6

Toward Innovation Creation for Space Activities

TAKAFUMI SHIMIZU
Monodzukuri Technology, Infrastructure and Frontier Research Unit

1 Introduction

Science fiction writer Arthur C. Clark has made future science and technology predictions, and Table 1 describes those predictions of him that concern space activities.[1] The recent emergence of carbon nanotubes, which are very strong and light, has raised the possibility of developing the space elevator listed in the table's first column, and it is predicted that the elevator would come true around 2050 according to the nanotechnology field of the technology strategy map 2009 published by the New Energy and Industrial Technology Development Organization (NEDO), a Japanese independent administrative agency.[2] Demands for the space guard listed in the second column have always been high. About one hundred years ago, a small solar system body entered into Earth's atmosphere, and blasted near Tunguska, Siberia on June 30, 1908.[3,4] Since the blast area was not a big city and was scarcely populated, there were no human casualties then; however, photos recording the blast area vividly show how powerful, destructive and devastating the blast was. Since a small solar system body impact to Earth, though catastrophic, is very rare, and since to prevent such an impact beforehand is not technically and economically feasible, the space guard initiative that protect humans from such disasters is not yet realized. The geostationary satellite listed in the third column has already been realized, and has become essential to our daily life in the communication and broadcasting fields. With regard to the nuclear space propulsion listed in the fourth column, the U.S. National Aeronautics and Space Administration (NASA) once planned it for the exploration mission that would orbit around Jovian moons; however, the plan was terminated thereafter.

Launch costs of rockets, which are the only space transportation systems currently available, are on the order of 10,000 dollars per kilogram. Since an artificial satellite is required to be rigid to withstand the severe rocket launch environment as well as to be lightweight because of the expensive rocket launch cost, and furthermore since it is required to be highly reliable and to have a long design-life because its on-orbit maintenance and repair are impractical, the satellite itself is inevitably expensive.

On the other hand, there is an argument that by introducing not mere improvements of existing proven technologies, but totally new concepts that are not illogical and absurd empty theories but are based on sound physical principles, space activities with far less costs could be realized and totally new perspective could be opened for space activities.[5]

This report will show first that space technology has potential to deal with global issues, and then introduce concepts and ideas that could bring innovation to space activities (hereinafter referred to as "space innovation") as well as a research institute that supported such advanced concept research activities, deriving examples mainly from the U.S., which is one of the most advanced space-faring nations.

2 Clear and Present Global Issues, and Their Solutions with Space Technology

A U.S. National Research Council (NRC) report published in 2009 recommends promoting space activities that address U.S. national imperatives as well as such activities as climate and environmental monitoring, science inquiry, advanced space technology developments, and international

