tons using conventional system requires hundreds of rockets, making the project almost unachievable. Conversely, a transportation infrastructure like the space elevator enables routine movement of mass to orbit at very low cost and little risk of system loss.

## **2.5. Interplanetary Exploration**

The essential feature of the Space Elevator is that spacecraft, cargo, and crew can be sent to the other planets or the orbits around the Sun. The planets include Mercury, Venus, Mars, asteroids, Jupiter, and Saturn. This expansion of robotic and human movement off-planet will be truly revolutionary in human history.

## **2.6. Space Resource Utilization**

The upward transportation cost being low means the downward transportation cost is also low. Not only outbound shipping but also inbound vehicles receive benefit from the Space Elevator. The tether, of tentative 100,000 km length, allows exploring spacecraft to make interplanetary travels to asteroids, Jupiter, or Saturn. Valuable rare metals are easily mined from asteroids or deuterium resources from the Jovian atmosphere. These resources, once sent back to near earth space, can be retrieved and brought back to the Earth surface at reasonable cost using the Space Elevator. Delivery of space-mined minerals to the Earth's surface becomes much cheaper and safer.

## **2.7. Manned Spaceflight**

One of the biggest benefits of the Space Elevator is a prospect for manned spaceflight, especially, for tourism open to the public. Even at the construction phase, although most of the work will be carried out unmanned, the help of crew will be expected. As a space travel becomes accessible, the number of space visitors will dramatically increase.

*The impact of space radiation on the human body shall be evaluated and verified.*





## **2.8. Colonization of the Solar System**

Moon and Mars are two destinations for humanity, and the Space Elevator can facilitate the accessibility. Colonization of the Solar system will become realistic once the Space Elevator is built. Movement off-planet will become real and routine, enabling survival of the human race.

## **2.9. Disposal of Nuclear Power Wastes**

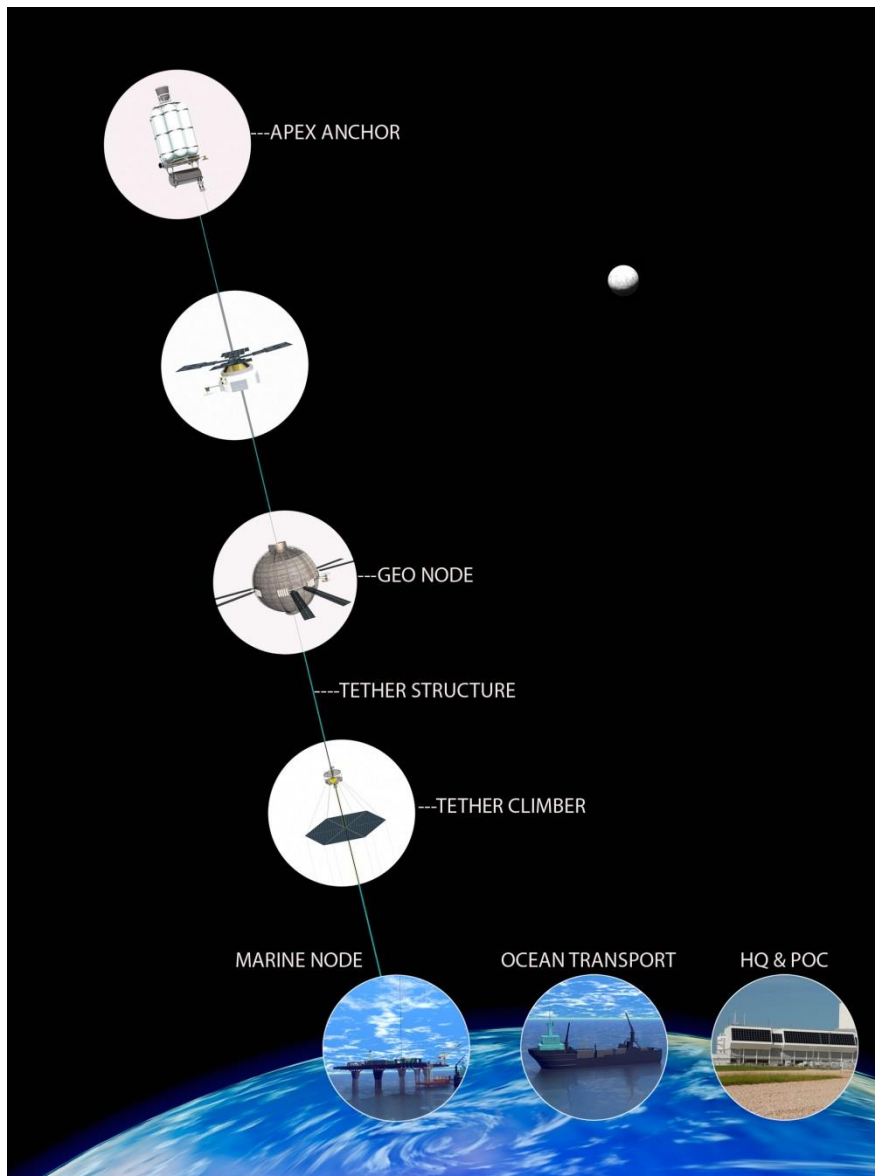
Nuclear power wastes generated on the Earth shall be transported, using the Space Elevator, and disposed at the orbits beyond the Earth towards the Sun. This would require the expected high reliability and acceptance of many concerned citizens. Sending nuclear wastes out of planet with chemical rockets is extremely expensive and risky task. Space elevator makes it safer and significantly cheaper.

## **2.10. Academic Experiments in Space**

Cheap and safe access to space enables carrying out numerous experiments in space that are not feasible now.

## **3. MISSION OUTLINE**

**Insert image here**



### 3.1. System Element

- The system shall be broken into the space element and the ground element.

#### 3.1.1. Space Element

- The space element shall be comprised of tether (also called cable), climbers, Apex Anchor Node (also called counter weight), and nodes/gates (GEO Node, LEO Gate, Moon Gate, and Mars Gate).



### 3.1.1.1. Tether

- The tether shall be designed in terms of material, shape, dimension, and mass based on a tether dynamics analysis to be carried out separately.

*One of the most unknown factors for defining system requirements is the property of the tether material. Carbon nanotube is the most plausible candidate for it, and the intensive investigation and verifications are required.*

*The design examples for the ribbon-shape tether using carbon nanotube are shown in the following.*

	Length (km)	Thickness (mm)	Width (mm)		
			Earth	GEO	Space
IAA [RD2]	100,000	#s	#s	#s	#s
Obayashi [RD3]	96,000	1.38	18	48	36

*The cross section of the carbon nanotube fiber is about several square centimeters at the bottom and increases by the factor of 6 at the altitude of the geostationary orbit. Afterwards tether's cross section decreases up to the altitude of the counterweight placed in 100,000 kilometers from the Earth's surface.*

- The tether shall have bifurcation tracks so that upward and downward climbers can pass each other, or a multiple number of tethers shall be assigned to either upward tether or downward tether.

### 3.1.1.2. Climber

**needs both IAA and RD3's numbers**

- Climbers shall be a self-propelled type.
- Climber powering is still an open issue. Power beaming or the use of space-based laser shall be considered as an alternative scheme.
- Climber cargo types shall be specified, for example: number of passengers for a civil climber; maximal volume of a climber; list of possible goods (construction materials,



life support materials) and their possible amount as a payload for climber; and so on.

- Detailed info shall be used to estimate the time of a future spaceships construction process in orbit with the use of a space elevator to deliver construction materials to space.
- Climbers shall weigh TBD tons, and have TBD shape.

*The weight is 100 tons with six-car configuration in [RD3].*

*The weight is 20 tons with six-car configuration in [RD2].*

- Climbers shall have an ascending and descending cruising speed of TBD km/h.

*The speed is 200 km/h in [RD2] and [RD3]. The cruising speed can change with height (can be faster at the higher height where the gravity force is much smaller).*

### **3.1.1.3. Apex Anchor**

**needs both IAA and RD3's numbers**

- The mass of apex anchor shall be determined based on a tether dynamics analysis.
- 
- Apex Anchor Node shall be a major space element or the upper terminus of the Space Elevator.
- Apex Anchor Node will also enable construction of space systems and refueling of spacecraft.
- Apex Anchor Node shall serve as a platform for climbers to halt and depart downward, a platform to deploy, recover, maintain, and repair satellites bound for outward locations. It will also be a lab to conduct experiments utilizing the low-"g" environment and analyze the material samples mined and retrieved at Moon, asteroids, or planets, a space-based control center to manage and control the operation of the Space Elevator, and, at a later stage, a facility to house tourists.
- Apex Anchor Node shall be equipped with facilities to manage tether dynamics,



telecommunication, attitude control, collision avoidance with meteorites or space debris, manned activity including EVA, and transfer vehicles.

*The ratio of the tether mass to the apex anchor mass shall be constant throughout the construction and operation phases to keep the balance.*

#### **3.1.1.4. Node/Gate**

- GEO Node shall be a major space element or a space hub of the Space Elevator. Thanks to the weightless environment at GEO, there is no physical restriction from the point of mass balance on the mass of GEO Node.
- GEO Node will also enable construction of space systems and refueling of spacecraft.
- GEO Node shall serve as a platform for climbers to halt and depart upward and downward, a platform to deploy, recover, maintain, and repair GEO satellites and SSPS, and a lab to conduct experiments utilizing the weightless environment and analyze the material samples mined and retrieved at Moon, asteroids, or planets, a space-based control center to manage and control the operation of the Space Elevator, and, at a later stage, a facility to house tourists.
- GEO Node shall be equipped with facilities to manage tether dynamics, telecommunication, attitude control, collision avoidance with meteorites or space debris, manned activity including EVA, and transfer vehicles.

*Similar Gates such as MEO Gate, Mercury Gate, and Venus Gate can be set up as required.*

- LEO Gate, Moon Gate, Mars Gate, and apex anchor shall serve as a platform to deploy artificial satellites, unmanned or manned spacecraft to LEO, Moon, Mars, and asteroids and beyond, respectively.

Facilities to utilize the gravity environments at specific heights shall be constructed.



These include Lunar Gravity Center (8,900 km high) and Mars Gravity Center (3,900 km high) which use the gravity environment similar to those on the Moon's and Mars' surfaces for the purposes of research and training.

- The mass of all the Nodes and Gates shall be determined based on a tether dynamics analysis.

*The example of the mass distribution of all the Nodes/Gates is shown below. (In this case, the mass of tethers is 14,000 tons (two tethers x 7,000 tons per tether) [RD3])*

<i>Node/Gate (height)</i>	<i>Mass (ton)</i>
<i>Apex anchor (96,000 km)</i>	<i>12,500</i>
<i>Mars Gate (57,000 km)</i>	<i>100</i>
<i>Moon Gate</i>	<i>Not included</i>
<i>GEO Node (36,000 km)</i>	<i>4,000</i>
<i>LEO Gate (23,750 km)</i>	<i>100</i>
<i>Lunar Gravity Center (facility to utilize 0.17G environment at the height of 8,900 km)</i>	<i>100</i>
<i>Mars Gravity Center (facility to utilize 0.38G environment at the height of 3,900 km)</i>	<i>100</i>

**needs both IAA and RD3's numbers**

- The mass of all the nodes (fixed loads) and climbers (movable loads) shall be determined based on a time-depending tether dynamics analysis with taking the mass of the tether and the apex anchor into account.

### **3.1.2. Ground Element**

- The ground element shall be comprised of Marine Node (the function to be shared with the space element).

-

#### **3.1.2.1. Terrestrial Node and Others**

Skip [here we need your draft Marine Node Functional description [please send to A&S].

- The Marine Node shall be comprised of a climber arrival/departure area, a medical and quarantine area, a hangar, a service bay, an R/D facility, a facility management



area, workers' cabins, and cargo bays.

- Marine Node shall have a concrete floating structure of semi-submersible type.