Table 1 : Sir Arthur C. Clark's Future Predictions

(1) Space Elevator • A space elevator consists of the tether that connects a spacecraft and an anchor on the ground. The tether could also be used to transport materials from the ground to space. • In his 1979 novel "The Fountain of Paradise," it is constructed on top of a fictional mountain. He elaborated the concept in his 1981 technical paper. Actually, a Russian scientist named Konstantin Tsiolkovsky first conceived the idea in 1895. • NASA has studied space elevator concepts for a long time. Recent developments with carbon nanotubes have raised the possibility of developing a tether strong enough to connect a spacecraft to Earth, which is one of the most critical issues involved. • There have been competitions to encourage required technology developments.
(2)Space Guard • This prediction has not come true yet. In his 1972 novel "Rendezvous with Rama," astronomers working for Project Spaceguard, an Earth defense system against asteroid strikes, detect in 2131 an alien probe hurling toward the solar system. • Asteroids and comets frequently visit Earth. NASA has conducted investigation, named the Spaceguard Survey, to study how to monitor these visiting bodies and to assess the threat they may pose. The U.S.'s primary policy objective is to map 90% of Near Earth Objects (NEOs). • In his novel "The Hammer of God," he envisaged that a rouge asteroid could be deflected from its Earth-bound orbit course by landing on it and fitting thrusters. • Japan's asteroid explorer "HAYABUSA" (MUSES-C) successfully landed on asteroid Itokawa in 2005; however, deploying thrusters and attempting a deflection is still science fiction.
(3)Geostationary Communications Satellite • Herman Potocnik and Konstantin Tsiolkovsky earlier conceived the idea. His contribution, outlined in his 1945 article, was the proposal to use a set of satellites to form a global communications network. • Since the orbital period of a satellite orbiting precisely 35,786 kilometers above the equator coincides with Earth's rotation period, such a satellite always remains over the same place. • The first "Syncom 3" satellite was placed into geostationary orbit in 1964, only 19 years after his 1945 article. It orbited above the Pacific Ocean and beamed pictures from the Tokyo Olympics to the U.S., the first trans-Pacific TV transmission. • Geostationary satellite communications networks now provide services such as phone calls, data transmission, and TV broadcasting for most of the world's inhabited regions. Geostationary meteorological and ground observation satellites are also operational now. • What he did not foresee was the development of the transistor and later the integrated circuit, which mean satellites are far smaller than what he imagined, which would have used valve technology and needed regular maintenance.
(4)Nuclear Power Space Flight • His 1951 novel "Prelude to Space" envisaged bringing nuclear energy into use, powering a spacecraft named Prometheus. • In the early days of the Cold War, U.S. planners studied Project Orion, which involved a spacecraft propelled by detonating a series of nuclear bombs behind it. • NASA once studied Project Prometheus, a plan to launch a nuclear-powered explorer. The plan called for a Jupiter Icy Moon Orbiter (JIMO) that could circle around one Jovian satellite to another in search of life. The project was terminated, and there is little sign of restarting such a project.

Source: Reference[1]

cooperation under the U.S.'s leadership.[6] It states that those areas where space is not traditionally considered should also be addressed.

The global warming and energy issues are now one of the most critical that we humans face. As reported by English scientific journal "Nature," many countries in the world are promoting the technology development and utilization of new renewable energy sources such as wind, geothermal, solar and ocean tide as well as bio fuels to replace fossil fuels with them.[7] In addition, Japan's greenhouse gases observing satellite "IBUKI" (GOSAT) is the first satellite ever launched in the world to globally monitor the density distributions of greenhouse gases that cause global warming.[8] The satellite is expected, by identifying CO_2 sources and sinks, to help us tackle global warming although it is not able to directly control greenhouse gas emissions as could be done with the carbon capture and storage (CCS) technology.[9]

Could space activities contribute to us humans more actively? For example, one proposal is "space solar power" where solar power would be generated by satellites circling geostationary and other Earth orbits, and the generated energy would be transmitted to the ground as microwave or laser beams.[10,11] Another proposal is "Earth's sunshade," one of geoengineering/climate engineering techniques, where numerous spacecraft would be placed at a Lagrange point between the Sun and Earth to reduce the amount of incoming solar radiation to cool Earth.[12] Notwithstanding such proposals, the space solar power is still not deemed to be a practical solution to the energy issue because of its technical and economic aspects, for example, as described in the Nature article mentioned above.[7]

2-1 Tackling Global Warming

Global warming is one of the most urgent critical issues that we humans face, and the leaders of the Group of Eight, meeting in L'Aquila, Italy and aiming to reach an agreement by the end of 2009 in Copenhagen, reiterated their willingness to share with all countries the goal of achieving at least a 50% reduction of global emissions by 2050 to keep the increase in global average temperature above preindustrial levels no more than two degrees

Centigrade.[13] Although it is needless to say that to reduce greenhouse gas emissions is important to prevent global warming, geoengineering that tries to artificially control climate is under discussion as a last resort when the reduction efforts alone could not stop global warming.[14]

The UK's Royal Academy published in September 2009 a comprehensive report on geoengineering, in which carbon dioxide removal (CDR) techniques that artificially remove CO_2 from the atmosphere and solar radiation management (SRM) techniques that artificially reflect a small percentage of the Sun's light and heat back into space are discussed.[15] The SRM's effectiveness has already been proven because of the fact that volcanic ashes due to the eruption of Mt Pinatubo remained in the atmosphere for a long time, the amount of sunlight reflected back into space increased, and then came a peak global cooling of about 0.5 degrees Centigrade.

According to a report of the Intergovernmental Panel on Climate Change (IPCC), the global radiative forcing would increase about 4 W/m^2 if the atmospheric CO_2 concentration became twice that of the preindustrial concentration.[16] Radiative forcing is an index that expresses a change in the energy equilibrium between the ground surface and the atmosphere due to changes in various factors, including those in the concentration of greenhouse gases, as the rate of energy change per unit area at the tropopause, which represents the atmospheric boundary between the troposphere and the stratosphere, and is expressed as a positive figure when it has the effect of warming the ground surface and as a negative figure when it has the effect of cooling it.[16,17]

Figure 1 shows the energy balance between the Sun and Earth, indicating that Earth's atmosphere is in the equilibrium of 235 W/m^2. Roughly speaking, if incoming solar radiation could be reduce by one percent, the Sun's radiative forcing could be reduced by about 2.35 W/m^2, and to reduce the incoming solar radiation by about 1.8 percent would suffice to cancel out the above mentioned radiative forcing increase of about 4 W/m^2.

In Table 2, various SRM techniques are compared with respect to their maximum radiative forcing values, annual costs per unit of radiative forcing, and associated risks. Those compared are (1) the human settlement albedo technique that would increase the albedo, which is the ratio of the diffusely reflected to the incident light, of buildings, roads and pavements, (2) the grassland and crop albedo technique that would change crop varieties and grasslands to more reflective species, (3) the desert surface albedo technique that would cover desert areas with reflective sheets, (4) the cloud albedo technique that would disperse sea water to the sky to increase the number density of cloud-condensation nuclei (CCN) and thereby to increase the albedo of maritime cloud, (5) the stratospheric aerosol approach, as the eruption of Mt Pinatubo has already proved its effectiveness, that would increase the amount of aerosols in the stratosphere to reflect more incoming solar radiation, and (6) the space-

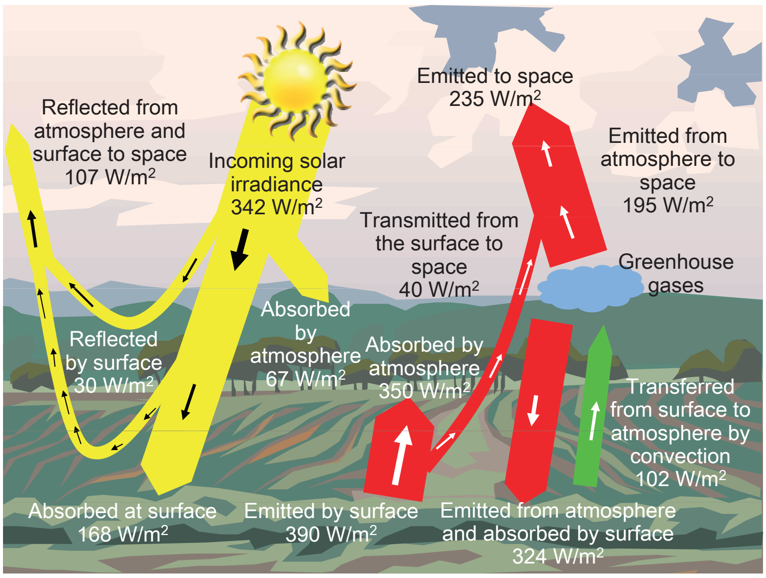

Figure 1 : The Global Average Energy Budget of Earth's Atmosphere

Source : Reference[15]

Table 2 : Comparison of SRM Techniques

SRM Technique	Maximum Radiative Forcing (W/m^2)	Cost per Year per Unit of Radiative Forcing ($\$10^9/yr/ W/m^2$)	Possible Side-effect	Risk (at Max Likely Level)
Human Settlement Albedo[(a)]	−0.2	2,000	Regional Climate Change	L
Grassland and Crop Albedo[(b)]	−1	N/A	Regional Climate Change Reduction in Crop Yields	M L
Desert Surface Albedo[(c)]	−3	1,000	Regional Climate Change Ecosystem Impacts	H H
Cloud Albedo[(d)]	−4	0.2	Termination Effect[(h)] Regional Climate Change	H H
Stratospheric Aerosols[(e)]	Unlimited	0.2	Termination Effect Regional Climate Change Changes in Strat. Chem.	H M M
Space-based Reflectors[(f)]	Unlimited	5	Termination Effect Regional Climate Change Reduction in Crop Yields	H M L
Conventional Mitigation[(g)] (for comparison only)	−2 〜 −5[(g)]	200	Reduction in Crop Yields	L