*The semi-submersible type consists of an underwater floating hull, deck, and connecting hollow columns, and is used mostly for outer seas where waves are high with long periods. The hulls are moored with tension legs (high tensile steel) to suction anchors buried on the sea bottom [RD3].*

- Additional ground facilities that support the Space Elevator shall include, but not be limited to, an airport, a port, hotels, residential area, and visitor centers.
- One potential solution [RD3] uses lasers to power tether climbers, located around the Marine Node.
- Electric powering of atmospheric climbers with electric current running in tether can be used. In this case Marine Node will include transformer node that will feed tether (two or three parallel lines) with alternating current, while power plant can be based on land. This scheme will allow climbers to reach 40...50-km altitude by using Earth-based power source.

### **3.1.3. Payload**

- Payloads shall be lifted after being installed in climbers. They include scientific instruments, experimental apparatuses, artificial satellites, interplanetary spacecraft, life support system, and crew.
- When material resources are mined at asteroids or other planets to be transported to the Earth, they constitute payloads in a downward direction.

## **3.2. Mission Phases**

### **3.2.1. R/D Phase**

- The subjects for R/D shall be determined with reference to Section 3.7 of [AD1].





### 3.2.2. Construction Phase

- The construction phase shall consist, in chronological order, of the construction of Marine Node, the deployment of tether, and the establishment of Nodes/Gates.
- The construction of Marine Node shall consist of the manufacture of the pieces, assembly, towing to the site, and installment.
- The deployment of tether shall consist, in chronological order, of the launch of an initial tether by a rocket, transportation of the initial tether to GEO, deployment of the initial tether, and reinforcement of the tether.

*See [RD2] and [RD3].*

- The deployment of Nodes/Gates shall be carried out by climbers using the completed tether.
- In addition, Solar Power Satellite System shall be erected at the GEO Node with their parts transported by the Space Elevator.

### 3.2.3. Operation Phase

- The operation phase shall consist of official and routine transportation of cargo and/or crew, collection of space debris, SSPS power generation and power transmission to Earth, interplanetary exploration, manned spaceflight including tourism, colonization of the solar system, and disposal of nuclear wastes.

### 3.2.4. Disposal Phase

- TBD

*The example of the mission phases is shown below. ([RD3])*

<i>Phase</i>	<i>Years</i>
<i>R/D Phase</i>	<i>TBD to 2030</i>
<i>Construction Phase</i>	<i>2030 to 2050</i>



<i>Operation Phase</i>	<i>2050 to TBD</i>
<i>Disposal Phase</i>	<i>TBD</i>



## 4. MISSION REQUIREMENTS

**All this section has to be re-written with two sets of information**

**Suggestion –**

**IAA called      Space Elevator Initial Operational Capability [robotic]**

**Obayashi called – Space Elevator Full Operational Capability [humans]**

### 4.1. Programmatic Requirements

#### 4.1.1. Cost Policy

- The Space Elevator shall comply with the cost policy stipulated in a business plan (TBD) to be established separately.
- The cost of transportation by the Space Elevator shall be two orders of magnitude lower than those of the conventional methods.

*The initial construction cost is estimated to be 6 billion USD ([RD2]) or roughly 100 billion USD ([RD3]).*

#### 4.1.2. Launch Vehicle

- The initial tether shall be compatible with launch by TBD.

*Vehicles with maximum launch capability shall be chosen (such as Delta-class rocket, if chosen from currently available rockets).*

#### 4.1.3. Launch Mass

- The total mass of the first spacecraft which carries an initial tether shall be TBD.

*The total mass of the first spacecraft is estimated to be 125 tons including two tethers (20 tons per tether) ([RD3]).*

### 4.2. Orbit Requirements

- The Space Elevator orbit shall be such that its tether extends from the Earth surface to the height of approximate 100,000 km over the site on an Equator.



### 4.3. Site Requirements

- The Space elevator's Marine Node shall be placed on or around an Equator. Example: the loss of 35 degrees north latitude is a cosine of 35 degrees time max capability.
- Too great a loss to accept anywhere north or south of say small angel.

*See [RD2].*

### 4.4. Payloads/Crew Lift Requirements

- The Space Elevator shall be able to lift payloads to LEO, MEO, GEO, and also up to the height of the apex anchor.
- The Space Elevator shall have the cable of 100,000 km so that payloads can be sent to the Moon and the outer and inner planets using the cable's sling mechanism, and, when needed, with the help of reasonable amount of further acceleration. The planets include Mercury, Venus, Mars, asteroids, Jupiter, Saturn, Uranus (TBD), and Neptune (TBD).
- The Space Elevator shall be equipped with the stations which serve as the platforms to deploy artificial satellites or spacecraft at the heights determined according to their destinations. The stations include GEO Node, Apex Anchor Node, LEO Gate, Moon Gate, and Mars Gate.
- One climber shall lift 70 tons (TBD) per travel. The climber shall depart the Earth every two and half (TBD) days.

*The numbers are based on [RD3].*

### 4.5. Mission Duration or Lifetime Requirements

- The mission lifetime shall have a duration of thirty years (TBD) or longer.

*The lifetime depends majorly on the durability of the tether material. The candidate material is carbon nanotube, and hardly anything is known about the material's*



*durability in the space environment. This issue shall be verified by space environment exposure tests.*

#### **4.6. Non-Technical Requirements**

##### **4.6.1. Commitment**

- Long-term financial, managerial, and political commitment is required.

*Decades of period are prospected for the construction (for example, 20 years in [RD3]). Business models which produce profits even before the construction is completed shall be sought and developed.*

##### **4.6.2. Legal Compliance**

- The Space Elevator shall comply with any international laws on ground/sea, sky, and space.
- The jurisdiction which governs the Space Elevator shall be clearly defined.

*Obviously, the currently available laws are not applicable to the Space Elevator, and the laws shall be revised or new laws shall be established.*

##### **4.6.3. Organization/Structure**

- The organization that manages and promotes the project shall be financially secure and have strong and continuous commitment to the mission.

#### **4.7. Technology Requirements**

- Only technologies at a minimum of TRL 5 (TBD) by the end of the R/D phase shall be implemented in the mission design.

#### **4.8. Operations Requirements**

- Climbers shall depart only every two and half (TBD) days.



*See [RD3].*

- Upward and downward climbers shall avoid the collision with each other.
- The movement and the position of climbers along the tether shall be determined based on the analysis on the tether dynamics with considering their loads to the tether, the Coriolis forces due to their movements, and the balance of the tether.
- No flying objects are allowed to enter within a TBD meter-radius of the Tether.

#### **4.9. Subsystem Requirements**

Refer to [AD1] for the requirements in each subsystem.



## **5. SUCCESS CRITERIA**

### **5.1. Minimum Success**

- The components including tether, apex anchor, and nodes/gates are fully constructed. Climbers go up and down along the tether to lift payloads to GEO Node and the apex anchor.

### **5.2. Full Success**

- Artificial satellites and unmanned/manned spacecraft are sent to the orbits circling around the Earth and the Sun.

### **5.3. Extra Success**

- Space Solar Power System is constructed using the Space Elevator and the power is utilized on the Earth.
- The material resources mined at asteroids or the other planets are retrieved and transported to the Earth surface via the Space Elevator.
- Colonization of the solar system starts.

## **6. SCHEDULE**

- The launch of an initial tether shall occur by 2030.
- The operation shall start by 2050.

*The numbers are tentative. See [RD3].*

## **7. RISKS**

### **7.1. Functional Risks**





## **7.2. Interface Risks**

## **7.3. Safety Risks**

## **7.4. Operational Risks**

## **Appendix-A      Acronyms**

## **Appendix-B      Terminology**



## Chapter 3

### Space Elevator System Requirements



(High Level System Requirement (not in detail like Sakurako provided previously, it was definitely bad example) should be described based on Mission Definition so that "Critical technologies required to implement the Space Elevator" can be defined. So I suggest add one paragraph in mission definition as "rough order development plan and cost" )

(Pete and David, I think for this purpose, it is too early to define IOC and FOC concept in MDD. I regret not to be in Seattle in Aug 2015. )



## Chapter 4

### Critical technologies required implementing the Space Elevator





## Chapter 5

### Space Elevator Prediction Feasibility Index (SEPFI)







## Chapter 6

### Recommendation of on-orbit verification/demonstration experiment





## Acknowledgement





## Appendix List

	Title	Remarks
Appendix-1	SG3.24 “Road to Space Elevator Era” contributor list	
Appendix-2	Common Terminology	
Appendix-3	Research Topics List	Originated by ISEC
Appendix-4		
Appendix-5		



## Appendix-1

### SG3.24 “Road to Space Elevator Era” contributor list



#### Contributor List

#	Name	Country	Affrication	SEMD	SESR	Crit. Tech.	SEPFI	On-Orbit V.
1	Akira Tsuchida	Japan	JAMSS					
2	Peter Swan	USA						
3	David Raitt	Netherland?						
4	Sakurako Takahashi	Japan	JAMSS					
5	Brij N. Agrawai							
6	Setsuko Aoki	Japan	Keio Univ.					
7	Vladimir Aslanov	Russia						
8	Yoshio Aoki	Japan	Nihon Univ.					
9	Yevgeny Baranov	Ukraine	Yuzhnoye SDO					
10	Stephen Cohen							
11	Hironori Fujii	Japan						
12	Yoji Ishikawa	Japan	Obayashi Corp.					
13	Sunao Kai	Japan	Nihon Univ.					
14	John Knapman	UK						
15	Olexandr Kushnar`ov	Ukraine	Yuzhnoye SDO					
16	Shen Lin	China						
17	Arun Misra							
18	Shuichi Ohno	Japan	JSEA					



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Contributor List

#	Name	Country	Affiliation	SEMD	SESR	Crit. Tech.	SEPFI	On-Orbit V.
19	Gennadiy Osinovy	Ukraine	Yuzhnoye SDO					
20	Robert "Skip" Penny	USA						
21	Minoru Sato	Japan	Toukai Univ.					
22	Cathy Swan	USA						
23	Yoshiki Yamagiwa	Japan	Shizuoka Univ.					
24	Anna Guerman							
25	Vadym Pasko	Ukraine	Yuzhnoye SDO					