(a) Radiative forcing estimate from Lenton & Vaughan (2009). Mark Sheldrick (private communication) has estimated the costs of painting urban surfaces white, assuming a re-painting period of once every 10 years, and combined paint and manpower costs of £15,000/ha. On this basis the overall cost of a 'white roof method' covering a human settlement area of $3.25x10^{12}$ m^2 would be £488 billion/yr, or £2.4 trillion per W/m^2 per year.
(b) Radiative forcing estimate from Lenton & Vaughan (2009).
(c) Radiative forcing estimate from Gaskill (2004).
(d) Radiative forcing estimate from Latham et al. (2008). Cost estimate from Brian Launder assuming 300 to 400 craft per year plus operating costs, giving a total cost of £1 billion per year.
(e) Costs here are the lowest estimated by Robock et al. (in press) for the injection of 1 TgC H_2S per year using nine KC−10 Extender aircraft. It is assumed that 1 TgS per year would produce a -1 W/m^2 radiative forcing [cf. Lenton & Vaughan (2009) quote 1.5 to 5 TgS/yr to offset a doubling of CO_2].
(f) For a radiative forcing sufficient to offset a doubling of CO_2 (-3.7 W/m^2), a launch mass of 100,000 tons is assumed. Cost assessment is predominantly dependent on expectations about the future launch costs and the lifetime of the solar reflectors. Launch costs of $5,000/kg are assumed, and that the reflectors will need to be replaced every 30 years. This produces a total cost of $17 billion per year for -3.7 W/m^2, or about $5 billion per year per W/m^2 (Keith 2000; Keith, private communication).
(g) Conventional mitigation: 0.5 to 1% of Global World Product (GWP) required to stabilize CO_2 at 450 to 550 ppmv (Held 2007). Current GWP is about $40 trillion per year, so this represents about $400 billion per year. Assuming that unmitigated emissions would lead to about 750 ppmv by 2100, then the unmitigated RF = 3.7/ln(2)*ln(750/280) = 5.25 W/m^2, and the conventional mitigation instead leads to a RF = 3.7/ln(2)*ln(500/280) = 3.1 W/m^2. So the net change in radiative forcing due to this mitigation effort is about 2.15 W/m^2. On this basis the cost of conventional mitigation is about $200 billion per year per W/m^2. Stern estimates 1% of global GDP per year, which is currently about $35 trillion (amounting to an annual cost of $350 billion per year), to establish at 500 to 550 ppmv of CO_2 equivalent (http://www.occ.gov.uk/activities/stern_papers/faq.pdf). This gives a similar conventional mitigation cost of $150 to 200 billion per year per W/m^2.
(h) 'Termination effect' refers here to the consequences of a sudden halt or failure of the geoengineering system. For SRM approaches, which aim to offset increases in greenhouse gases by reductions in absorbed solar radiation, failure could lead to a relatively rapid warming which would be more difficult to adapt to than the climate change that would have occurred in the absence of geoengineering. SRM methods that produce the largest negative radiative forcings, and which rely on advanced technology, are considered higher risks in this respect.

Source: Reference[15]

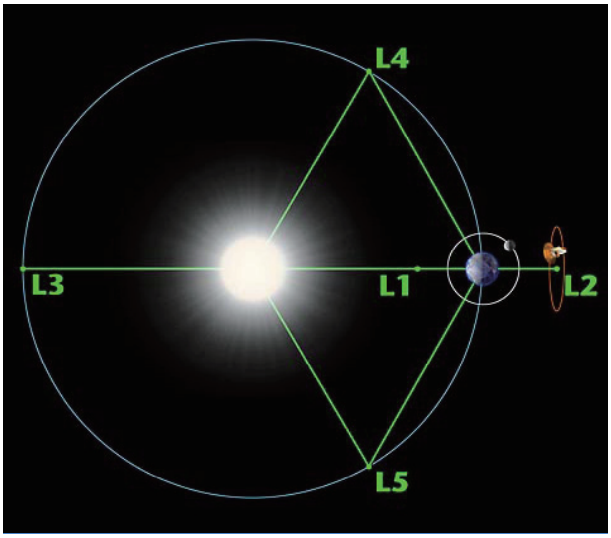

Figure 2 : Sun-Earth System Lagrange Points

Source : NASA

based reflector technique that would place reflectors or other devices between the Sun and Earth, for example, at one of the Sun-Earth Lagrange points, L1 shown in Figure 2 to reduce the amount of solar radiation incoming to Earth as well as (7) the conventional mitigation approach to reduce greenhouse gas emissions.

If their potential risks are not taken into account, the cloud albedo and stratospheric aerosol approaches, both of which could cool Earth, seem attractive when only their costs are compared with that of the conventional mitigation approach. Except for the timing when the required technologies could be ready, the space-based reflector technique, which might give a first impression that it could be very expensive, is estimated to be comparatively less expensive in this comparison.

Prescribed geoengineering radiative forcing (a), simulated globally averaged surface air temperature (b), simulated atmospheric CO_2 (c), and simulated change in combined land and ocean carbon storage (d) for runs A2 (red), GEO (blue), ON_2025 (green), ON_2050 (orange), and ON_2075 (purple).	Simulated surface air temperature (a) and annual rate of temperature change (b) for runs A2 (red), GEO (blue), OFF_2025 (green), OFF_2050 (orange), and OFF_2075 (purple).

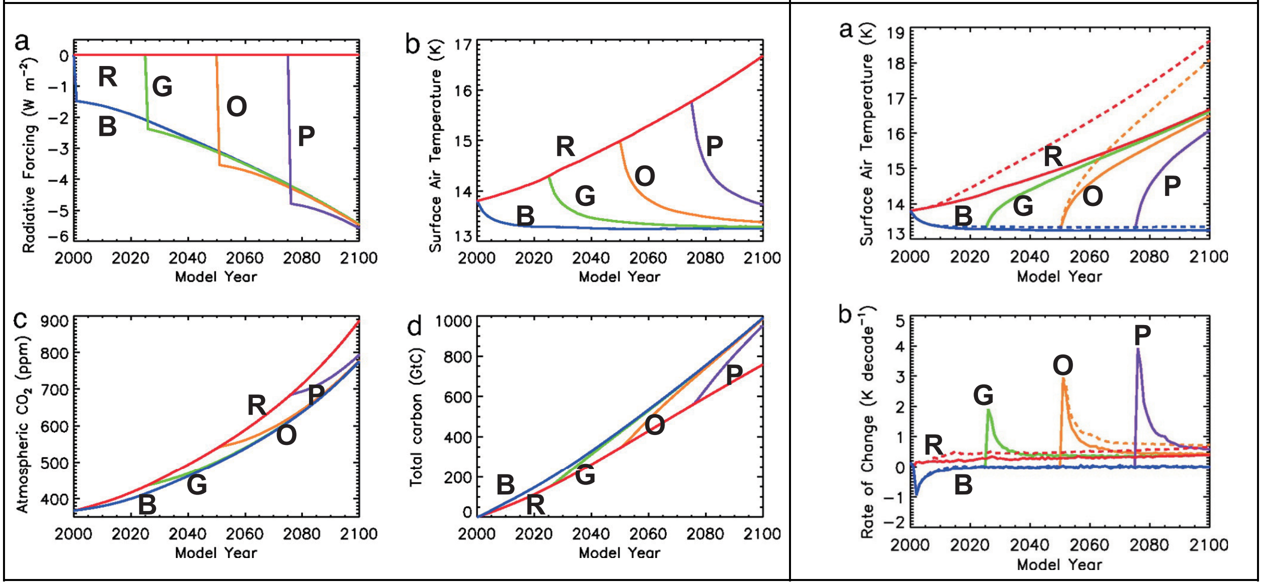

Figure 3 : Geoengineering Cooling and Termination Effects

Source: Reference[18]