## Appendix-2

### Acronyms and Common Terminology

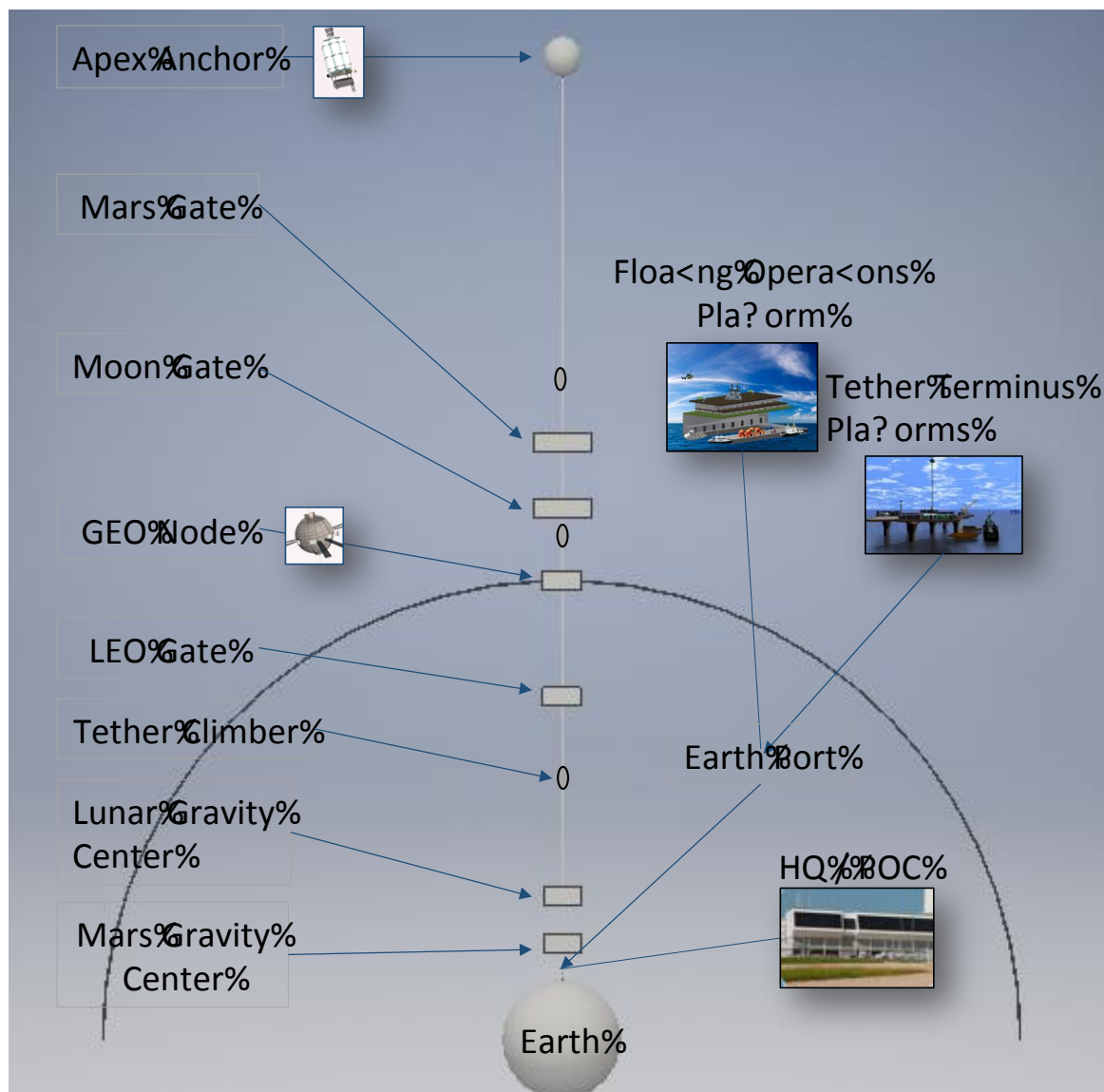
## **8. Acronyms**

FOC	Full Operational Capability
FOP	Floating Operations Platform
GEO	Geosynchronous Earth Orbit
HQ/POC	Headquarters Primary Operations Center
IOC	Initial Operational Capability
IAA	International Academy of Astronautics
ISEC	International Space Elevator Consortium
kg	kilogram
km	kilometers
LEO	Low Earth Orbit
LOA	Length Overall
MT	metric ton
MDD	Mission Definition Document
R&D	Research and Development
SSPS	Space Solar Power System

### 8.1.1. Terminology

IAA study group #3-24 met in Seattle in August of 2015. The team agreed to use, as much as possible, consistent terminology for this report. Below are those terms shown in the figure. This general list of terminology is shown in the next table: The agreed upon terms should be:

Apex Anchor Node	LEO Gate	Earth Port
Mars Gate	Lunar Gravity Center	- Earth Terminus
Moon Gate	Mars Gravity Center	- Floating Operations Platform
GEO Node	Tether Climbers	Headquarters and Primary Operations Center



**Figure 3 System Description**

As this document is establishing the system description [in general] and defining the general missions of the space elevator, a set of terms have been suggested for usage. They are listed in the following table.

**8.1.2. Table of Suggested Terminology**

<i><b>Terminology</b></i>	<i><b>Explanation</b></i>
Apex Anchor	The upper end at roughly 100,000 kms altitude
Carbon Nano Tube	High Tensile Strength material under development
Climbers [Tether Climbers]	Vehicle able to climb or lower itself on the tether
Deployment	Releasing the tether from the GEO construction up and or down during the initial phase of construction
Earth Anchor	Earth Terminus for space elevator
Earth Port	Consists of Earth Anchor [terminus] and Floating Operations Platform
European Space Agency	European space agency equivalent to NASA
Final Operational Capability	Design for full capability of the space elevator
Floating Operations Platform	The Op's Center for the activities at the Earth Port or Earth Terminus
GEO Node	Geosynchronous Earth Orbit (GEO) Release Point – roughly 36,000 kms
Headquarters and Primary Operations Center [HQ/POC]	Location for the Operations and Business Centers – probably other than on Earth Port
Initial Operational Capability	A term to describe the time when the space elevator is prepared to operate for commercial profit - robotically
International Academy of Astronautics	International organization that consists of elected members with space expertise
International Space Elevator Consortium	Association whose vision is to: A world with inexpensive, safe, routine, and efficient access to space for the benefit of all mankind.
Japanese Space Elevator Association	JSEA handles all the space elevator activities for universities and STEM activities. Also handles the global aspects of space

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	elevators.
JAXA	Japanese Space Agency
Length Overall	Full length of the space elevator, est. from 96,000 to 100,000 km
LEO Gate	Elliptical release point for LEO – roughly 24,000 kms
Lunar Gravity Center	Point on Tether with Lunar gravity similarity – 8,900 kms
Marine Node	Alternate term for Earth Terminus for space elevator
Mars Gate	Release Point to Mars – roughly 57,000 kms
Mars Gravity Center	Point on Tether with Mars gravity similarity – 3,900 kms
Moon Gate	Release Point towards Moon – roughly 47,000 kms
NASA	National Aeronautics and Space Administration, US space organization
Ocean Going Vehicle (OGV)	Vehicle able to travel over the open ocean
Primary Operations Center	Center of all activities for the space elevator. Could be distributed or centralized.
Seed Ribbon	The initial tether lowered from GEO altitude which would then be built up to become the space elevator tether
Tether	96,000 to 100,000 km long woven ribbon of space elevator
Tether Climbers	Vehicle able to climb or lower itself on the tether

## Appendix-3 Research Topics List





## 9. Space Elevator Research Topics<sup>1</sup>

This document is a work in progress. We intend that each topic in the list can be hyperlinked to a more detailed page or so, following the layout at [Research Topic Template](#) and descriptions below.

The objectives of this work are as follows.

1. To give advice and counsel to potential collaborators
2. To ease the entry of new participants
3. To promote a consistent set of assumptions between different projects
4. To conserve resources by avoiding duplication of research work

We intend that this work should become a resource of a non-profit foundation that may be able to provide some research funding. First, a high-quality document or set of documents must be produced in which we all have confidence; this will take some time and effort.

The topics are grouped into three categories, depending on the resources required to carry them out: major investment, intermediate and little investment. Each listed topic is hyper-linked to a description.<sup>2</sup> There is also a list of topics not yet classified.

### 9.1. Topics requiring major investment

Some topics require a sustained effort over an extended period and involve laboratory work, not just simulation. However, there must be clear boundaries between different phases, so that we can assess progress and make appropriate decisions about continuing with support.

1. [Tether materials development, testing and manufacture](#)
  - a. Macro structure: strength, length and weave
    - Resilience to small impacts
    - Provision for tapering and other shape variations
  - b. Micro structure: the materials science
    - Process for forming the fibres

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<sup>1</sup> Document owner Dr John Knapman [JMKnapman@aol.com](mailto:JMKnapman@aol.com) – this version January 2014

<sup>2</sup> Press Alt+Enter to follow a link in Google Docs. In MS Word, press Ctrl+Click.

- c. Friction
- d. Electrical properties
- e. Alternatives to CNT

2. [Tether climber design](#)

- a. Structure
- b. Friction (critical for a climber's traction on the tether)
- c. Brakes or similar for parking overnight on the tether
- d. Heat management
- e. Shielding against radiation
- f. Evaluate 20-ton-capable electric motors for operations on tether
  - What design features and/or attributes must be considered? (e.g. thermal control, radiation hardening)
  - What instrumentation would be required?
  - What functions could be self-managed (automated) by the climber?
  - What functions must have a man-in-the-loop, managed from the ground?
- g. Descending climbers – brakes
- h. Safety and escape procedures

3. [Tether climber power source](#)

- a. The choice is between laser power transmitted from the Earth's surface and solar power. Microwave power transmission has now been ruled out.
- b. Determine the extent of space between LEO and GEO that would be illuminated by Earth-based lasers pointing at tether climbers.
- c. Assess the threat to existing operational satellites – how often would lasers or microwave transmitters have to be shut down to avoid risk of damage to satellites?

4. [High Stage One prototyping and development](#)

- a. Detailed design and construction of an indoor prototype up to 10 meters high
- b. Development and construction of outdoor prototypes on land, eventually reaching a height of 1km
- c. Construction of a large prototype at sea

## 9.2. Topics requiring intermediate-level investment

These may consist of simulations or theoretical studies that are important to the future of the space elevator but are unlikely to happen unless some funding is forthcoming. The projects will typically take experts several years to complete.

### 1. [Tether dynamics](#)

Various pieces of work have been done on the dynamics of the tether, but there is a need for much greater consistency. A comprehensive simulation tool is needed that is consistent with recent configurations (100,000km length) but with enough latitude that engineers, scientists and strategists can examine variations and effects of several kinds of disturbance.

### 2. [Tether electrodynamics](#)

- Calculate size of discharge voltages and currents in the region of strand breaks in the tether
  - a. Function of time (day/night)
  - b. Geometry of ribbon
- Calculate charging time and equilibrium potential on entire tether – see Garrett and Whittlesey
- Assess the tether as a possible power transmission line
  - a. Input power from solar cells
  - b. Transformers in space
  - c. Power, including losses, vs. distance
  - d. Ohmic heating
- Extend the electric potential model of Earth down to the surface and out past 16 Earth radii (the magnetopause)
- Study how the tether couples electrostatically to plasma
  - a. Plasma contactors
  - b. Ion guns

### 3. [Radiation environment of the tether and climbers](#)

## 9.3. Topics requiring little investment

These are typically suitable as projects for graduate students or are research areas for which someone, typically an academic, already has funding. One goal is to stimulate involvement among the community of interest for the space elevator. Another goal is to provide coordination to ensure that the work is compatible with other projects and so

maximize the benefits.

1. [Power cord for climber](#)

Evaluate carbon nanotubes and other materials for function as an electrical power cord for use in providing power to the tether climber from the Floating Operations Platform to 40 km altitude.

2. Powering Climbers through the Tether

It may be possible to transmit power through the tether to the climbers. Experts are needed to assess the feasibility.

3. [Tether climber competition](#)

A versatile design for a competition is proposed that can operate indoors but can be very open ended.

Other topics of this kind could include the following.

4. The trade-off between robotics and human work in tether operations, including satellite deployment and possibly the collection of spent satellites
5. Studies of the communications mechanisms between Earth, tether climbers, the GEO node and the apex anchor

#### **9.4. Topics not yet classified**

These cover a wide range. They fall into two main categories: management and technology. Over time, we intend to produce enough detail on these and place them in the most suitable category.

##### *[Management](#)*

1. System operations

- a. Develop a more complete Concept of Operations
- b. Select some locations [depending on owners] that would lead to real description of Headquarters locations and places for each of the proposed operations centers.
- c. Determine requirements for each of the locations of the operations centers.
- d. Layout the requirements for the communications architecture.
- e. Estimate the needs for staffing at each of the nodes in the architecture, including the Marine node, above atmosphere at 40kms, at GEO node and maybe at Apex Anchor node.
- f. Initiate the search for the proper Pacific location to base the initial space elevator.

2. Law

- a. Look at the conclusions from the IAA Space Elevator Study Report and solidify the argument.
- b. Establish an approach to present the arguments to the appropriate organizations.
- c. Identify legal precedence that will support the position of ISEC on the global stage.
- d. Develop concept of legal approach to the entities responsible for Terrestrial [both land and sea], Aeronautical, and Space Laws.

3. International policy

- a. Evaluate the issues to be addressed at the international level.
- b. Investigate each of these issues with the desire to "prepare" the community for space elevator proposals.
- c. Determine best approach for ISEC to "win" at the UN level, especially with a draft proposal to the UNCOPUOS and the UN's frequency control office.

4. Marketing

- a. Determine the scope of potential customers – historic space users.
- b. Determine the scope of potential customers – new space users.
- c. Provide a plan for the space elevator to improve the human condition.
- d. Investigate an approach where the space solar power community recognizes their need for the space elevator developmental success.
- e. Develop a plan for near term, mid term and long term approaches for the international community, with special emphasis towards the policy and legal arenas.