Figure 3 shows climate model simulation results of geoengineering cooling and termination effects using “the A2 scenario,” one of six IPCC global warming scenarios, as a baseline.[18] The left hand side of Figure 3 shows surface air temperature and other simulation results where geoengineering processes are initiated in 2000 (GEO: blue), 2025 (ON_2025: green), 2050 (ON_2050: orange) and 2075 (ON_2075: purple), respectively to cancel radiative forcing increases due to carbon dioxide accumulations. The right hand side shows, using the case where geoengineering cooling is initiated to cancel temperature increase due to carbon dioxide accumulations in 2000 (GEO: blue) as a baseline, simulated surface air temperatures where the geoengineering techniques are terminated in 2025 (OFF_2025: green), 2050 (OFF_2050: orange) and 2075 (OFF_2075: purple), respectively.

If some SRM technique were implemented, the surface temperature could be reduced in several years unlike a CDR technique that would require a much longer time period to do so. However, since a SRM process would not help reduce carbon dioxide and other greenhouse gases in the atmosphere, and since to terminate a once implemented geoengineering process would cause abrupt warming and thereby environment changes, it would be absolutely necessary to continue such a geoengineering process once initiated. The acidification of sea water caused by dissolving carbon dioxide gases would also remain a problem to be tackled.[19] When considering the fact that carbon dioxide remains in the atmosphere quite a long time, it can be said that the reduction of carbon dioxide emissions and the removal of carbon dioxide in the atmosphere are also necessary.

The UK Royal Society’s report recommends international research and development, and evaluation as well as multi-lateral governance by the United Nations or other international bodies for geoengineering because its unilateral implementation by a single nation or an organization could cause undesirable effects to other nations and regions.[15]

2-2 Space Solar Power

The Sun is a natural nuclear fusion reactor, and, unlike a ground nuclear fusion reactor still being studied for its realization, has existed for about 4.6 billion years. Since a space-based solar power system could generate electric power irrespective of day and night, weather and seasons for 24 hours a day and 365 days a year, it could be a base load power plant unlike intermittent ground-based solar and wind power plants.[10,11] The solar radiation intensity in the space environment near Earth is about 1,366 W/m^2 while that on the ground is about 250 W/m^2 on average due

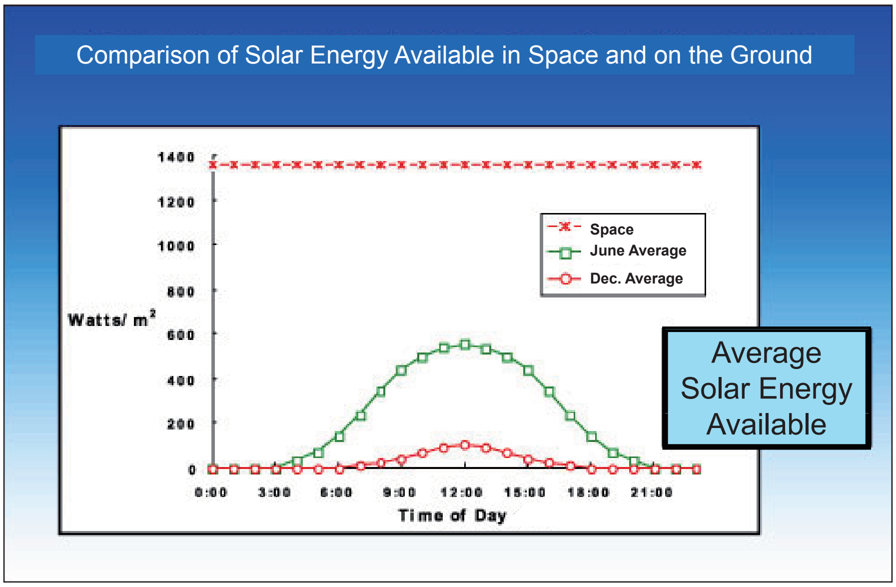

Figure 4 : Solar Energy Available in Space and on the Ground

Source: Reference[10]

to atmospheric scattering and absorption as well as due to seasonal, weather and day-and-night changes (Figure 4).[11]

A large space structure to generate GW-class electric power was once studied because on-orbit solar radiation energy intensity per unit area is higher.[20] A space solar power satellite is assumed to transmit generated electric power as microwave or laser beams. While there exist concerns that the transmission beam might cause environmental and biological problems, there are also an opinion and survey results that if the energy density is no more than 10 mW/cm^2, which is the exposure limit set by the U.S. Occupational Safety and Health Administration (OSHA),[21] it would do no harm to biota.[22,23] Such transmission facility could also be applied to areas where a power grid from a power plan and other infrastructure were not established.