5. Finance

- a. Determine the estimate for the development and construction of the space elevator infrastructure – first one and then a series of follow-on space elevators [must have more than one to ensure we never again fall victim to gravity].
- b. Lay out a plan for the necessary actions with four phases: Near term preparation, mid-term commitment, long-term construction, and

operations.

- c. Investigate three approaches to financing the development of the space elevator: government sponsored, international joint venture, and private enterprise [all with government sponsorship].
- d. Identify, in the near term, a plan for gaining funds to establish a Space Elevator Foundation. This foundation would then stimulate research and development focussed upon the specific needs of space elevators through grants and contracts.

### *Technology*

1. Hazards to the tether and to tether climbers
  - a. Space debris and meteors
  - b. Wear, tear and erosion due to collision with small particles
  - c. Erosion due to radiation
  - d. Probabilities of damage
  - e. Rates of wear and erosion
  - f. Others to be identified if necessary
2. Hazards caused by the space elevator
  - a. Risks to other spacecraft of collision with high-strength tether
  - b. Risks to the Earth’s surface due to, e.g., severance
  - c. Others to be identified if necessary
3. Tether maintenance
  - a. Types of damage, e.g., erosion, radiation, collision
  - b. Maintenance strategy
  - c. Inspection and repairs
4. Laser interference with existing operational satellites<sup>3</sup>
  - a. Determine the extent of the GEO band that would be illuminated by Earth-based lasers pointing at tether climbers – at altitudes just above the FOP and in steps up to GEO
  - b. Assess threat to LEO satellites – how often would lasers have to be shut down to avoid illuminating operational satellites?

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<sup>3</sup> Contact Mr Skip Penny [skip.penny@isec.org](mailto:skip.penny@isec.org)

5. Marine node design

- a. Leveraging the existing capabilities of the oil and exploration industries
- b. Examining the kinds of movement required – and possible – particularly for moving the tether to avoid space debris and dealing with severe weather

6. GEO node design

- a. Determine the extent of the GEO mission set.
- b. Determine criteria and requirements for GEO Node.
- c. Investigate with special interest in the moderation/control of tether dynamics possible from there.
- d. Determine what type of thrusters would work optimally [mono-propellant, electromagnetic, or ion thruster] when faced with the range of requirements.
- e. Estimate when the need for human occupancy will occur and what additional requirements surface to support those missions.

7. Apex anchor design

- a. Determine the requirements for the Apex Anchor.
- b. Evaluate the minimum mass needs and estimate the maximum mass for the optimum tether design. [as a variable with tether mass]
- c. Determine what type of thrusters would work optimally [mono-propellant, electromagnetic, or ion thruster] when faced with the range of requirements.
- d. Determine the role of the Apex Anchor in severance scenarios.
- e. Estimate when the Apex Anchor could support humans, or if that is even a future need.

### 9.5. Research Topic Template

Each topic in the list should have a linked entry, which should begin with a brief description of the project.

#### *Research Goals*

Answer the question: what is the aim of the research? Examples might be to evaluate a theory, to advance the state of the art or to prove a concept.

#### *Work Plan*

Outline the work at a coarse level of granularity. A table with cost estimates in US dollars should be given for the years from the starting point, as illustrated. Supporting detail should be included.

Years from start	1	2	3	4	5	6
Activities						
Item 1	-	-	-	-	-	-
Item 2	-	-	-	-	-	-
Totals US\$ thousands	100	300	200	500	800	1000

#### *Contacts*

**9.6.** Name and contact details of the primary contact plus other contributors or potential contributors. Where possible, make clear who could carry out the work.



## 9.7. Tether Materials

Tether material is arguably the single most important issue in the realization of the space elevator. Although numerous groups worldwide have carried out research on the manufacture of materials with strength suitable for the tether, no macroscopic sample with suitable specifications has ever been manufactured. Indeed there are a number of materials suitable for the tether, ranging from polymers to carbon nanotubes, but strengths vaguely close to the required values have been observed only in microscopic samples with sizes substantially smaller than 1mm.

A considerable amount of work needs to be done on the subject, including:

1. Experimental investigation of materials that exhibit strengths suitable for the tether
  - a. Carbon nanotube bundles
  - b. Aligned polymers
  - c. Crystalline materials
2. Investigation of catalysts and/or processes capable of manufacturing samples of the above at least 1cm long
3. Technologies capable of increasing the size of bundles above 1mm
4. Scaling of the process to lengths in excess of 1m
5. Development of technologies to weave bundles in yarns maintaining their high strength
6. Scaling of the process to lengths in excess of 1km
7. Developing the continuous manufacturing technique suitable for yarns greater than 100km long
8. Study of material and yarn performance under stress
9. Study of degradation mechanisms

### *Research Goals*

At the present time, a large amount of funding (\$100M) has been injected worldwide into the research on carbon nanotubes for structural applications, resulting in a technique (the dry sock) capable of producing yarns with strength of the order of 7-9 MYuri (less than half the desirable value) over lengths of 1cm. This is well below the target, mainly because of the imperfect alignment between the various CNTs, which results in a non-uniform stress distribution. The single goal of this research is the demonstration that tethers of suitable specifications (lengths in excess of 100,000km and strength in

excess of 25MYuri) can be achieved.

Research can be subdivided into three major groups:

1. Discovery of a suitable material that exhibits the desired strength
2. Development of a process capable of manufacturing the desired material in long lengths
3. Engineering the process to implement it in a reasonable time frame (of the order of 1-5 years)

### *Work Plan*

Although there is a general inclination towards carbon nanotubes, there is no consensus as to the ideal material for the tether. The first order of business would be to identify suitable materials that exhibit the required specification on specimens that can be handled in research labs. The second would be to develop processes capable of scaling up the manufacturing capabilities while maintaining the required material specifications. The third task would be to engineer suitable processes capable of manufacturing the tether with suitable length and strength. Finally, the design of suitable packaging and testing would represent the last stage.

If funding becomes available, the following schedule is proposed with cost estimates for building larger working models.

<b>Years from start</b>	1-3	4-6	7-9	10-12	13-15
<b>Activities</b>					
Research on aligned polymers	1000	1000	-	-	-
Research on aligned CNTs	1000	1000	-	-	-
Research on aligned crystalline materials	1000	1000			
Catalyst nanostructuring and process development	2000				
Bundle fabrication (CNT)			2000		
Bundle fabrication (polymer)			1000		

Bundle fabrication (crystals)			1500		
Engineering scaling up of process to produce meter-long specimens				2000	
Engineering process to make yarns with size>1mm (weaving)				3000	
Continuous manufacturing system to produce km-long tethers					5000
Engineering fast process					7000
Packaging and testing of manufactured tether					2000
<b>Totals US\$ thousands</b>	4000	4000	4500	5000	14,000

After this program of research, development and engineering, we can commence manufacturing. The cost to manufacture a tether of length 100,000km with an average cross section of 10cm<sup>2</sup> is estimated to be in excess of \$1 billion. If the tether is assumed to be made from CNTs or polymers (density of 1g/cm<sup>3</sup>) and methane is used as precursor; considering that 1g of methane occupies 1.5 liters at room temperature, thus 1m<sup>3</sup> of tether requires 1500m<sup>3</sup> of methane, resulting in a total volume of methane of 150 million m<sup>3</sup>. Assuming a cost of \$0. 30 per m<sup>3</sup> of methane (current price of the commodity at source), this results in a total of \$50 million. This assumes 100% efficiency in converting methane into the tether material. Although conversion efficiencies of a single process are considerably smaller, it can be envisaged that methane can be recirculated. The electric power needed to convert methane into CNTs or polymers will be a major cost – most likely more than 20 times the amount of raw material.

### *Contacts*

**9.8.** Gilberto Brambilla (author): [gb2@orc.soton.ac.uk](mailto:gb2@orc.soton.ac.uk)

We expect that Dr Gilberto Brambilla would direct this work at the University of Southampton, UK.

### 9.9. Tether Climber Design

A suggestion for making progress on this topic is to consider a new style of competition that uses a moving tether in a loop that acts like a vertical treadmill. There is a description in the discussion document called "Tether Climber Competition".

Beyond that, we need research into several areas.

#### *Research Goals*

The overall objective is to keep the mass as low as possible. Several high-priority areas are listed here:

1. The layout of the power source, which itself depends on the choice between transmitting laser power from the Earth and utilizing solar power
2. Heat management, as all excess heat must be radiated away into space
3. Traction between climber and tether, which depends critically on the surface friction of the tether
4. Electric motors that are light enough yet capable of producing the required power and operating in a vacuum

#### *Work Plan*

The most promising candidate for a suitable electric motor is the axial gap motor. To operate in a vacuum, the motors would need to be liquid cooled with associated radiators to disperse the excess heat away from the sun. Ideally, a single motor would be capable of producing a motive power of 100kW or higher. Then a set of 40 motors would be needed to produce the required motive power of 4MW. The higher a motor's efficiency, the less heat has to be radiated away. If 95% efficiency can be achieved, only 200kW has to be disposed of. A reasonable operating voltage would be 2500 V. Each motor would need to be very light, preferably with a mass no greater than 25 kg.

Axial gap electric motors are limited to smaller rotational speeds than the more conventional radial gap motors. With climbers operating at constant power (up to a limit), it will be necessary for the speed to vary between 20 m/sec and 80 or more m/sec, and this requirement must be factored in to the research.

After some theoretical work, practical construction and testing of prototype motors is proposed. In the absence of expert input, a similar pattern of expenditure is suggested for the other areas but deferred by one, two or three years. Traction is the last to start, as it depends substantially on the research into tether materials. The following estimates are indicative only. They are our best estimates but do not represent expert opinion.

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<b>Years from start</b>	1	2	3	4	5	6
<b>Activities (motors)</b>						
Theoretical design studies	100	-	-	-	-	400
Prototype construction	-	500	-	500	-	-
Testing in air and vacuum	-	-	800	-	800	-
<b>Totals US\$ thousands (motors)</b>	100	500	800	500	800	400
Heat management	-	100	500	800	500	800
Power source	-	-	100	500	800	500
Traction	-	-	-	100	500	800
<b>Totals US\$ thousands</b>	100	600	1400	1900	2600	2500

### *Contacts*

**9.10.** John Knapman [JMKnapman@aol.com](mailto:JMKnapman@aol.com) has put these notes together based on an informal discussion with Larry Bartoszek [design@bartoszekeng.com](mailto:design@bartoszekeng.com)

It is not clear who would carry out this work.

### 9.11. Tether Climber Power Source

There is a decision to be made between powering tether climbers using on-board solar panels and transmitting power from the Earth's surface. The option of using microwave power has been discarded because of the difficulties of focusing the beam. However, laser power transmission should be considered. A hybrid of solar power by day above 40 km and laser power below 40 km is also a possibility.

#### *Research Goals*

Both solar and laser power require further development. At present, photovoltaic (PV) cells are not light enough to fit into the mass budget of a tether climber. Laser systems may have divergence and diffraction issues and the receive optics may not fit into the mass budget of a tether climber.

For solar panels, the goal is to reach a point where at least 4 MW of useful power can be supplied to the tether climber's motors and fit into the mass budget.

For laser power, the goal is to refine the state of the art in laser systems to provide sufficient (4 MW **TBR**) power.

#### *Work Plan*

The work begins with a survey of progress in photovoltaics, both in space and on the Earth. Since this is a very active field of research and development, it seems appropriate to collaborate with a company or university that is already working in the area. Very lightweight thin PV films are already available commercially; for example it is possible to buy such film to put on the windows of a boat. A key piece of work, therefore, is to devise a sufficiently lightweight structure that is also strong enough to support a large enough area of film. It must be strong enough to support itself close to Earth, i.e., under near full Earth gravity. The system must either be steerable depending on the time of day or there must be film pointing in all the required directions.

The main effort on laser power is trading transmitted power, diffraction (including adaptive optics possibilities) and divergence against the mass of the receive optics and power conversion equipment. Since it is unlikely to be possible to focus the beam exclusively on the climber's receiver, some shielding must be devised to protect the whole of the climber, and this must also fit into the mass budget.

Studies must be undertaken of the safety issues arising from the risk to operators on the Floating Operations Platform, satellites, and aircraft of such a concentration of power.

Years from start	1	2	3	4	5	6
Activities (solar panels)						

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Survey of state of the art and key players	100	-	-	-	-	-
Upgrading terrestrial PV film to space rating	-	200	300	500	-	-
Support structure design and test of prototype	-	200	300	1000	-	-
<b>Activities (laser power)</b>						
Theoretical analysis of laser beam focusing, including atmospheric effects	300	200	-	-	-	-
Design of long-range high-power laser transmitters	-	200	400	600	-	-
Construction of prototype 30 MW laser transmitter					10,000	20,000
Design of power receivers	-	-	200	200	200	-
Study of safety of satellites and other third-party bodies	-	200	300	200	200	200
Shielding of tether climbers	-	-	-	100	500	800
<b>Totals US\$ thousands</b>	400	1000	1500	2600	10,900	20,800

### *Contacts*

**9.12.** John Knapman [JMKnapman@aol.com](mailto:JMKnapman@aol.com) put these notes together based on an informal discussion with Skip Penny [skip.penny@isec.org](mailto:skip.penny@isec.org), Martin Lades [martin.lades@isec.org](mailto:martin.lades@isec.org), and others.

### 9.13. High Stage One

High Stage One is an adaptation of the Launch Loop<sup>4</sup> to relieve the main space elevator tether of Earth's turbulent atmosphere. Various versions of this have been described in the literature.<sup>5,6,7</sup> Theoretical work shows that it can maintain stability in strong winds using a technique called "active curvature control."<sup>8</sup>

#### Research Goals

The theory requires validation by building working models, starting small (between 1 and 10 meters high) and increasing the size step by step. Over the next 14 to 15 years, this is intended to culminate in a working version at sea that is 20 km high. A more accurate schedule will be produced after completion of the first working model.

#### Work Plan

At present, individual components are being built and tested with a view to producing a detailed design document for the first working model. This work is expected to be complete in 2014. The project could continue to the construction of a working bench-top model up to 1 meter high as a proof of concept. A model of this size would not require evacuated tubes.

If funding becomes available, the following schedule is proposed for building larger working models.

Years from start	1	2	3	4	5	6
Activities						
Design and construct 10 meter-high prototype indoors	610	510	-	-	-	-

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<sup>4</sup> Lofstrom, K., 1985, "The Launch Loop," *AIAA Paper 85-1368*, July 1985

<sup>5</sup> Knapman, J., 2005, "Dynamically Supported Launcher," *Journal of the British Interplanetary Society*, Vol. 58, No. 3/4, pp. 90-102

<sup>6</sup> Knapman, J., 2010, "Diverse Configurations of the Space Cable," *61<sup>st</sup> International Astronautical Congress*, Prague, Czech Republic, 27 September 27- 1 October 2010

<sup>7</sup> Knapman, J., 2012, "High Stage One," *Space Elevator Conference*, Seattle, WA, USA, August 25-27

<sup>8</sup> Knapman, J., 2009, "The Space Cable: Capability and Stability," *Journal of the British Interplanetary Society*, Vol. 62, No.6, pp. 202-210



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Test 10 meter-high prototype			320	-	-	-
Design and construct 60 meter-high prototype outdoors	-	-	-	1710	1580	-
Test 60 meter-high prototype	-	-	-	-	-	590
<b>Totals US\$ thousands</b>	610	510	320	1710	1580	590

The proposed versions are as follows.

1. 10 meters high indoors to test the vacuum technology, scalability and higher rotor speeds
2. 60 meters high outdoors to test the stability technology
3. 1 km high to show that large scales are viable, rivaling the tallest structures ever built. The outline cost estimate is \$18 million.
4. Up to 20 km high at sea to test all the techniques needed to build High Stage One.  
The outline cost estimate is \$480 million.

More details are available elsewhere.<sup>9</sup>

### *Contacts*

John Knapman (author): [JMKnapman@aol.com](mailto:JMKnapman@aol.com)

We expect that Dr Knapman would establish a non-profit company in Hampshire, UK, to manage this project in the early years. Later, It would pass to a different organization.

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<sup>9</sup> Swan, P. et al, 2013, "Space Elevators: An Assessment of the Technological Feasibility and the Way Forward," *International Academy of Astronautics*

### 9.14. Tether Dynamics

Various pieces of work have been done on the dynamics of the tether, but there is a need for much greater consistency. A comprehensive simulation tool is needed that is consistent with recent configurations (100,000km length) but with enough latitude that engineers, scientists and strategists can examine variations and effects of several kinds of disturbance, including the following:

1. Propagation along the tether of both lateral and longitudinal movement
2. Effect of massive or fixed nodes (apex anchor, GEO, Earth's surface)
3. Effect of the moving tether climbers, including launching them to orbit or to interplanetary space – at least 10 below GEO and some above
  - a. Both ascending and descending climbers
  - b. Propagation of acceleration from Earth's rotation
4. Disturbance due to impact of meteors or small pieces of debris (<10cm), short of severance
5. Further work on severance scenarios at various altitudes
6. Tides, lunar and solar
7. Effect of external forces, including atmospheric winds and solar pressure in space
8. Effect of (hypothetical) thrusters to help manage tether movement
9. Positioning or moving the marine node off the equator
10. Long-term stability and station keeping
11. Elasticity of tether and the dynamics related to stretching
12. Special Case: deployment of bare tether from GEO, both up and down

#### *Research Goals*

The theory requires validation by developing the basic bare tether space elevator dynamics deployed to 143,000km [length tbd], which represents the 100,000km baseline without an Apex Anchor. Then, a step by step process must be utilized to understand the characteristics of the tether dynamics when the following space elevator nodes are simulated, one at a time, in pairs, and all together.

- Addition of the Apex Anchor [with and without thrust capability]
- Movement of the Marine Node [both at surface and at High Stage One]
- Effects of winds
- Addition of the GEO Node [with and without thrust capability] – This concept is

one where the GEO Node acts as a stability point with a very large mass so that the tether dynamics are similar to a fixed [Marine Node], fixed [GEO Node] to free [Apex Anchor] layout. The GEO Node would be a massive station for support to the missions which restricts the movement of the tether at that altitude.

- Addition of tether climbers [with and without thrust capability] – The idea is to show the dynamics resulting from a tether climber going up and going down. In addition, the analysis must show the option of two, three, etc. up to seven at one time between Marine and GEO Nodes.

Develop the dynamics of severance for a baseline space elevator and develop potential recovery scenarios with the following configurations:

- Bare tether
- With Apex Anchor [with and without thruster and reel out capability]
- With GEO Node [with and without thruster and reel out/in capability]
- With tether climbers [with and without thrusters]
- Define all dynamics for several severance altitudes
- Focus on recoverable severance, such as when it occurs at 800km altitude

### *Work Plan*

At the present time, there is great consensus as to the equations needed to develop a baseline. The first order of business would be to identify a master equation that represents the space elevator baseline and the various options needed to be simulated. The second would be to leverage current research topics to establish a reference set of information. The last task would be to put a plan in place and execute it so that it answers the various questions of the research team. The validation could come from past research or from independent simulations with similar goals.

If funding becomes available, the following schedule is proposed for building larger working models. The schedule is based on the following cost estimates.

Years from start	1	2	3	4	5	6
Activities						
Research current simulations	80	60	20	10	10	

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Develop prototype simulation	20	80	80	20	5	
Validate		60	50	70	35	25
Illustrate dynamics			100	300	600	775
Discuss severance scenarios			50	100	150	200
<b>Totals US\$ thousands</b>	100	200	300	500	800	1,000

Table 1, Financial spread for six years

### *Contacts*

Peter Swan (author): [dr-swan@cox.net](mailto:dr-swan@cox.net)

We expect that Dr Peter Swan would manage the project and the work would be undertaken either at McGill University, Montreal, Canada, under Professor Misra's supervision, or at Kanagawa Institute of Technology, Japan, supervised by Professor Fujii.

### **9.15. Tether Electrodynamics**

The electrodynamics of the tether couple strongly to its motion and stability. Electromagnetic properties and their interaction with the space environment must therefore be well understood in order to predict things like climber motion, endpoint motion and the possibility of power generation and transmission. It will also be necessary to understand the effects of electrical discharges in the vicinity of strand breaks, given that substantial charges may build up along the length of the tether. Work has already been done on many of the following topics, but others have not yet been addressed.

1. Electromagnetic properties of the tether: resistivity, capacitance as a function of tether geometry, material, temperature, radiation environment
2. Electromagnetic environment of the tether: magnetosphere, electric fields, storms
3. Coupling of tether motion with electrodynamics, gravity, angular momentum
4. Electromagnetic and dynamic effects of tether damage: breaks, material degradation
5. Exploiting tether electrodynamics: power transmission

### **9.16. Research Goals**

1. A complete simulation of the magnetospheric and electric field environment from the earth's surface to  $17R_e$  (earth radii)
2. A simulation of climber motion along the entire length of the tether, integrating the electromagnetic, gravitational and angular momentum effects – the work would need to be compatible with Tether Dynamics
3. Definitive statements of tether stability taking into account full coupling of all forces – the work would need to be compatible with Tether Dynamics
4. A software tool for calculating resistivity and capacitance for various specific tether geometries and materials
5. A model for tether charging and discharging, including coupling to plasma, current loops through the plasma, various charged particle sources and various time scales
6. An ability to calculate electric fields, discharge probabilities and currents for various models of strand breaks
7. Tether geometries that could double as power transmission lines and a model for

step-up, step-down transformers that could work in space

8. A model for injecting solar cell power into the tether as a power transmission line  
– one model could be as a waveguide or, alternatively, exploiting the excellent electrical conductivity of carbon nanotubes

### 9.17. Work Plan

The magnetospheric/electrical environment model and the tool for calculating electrical properties of the tether are basic to all other topics in this category. Funding for their development is therefore greater in the early years of the schedule. Similarly, the solar power injection study depends somewhat on the transmission line study, so its funding is shifted later. Because the climber motion and stability simulation depends on the tether dynamics study, its funding profile roughly mimics it. The schedule assumes that 1 FTE = 2×\$100K/year. The factor of two assumes a typical university overhead.

Years from start	1	2	3	4	5	6
Activities						
Magnetosphere model	200	200	200	100	-	-
Electrical properties calc. tool	80	-	-	-	-	-
Simulation of climber motion	60	100	160	160	100	-
Tether charging model	-	60	100	160	160	160
Discharges, currents at breaks	-	-	100	200	200	140
Power transmission study	60	60	80	80	-	-
Solar cell power injection	-	80	100	100	100	100
<b>Totals US\$ thousands</b>	400	500	740	800	560	400

### 9.18. Contacts

Dennis Wright (primary author): [dwright@slac.stanford.edu](mailto:dwright@slac.stanford.edu)

Steven Patamia: [patamia@gmail.com](mailto:patamia@gmail.com)

We expect that Dr Dennis Wright would direct this work at Stanford University, California, USA.

### **9.19. Radiation Environment of the Tether and Climbers**

**9.20.** The tether and climbers will pass through Earth's radiation belts and the solar wind beyond the magnetopause. They will as a result be exposed to large fluxes of charged particles which pose a radiation hazard to humans, electronics and materials. In order to estimate this hazard in terms of dose to passengers, cargo and equipment, it is essential to have a comprehensive model of the radiation field throughout the range of tether and climber motions. Detailed simulations of the effects of penetrating radiation on various materials will be required in order to understand increased cancer and morbidity rates in humans, single event effects (SEE) in electronics and material degradation in the tether and climbers. Simulations of passive and active shielding arrangements for the climbers and of radiation hardening schemes for sensitive electronics must be done, and the results factored into climber and tether design. The particle flux near the tether will also affect the electrodynamic forces it sees, thus coupling closely to its motion via the charging mechanism. The following topics should therefore be addressed:

1. Charged particle flux along the tether as a function of distance and time: electrons, protons, ions
2. Effect on humans (dose, cancer risk, etc.)
3. Effect on electronics (single event effects, etc.)
4. Induced activation of tether and climber materials
5. Climber shielding (needed for Tether climber design , part e)
6. Coupling of charged particle flux to tether electrodynamics (connected to Tether electrodynamics, part b)

The proposal is mostly based on updating and expanding the paper by Jorgensen, Patamia and Gassend (2007).