The National Security Space Office of the U.S. Department of Defense published a report on space solar power on October 10, 2007 at the time when the crude oil price was rising, and Japanese news papers reported this publication. A space solar power concept, like a space elevator concept, was proposed a long time ago but is still being discussed. Dr. Peter Glaser of the Arthur D. Little Company first proposed a space solar power concept in 1968 that would transmit microwave beams to the ground, and then from the 1970s to the 1980s, when the oil crises occurred, the Department of Energy (DOE) and the National Aeronautics and Space Administration of the U.S. jointly studied such concepts, and announced a "1979 Reference System."[20,24,25]

According to this joint study, a solar power satellite (SPS) was like a flat-panel, whose dimension was about 5 kilometers by 10 kilometers by 0.5 kilometers, and the diameter of whose transmission antenna was about one kilometer. Each satellite could generate about 5 to 10 GW electric power continuously.[20] The study envisioned that 60 such satellites would be deployed on-orbit, and asserted that reusable space transportation vehicles such as two-stage-to-orbit launchers were necessary to reduce costs to launch materials to low earth orbit.[20] The costs for non-recurring research and development, including the cost of the first SPS, for procuring a single SPS, and for the maintenance of a single SPS were estimated in 1979 dollars to be $102.4 billion, $11.3 billion and $204.4 million, respectively.[20] As a final verdict, the U.S. National Research Council (NRC) and the then U.S. Congressional Office of Technology Assessment (OTA) concluded that the DOE-NASA concept, while technically feasible, could not be programmatically and economically achievable.[24] However, space solar power concepts were studied in the United States in the 1990s and the 2000s.[25]

Figure 5 shows the advances in the science and technology areas related to space solar power in the last 30 years or so. With these advances, new solar power satellite configurations have evolved, and the design proposed in the report of the National Security Space Office (Figure 6) has a characteristic that the primary and secondary mirrors collect the sunlight to irradiate the solar arrays more efficiently, thereby

1977	2007
•Solar Power Generation – Efficiency @ ~ 10%	•Solar Power Generation – Efficiency @ ~ 40%, going to 50%
•Wireless Power Transmission – Solid State Amplifiers, with Efficiency @ ~ 20% – Mechanical Pointing, 200 meter gimbaled, carrying 7 GW to 1 km array	•Wireless Power Transmission – Solid State Amplifiers, with Efficiency @ ~ 80 ~ 90% – Electronic Beam Steering, not mechanically gimbaled
•SSPS Power Management Req'ts – Voltages @ ~50,000 Volts	•SSPS Power Management Req'ts – Voltages @ < 1,000 Volts
•SSPS Space Launch Req'ts – Unique Reusable Heavy Lift, with payloads @ ~ 250 tons	•SSPS Space Launch Req'ts – Any Commercial Launcher, with payloads @ ~ 25 tons
•Space Robotics – Degree of Freedom @ ~ 3 – Control ~ Programmed/Teleoperated	•Space Robotics – Degree of Freedom @ ~ 30++ – Control ~ Autonomous/Tele-supervised
•Space Assembly – 100's of Astronauts – Large Space Factory Required in GEO	•Space Assembly – ~ No Astronauts – No Space Factory Required

Figure 5 : Science and Technology Advances for Space Solar Power

Source: Reference[11]