### **9.21. Research Goals**

1. A complete model of Earth's radiation field from the surface to  $17R_e$  (earth radii)
2. Estimates of dose to humans accumulated during a typical journey to GEO, and the resulting increase in cancer and morbidity rates, with and without shielding
3. Estimate of effect on sensitive electronics in terms of percentage increase in single event upsets or other single event effects
4. Calculation of induced activities in all materials used in the tether and climbers
5. A simulation of tether charging along its full length due to the radiation field
6. For various combinations of active and passive shielding designs, simulations of the radiation field inside the climber (see item 2)



## 9.22. Work Plan

9.23. The radiation field model is basic to all other topics in this category. Funding for its development therefore occurs in the first two years of the schedule. The calculation of dose to humans inside the climber comes during the last three years as it depends on the climber design and shielding, the activation studies, and the radiation field model. The remainder of the studies are concentrated toward the middle four funding years. The schedule assumes that 1 FTE = 2 x \$100K/year. The factor of two assumes a typical university overhead.

Years from start	25. 1	26. 2	27. 3	28. 4	29. 5	30. 6
Activities						
Radiation field model	33. 200	34. 100	35. -	36. -	37. -	38. -
Dose to humans w/o shielding	40. 100	41. 200	42. 200	43. -	44. -	45. -
Estimate of SEE rates in electronics	47. 60	48. 100	49. 160	50. 160	100	52. 60
Calculation of induced activation	54. -	55. 100	56. 200	57. 100	58. -	59. -
Charging due to radiation	61. -	62. 60	63. 100	64. 200	65. 200	66. 140
Calculation of radiation field inside of shielding	68. -	69. -	70. 100	71. 200	72. 100	73. -
Dose to humans with shielding	75. -	76. -	77. -	78. 120	79. 200	80. 200
<b>Totals US\$ thousands</b>	<b>32. 360</b>	<b>33. 560</b>	<b>34. 760</b>	<b>35. 780</b>	<b>36. 600</b>	<b>37. 400</b>

## 9.88. Contacts

Dennis Wright (author): [dwright@slac.stanford.edu](mailto:dwright@slac.stanford.edu)

We expect that Dr Dennis Wright would direct this work at Stanford University, California, USA.

## 9.89.

### **9.90. Power Cord for Climber**

Evaluate carbon nanotubes and other materials for function as an electrical power cord for use in providing power to the tether climber from the Floating Operations Platform to 40 km altitude.

1. What might its shape be?
2. How might it be reeled in and out?
3. What tension might be required?
4. Must it be isolated from the tether itself?
5. Can the tether itself be used?
6. What line losses might be active (how much power is needed at sea level to ensure 4 MW is available all the way to 40 km?)
7. What vulnerabilities might it have from the environment (wind and rain)?
8. What safety issues might there be?

#### *Research Goals*

The aim of the research is to determine which power cords alternatives (if any) might be feasible for providing 4MW of power to the climber for its initial ascent from sea level to 40 km. Assess design attributes operational aspects of such a power cord.

#### *Work Plan*

This work is a suitable project for a graduate student. It does not require funding from us.

#### *Contacts*

**9.91.** Skip Penny [skip.penny@isec.org](mailto:skip.penny@isec.org) plus tether materials contacts.

We expect that Mr Penny would manage this work in conjunction with one of the universities in Arizona, USA.

### **9.92. Powering Climbers through the Tether**

There are two proposals for powering tether climbers: transmitting power via lasers or using solar panels. It is possible in principle that power could be transmitted via the tether itself. A paper at the 2015 Space Elevator Conference in Seattle addresses some of the issues and proposes transmitting high-voltage AC power at 30 kHz. There is no need for a return circuit, as AC power can be transmitted through a single conductor, either using capacitive storage or phase shifting at the climber. This should lead to a weight saving in each tether climber and may also improve the grip of the climber on the tether using electrostatic forces.

#### *Research Goals*

The goal is to investigate feasibility in more detail than has been done so far. The areas that require particular attention are:

1. Ensuring that the tether does not act as a giant radio transmitter
2. Examining in more detail the effects of incoming radiation, especially in the Van Allen radiation belts

There are also questions about the power engineering implications.

The result of the research should be an answer to the question of whether this topic is worth pursuing and a set of recommendations of next steps if the answer is affirmative.

#### *Work Plan*

Two classes of expertise are needed:

1. The electrical aspects of space radiation
2. Electrical engineering for the power generators at the Earth station and the techniques for receiving the power at the climber. Some knowledge of electrostatic motors would be an advantage

One of these experts should be the principal investigator. Those working on the project would need to consult with two other specialists:

1. A materials scientist to assess the feasibility of a thin layer of insulation on the tether
2. A broadcast engineer to understand the issues surrounding the risk of power dissipation through radio waves

The costing of \$150k is based on a total of 9 person months at an annual academic rate of \$200k. It should be completed in less than a year. Alternatively, an experienced person

could direct a Ph.D. student over three years.

### *Contacts*

John Knapman (author): [JMKnapman@aol.com](mailto:JMKnapman@aol.com)

Dr Dennis Wright at Stanford University, California, USA, would be a good person to direct this work as principal investigator.

### **9.93. Tether Climber Competition**

This document arose from a discussion during the research call on December 3rd 2013.

We are interested in building on the experience of the competitions, gradually increasing the capabilities of climbers in several directions, e.g., speed, weight, endurance (i.e., vertical distance climbed), tether thickness and tether width. A good focus is to concentrate on the design of a tether builder or construction climber, since it has to be much smaller than a tether climber for production use. A good way of doing this at reasonable cost would be to set up some vertical treadmills, one for each competing team. ISEC should come up with a standard for a treadmill, possibly something that can be taken apart. The reason is that standardization permits the use of the same interfaces for climbers across competitions. As the standard becomes accepted, it will enable different levels of competition, e.g., respective to age of participants and impression on the public. Each treadmill should consist of a loop of tether material and a mechanism for winding it. A next level would be to provide some environmental control on the treadmill; the Japanese have already demonstrated such things in the lab.

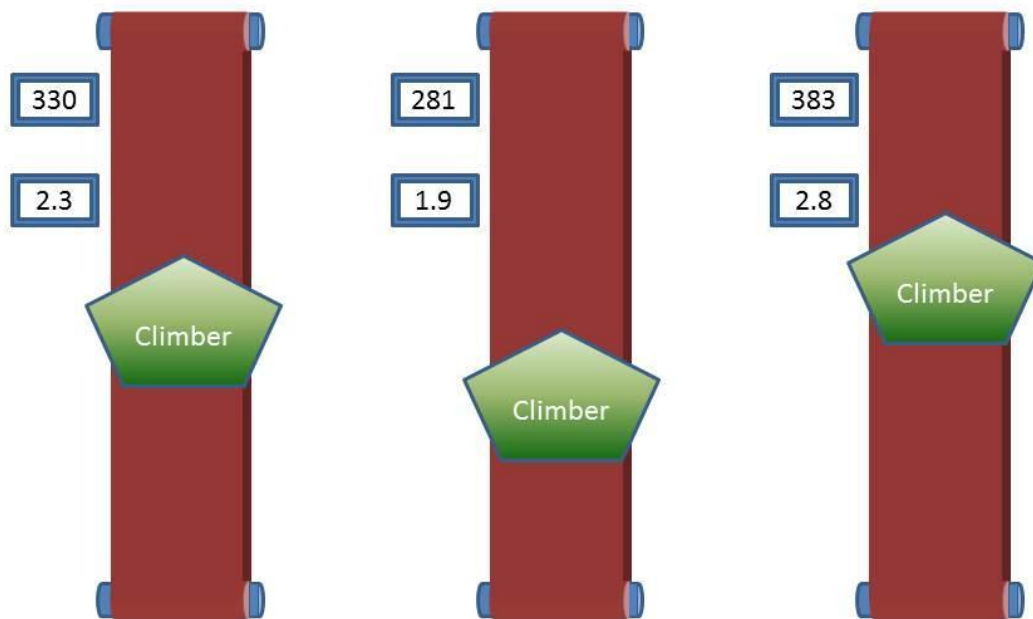


Figure 1 Tether climber competition using vertical treadmills

Each climber would be expected to climb vertically while in contact with the descending tether. Possibly the climber could be required to match the speed of the tether, but it is much better for the treadmill mechanism to adjust the tether's speed to hold the climber's position roughly constant with respect to the ground. Each treadmill would have meters showing speed, time elapsed and equivalent height climbed. Figure 1 shows a possible arrangement.

Such a competition could be held in a hall or an engineering laboratory. It does not need to be outdoors or subject to weather conditions. The cost would be much lower than would be the case for a long outdoor tether supported by a balloon or helicopter, and it would be much easier for teams to practice and carry out tests beforehand, thus raising the standard of the entries and increasing the value of the results. Furthermore, it would be easier to test various characteristics by varying the speed and tether properties such as thickness, roughness, shape, elasticity and even its macrostructure. Examples of different macrostructures include Hoyt tethers, ribbons, etc.

A competition for climber endurance could be most valuable. There could also be a competition to climb the tether with the smallest cross section per climber weight.

Various payload sizes could be tested. A key question is how the climber should be powered.

A competition in which several teams race against each other, rather than against the clock, is more immediate and exciting and allows for more trials. We can envisage a competition with several events, a triathlon, pentathlon, heptathlon or decathlon – all designed to increase the participation and increase the value of the results. Perhaps a company such as Otis Elevators or a sports equipment manufacturer would be interested in sponsorship to provide the treadmill mechanisms.

Yes, a treadmill is much closer to a traditional elevator. What could be most exciting are systems that could exceed the speed of standard elevators. At that point our goals could match the ones of a company like Otis, namely building faster elevators (for us faster treadmills).

Please do not forget to look into standardization of evaluation electronics. Shuichi had asked for that already building on Martin's request but received not much of a reply. The idea is to use/extend standard (read affordable) hardware such as IMUs intended for quadcopters with appropriate sensors to provide better data on the climber and the tether.

Martin advocates a 2 week retreat for such a competition or its preparation. The reason is that such things as standards could be worked out that way much faster and the competition could be held in the end with some leeway on weather. Affordable places could be for example Southern Tirol in the summer, where a semi-permanent track could be spanned along an aerial tramway, or a donated place in Japan. A retreat like that should be possible for under \$50k for ~30 persons. It could provide a big push for SE development.

#### *Contact*

**9.94.** Dr Martin Lades [martin@lades.net](mailto:martin@lades.net)

We expect that Dr Lades would manage this competition in conjunction with colleagues at ISEC, Eutospaceward and other organizations.

# **New Design for the Space Elevator**

John M. Knapman, PhD, FBIS

Director of Research, ISEC

[john.knapman@isec.org](mailto:john.knapman@isec.org)

# Working with Available Materials

- How far down from GEO can a tether reach at various strengths?
- How can we close the gap?
  - New configuration of High Stage One
- Areas of investigation



## Reach of the Tether at Various Strengths

35768km

GEO

Taper ratio 6:1  
(safety margin 40%)

19400km

2.4MYuri (1.7) — Kevlar

16180km

3.8MYuri (2.7) — Zylon

8770km

10MYuri (7.1)

4830km

17MYuri (12)

1630km

28MYuri (20)



## Reach of the Tether at Various Strengths

35768km

GEO

Tether mass 6400 tons  
(safety margin 40%)

14600km

2.4MYuri (1.7) — Kevlar

12000km

3.8MYuri (2.7) — Zylon

6000km

10MYuri (7.1)



# Zylon Tether: Closing the Gap

72,000km

Apex Anchor

Self-supporting tether  
with mass 6400 tons

35,768km

GEO

Zylon 3.8MYuri (2.7)

Taper ratio 22:1  
(safety margin 40%)

12,000km

Ambit

Supported Tether

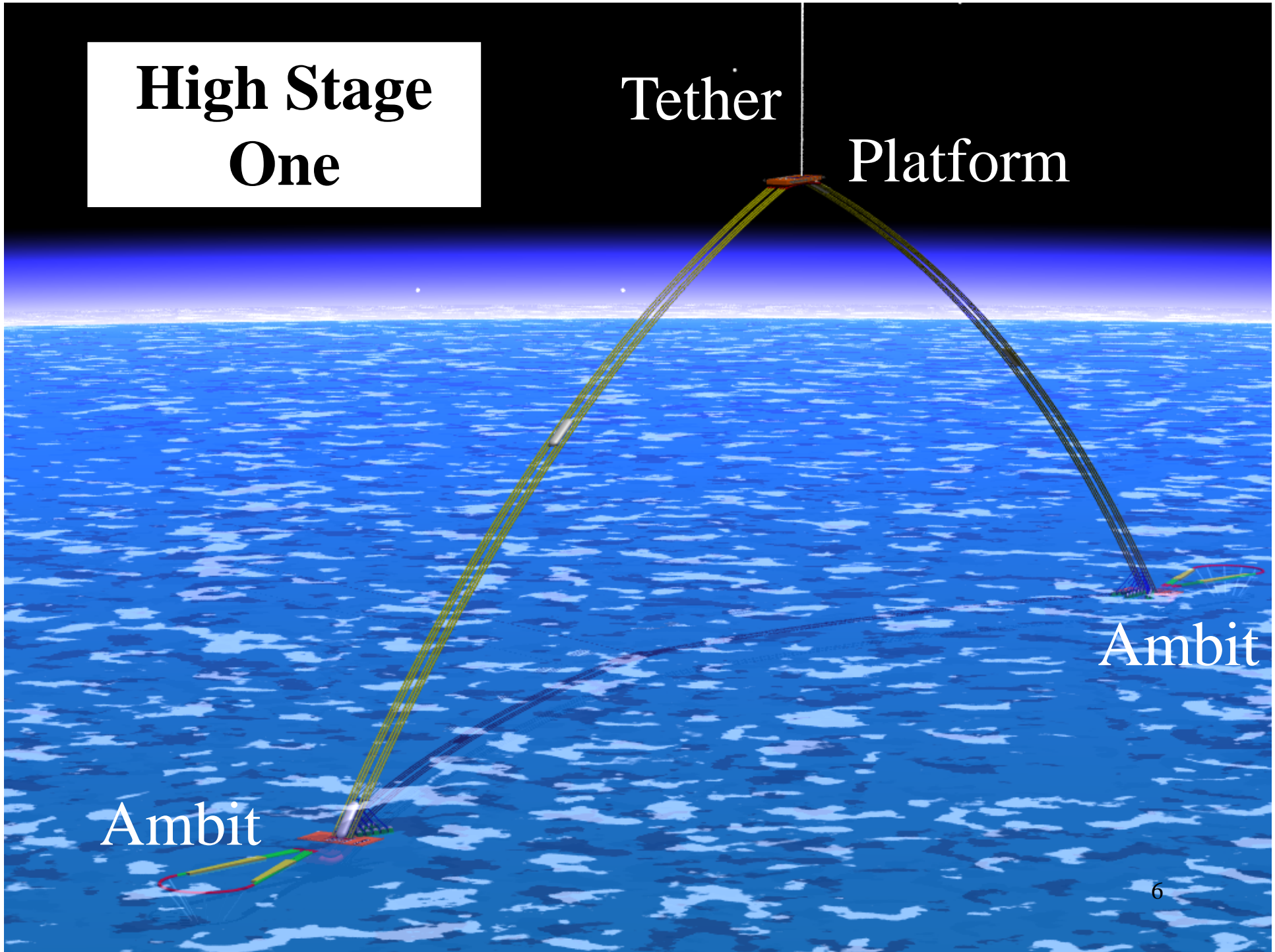
**High Stage  
One**

Tether

Platform

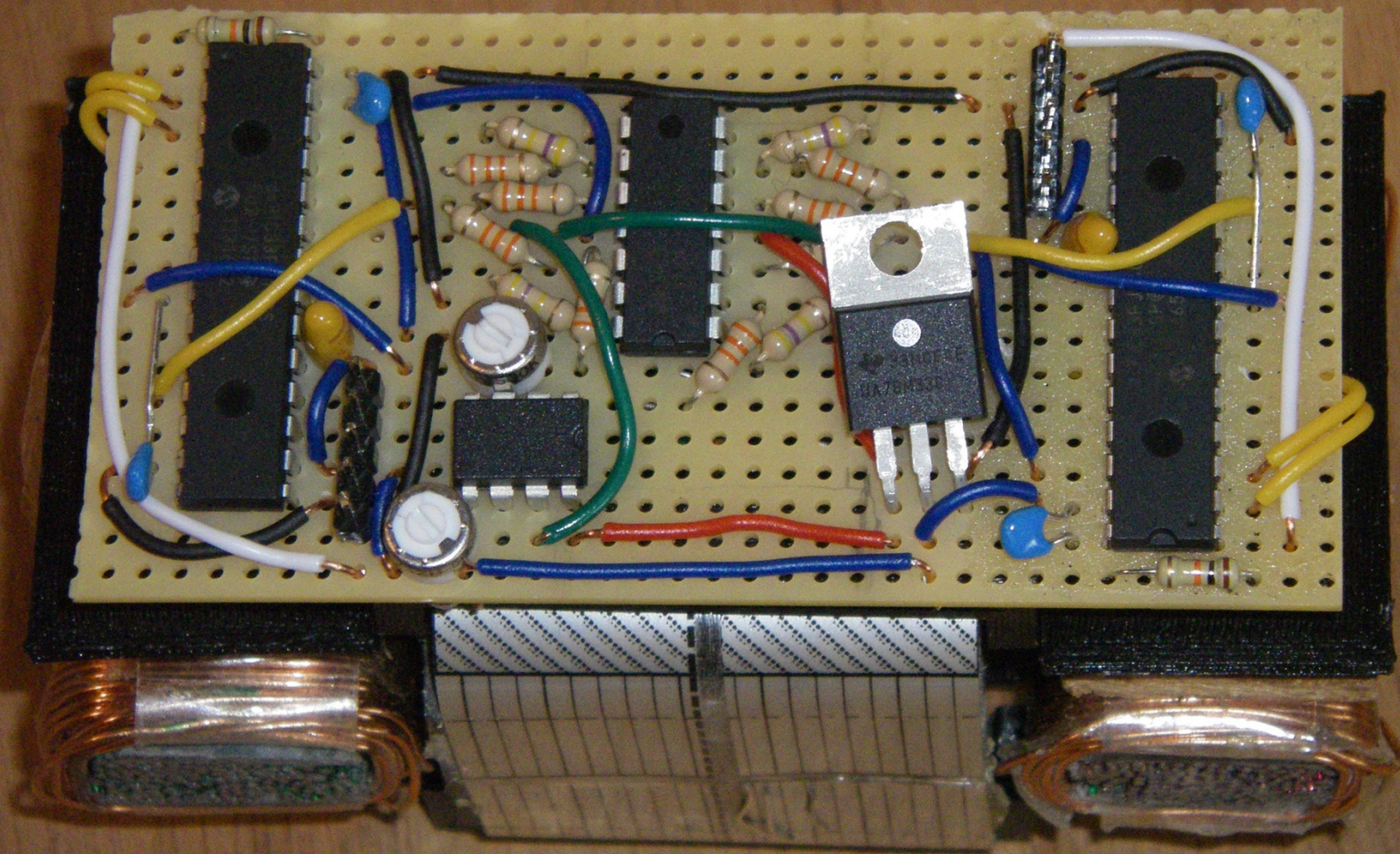
Ambit

Ambit



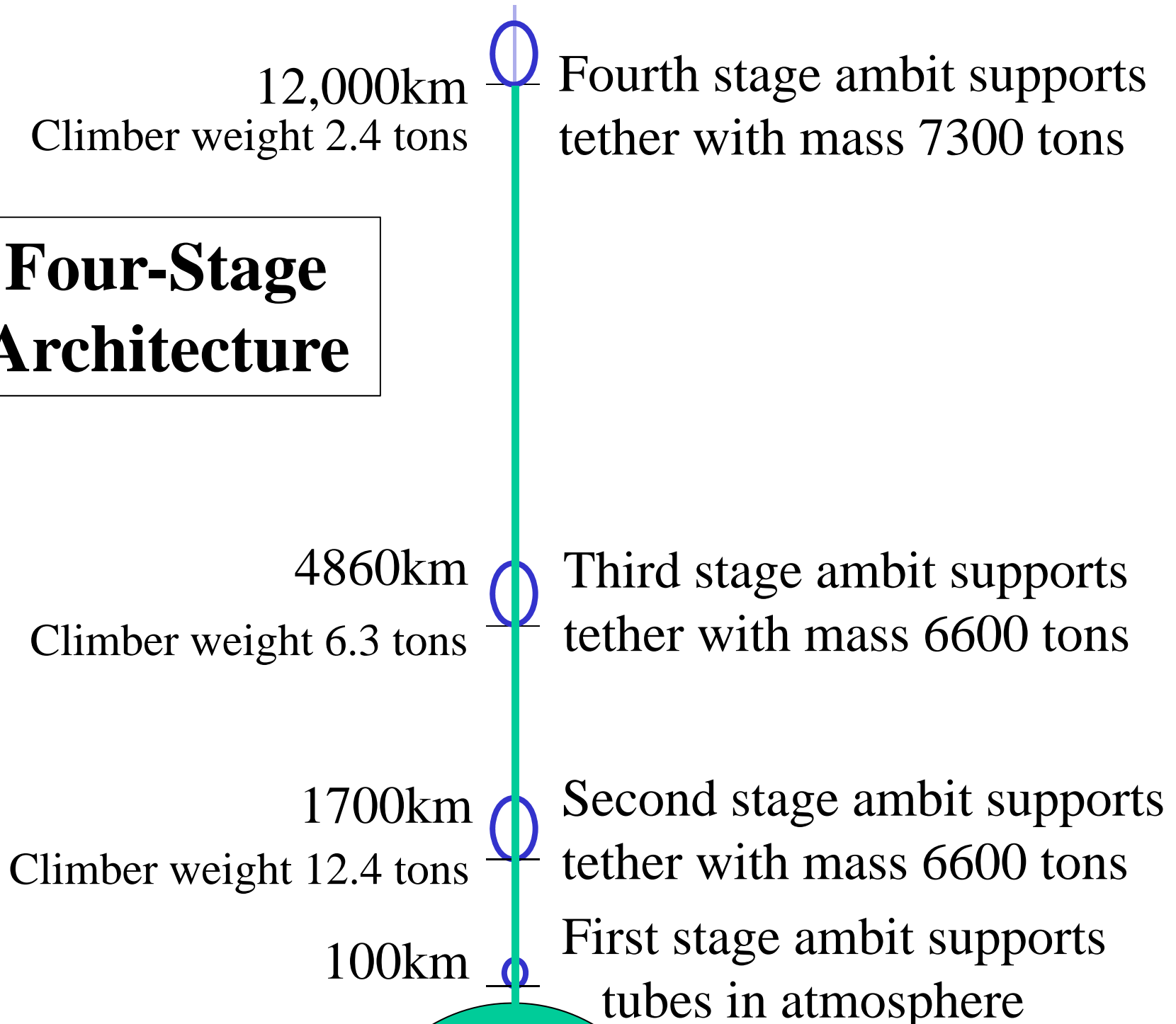


# A Bolt

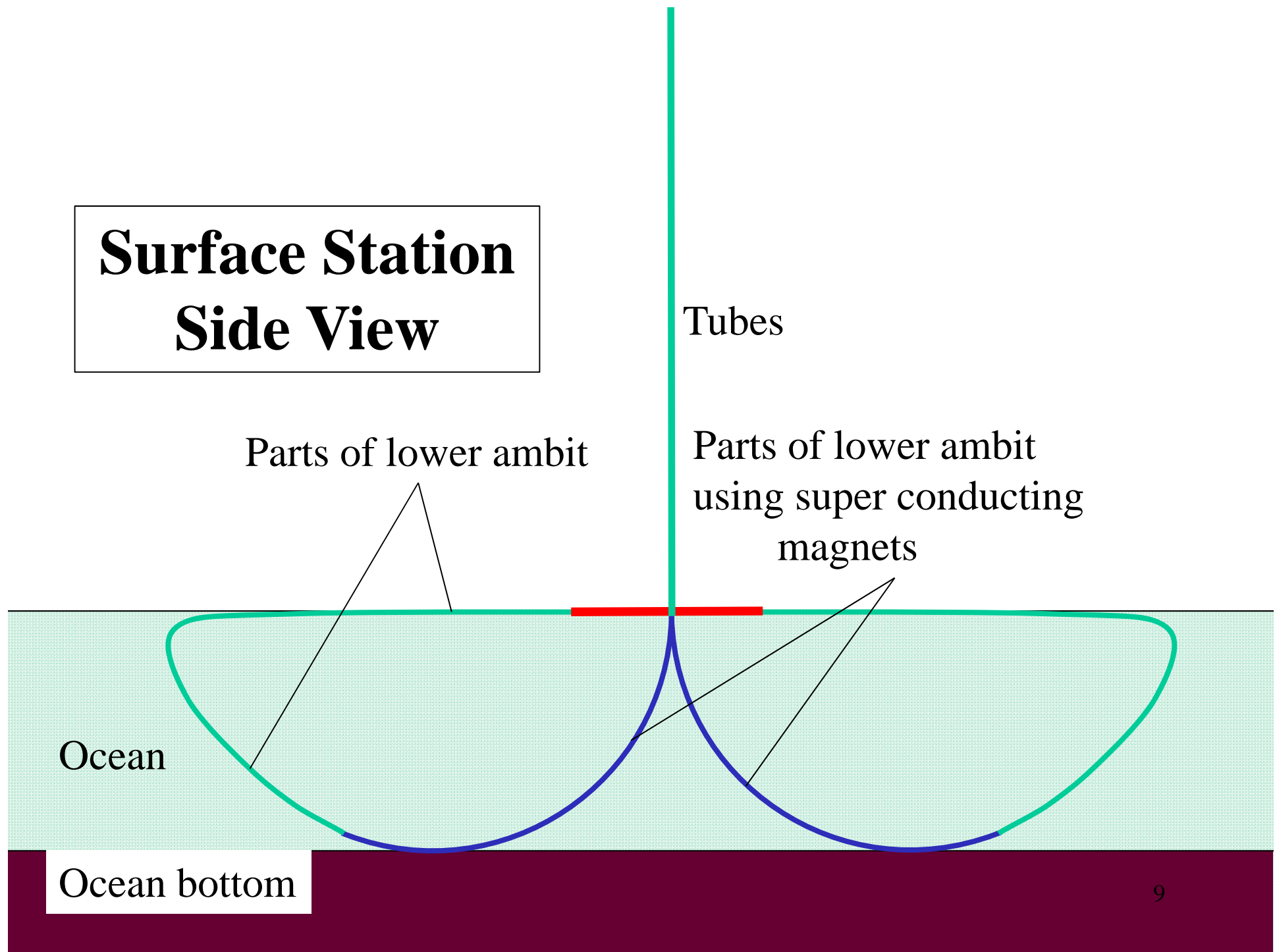




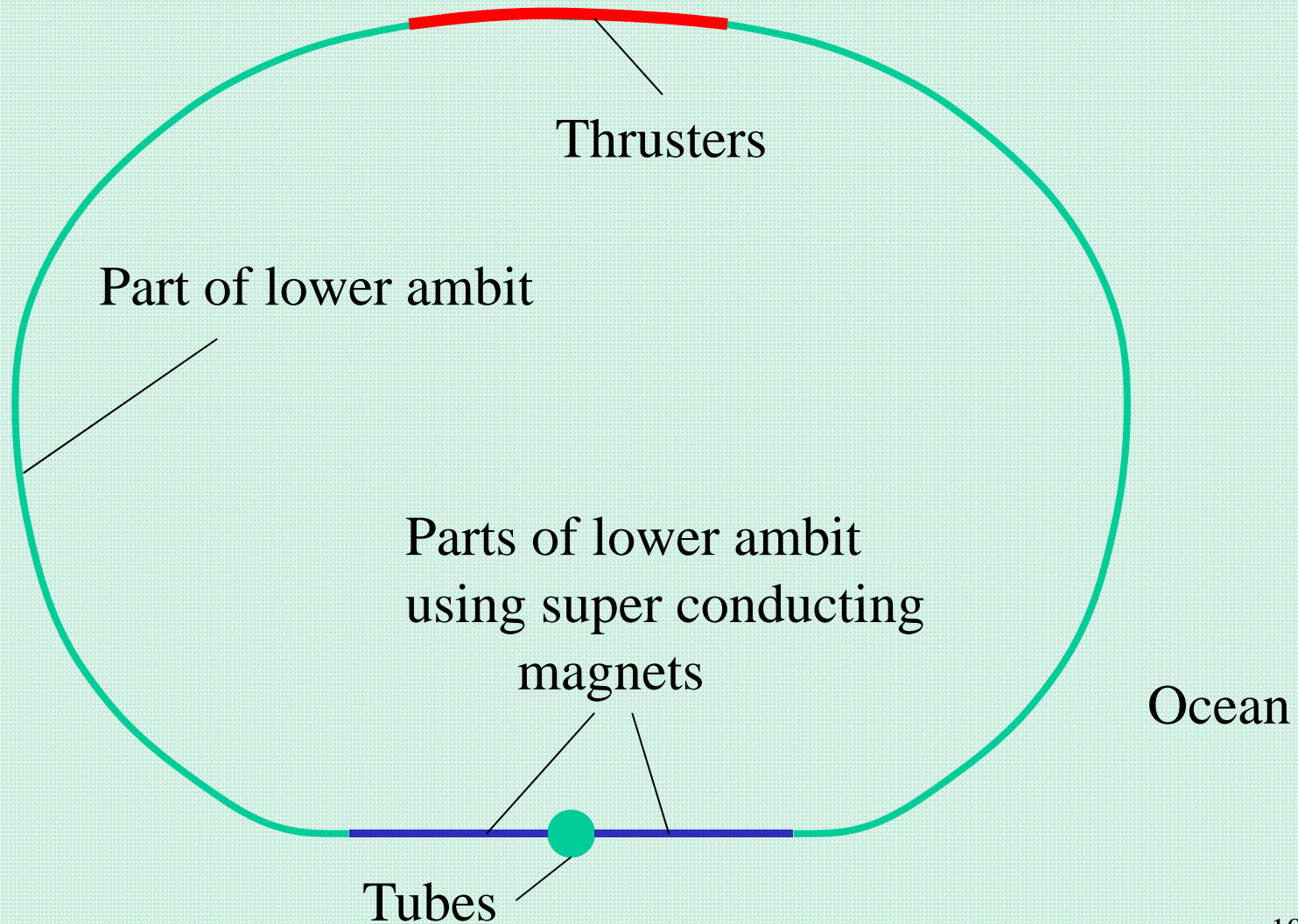
## Four-Stage Architecture



# Surface Station Side View

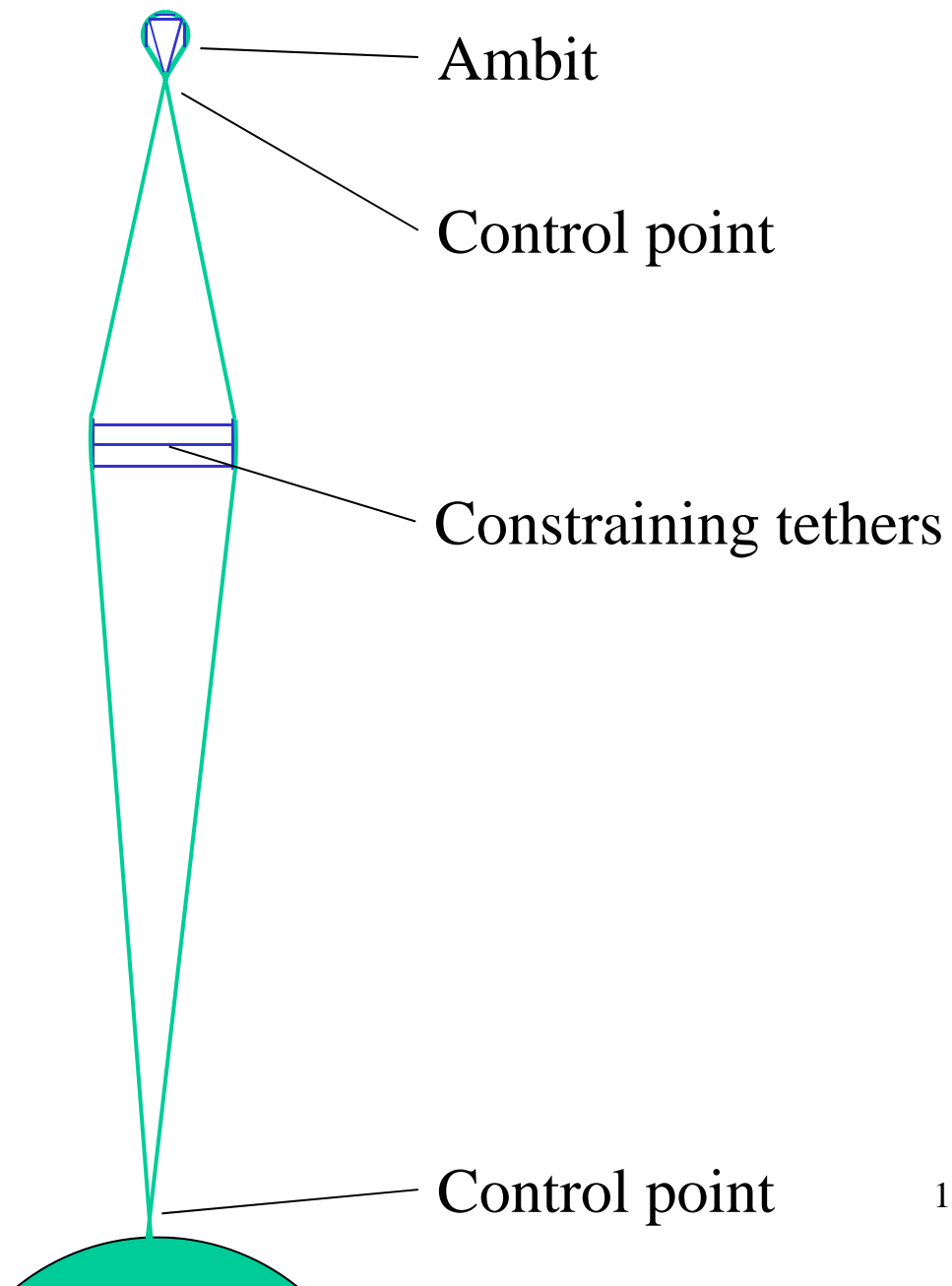


# Surface Station Plan View





# Space Debris Avoidance



# Areas of Investigation

- Space debris avoidance
  - Collision with objects  $< 10$  cm
- Coriolis forces
  - Lateral velocity 1340 m/s at 12,000 km
    - 465 m/s at the surface
- Methods of construction
- Servicing and maintenance

# Recommendations

- More research is needed
  - Small-scale prototyping
  - Testing of space debris survival
  - Powering of tether climbers
    - Extracting energy from descending bolts
- No need to wait for super-strong materials

International Academy of Astronautics (IAA)  
Minutes of meeting - Study Group 3.24 "Road to Space Elevator Era"  
5th meeting in Paris, France on March 21st, 2016



Appendix 5: List of Attendees

Name	E-mail	Country	Affiliation
John Knapman	<a href="mailto:John.knapman@isec.org">John.knapman@isec.org</a>	UK	ISEC
Sakurako Takahashi	<a href="mailto:takahashi.sakurako@jamss.co.jp">takahashi.sakurako@jamss.co.jp</a>	Japan	JAMSS

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