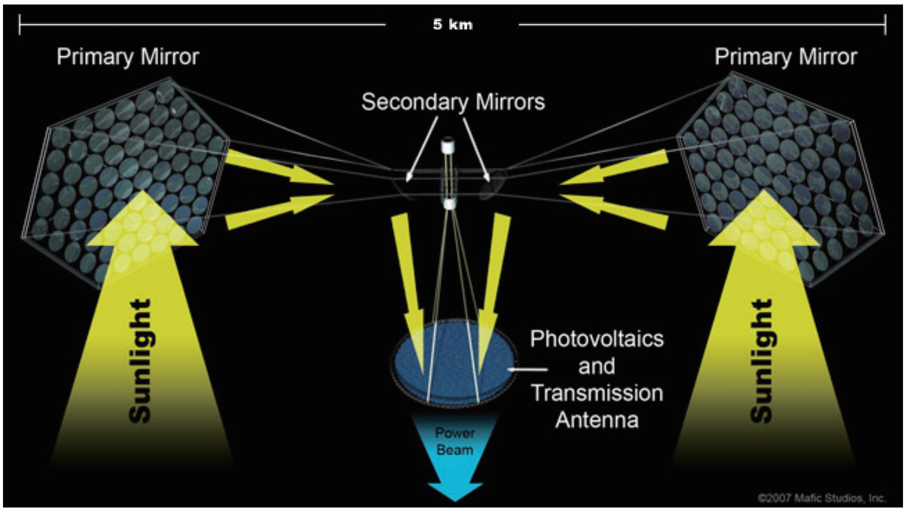

Figure 6 : An Example of Current Solar Power Satellite Design Proposals

Source : Reference[11] © Mafic Studios, Inc.

increasing the amount of electric power generated per unit mass.[11] The transmission antenna is placed just behind the solar array section to ease the wire harness problem.

An example of private sector initiatives is PowerSat's plan.[26] The company plans to deploy about 300 satellites in geostationary orbit, and to transmit generated power to a ground receiving antenna via microwave by forming a virtual antenna by these satellites as well as to transfer the satellites from low earth orbit (LEO) to geostationary orbit (GEO) with electric propulsion systems: the company has filed patent for these two ideas. The total power generated would be about 2.5 GW. The company plans to use thin-film solar cells to reduce the satellite's weight, and estimates that the program cost and the development period would be about $3 to 4 billion and about 10 to 12 years, respectively.

3 Space Innovation

3-1 The Reason Why Innovation for Space Activities

Table 3 shows an example of cost estimates for space solar power systems.[27,28] The estimates are for base power load generation cases because space solar systems could generate electric power continuously. The systems are assumed to be operational in 2020

Table 3 : Terrestrial vs. Space-based Power Systems

Total Power Supplied (GW)	Concept	Electricity Generation Cost (Euro/kWh)	Required Launch Costs (Euro/kg)
0.5	Terrestrial[NOTE 1] Space[NOTE 2]	0.09 (0.06)[NOTE 3] 0.28 (0.28)	N/A
5	Terrestrial Space	0.08(0.05) 0.04(0.04)	750 (200)[NOTE 3]
10	Terrestrial Space	0.08(0.05) 0.08(0.05)	620 (90)
50	Terrestrial Space	0.08(0.05) 0.04(0.03)	770 (270)
100	Terrestrial Space	0.08(0.05) 0.03(0.03)	770 (250)
500	Terrestrial Space	0.08(0.05) 0.04(0.04)	670 (210)
NOTE 1: Distributed solar power plants. NOTE 2: Microwave wireless power transmission based space systems. NOTE 3: Figures in parentheses are for pumped hydro-storage option scenarios.			

Source: Reference[27,28]

to 2030. The launch costs in the table are those required for the space systems to be competitive with the ground systems rather than actual costs. From the table, we may conclude that launch costs should be reduced at most by a factor of two from the current values to make the space solar power systems competitive with the terrestrial power systems. There is an initiative in Europe to develop large-scale solar thermal power plants in the Sahara desert, and there would be little incentives for Europe to construct a space solar system if they were developed.[29]

As the afore mentioned Earth sunshade and space solar power ideas imply, space technology has potential to tackle and solve global issues; however, such solutions cannot be realized economically at the current technology level because of, for example, launch costs and other factors. What is really needed is innovation that could implement space systems with totally new ideas rather than mere improvements of existing technologies. The Review of U.S. Human Space Flight Plans Committee, the final report of which was issued on October 22, 2009 after its summary report was issued on September 8, 2009, proposed alternate exploration goals and means as well as budget increase for the NASA exploration program, stating that given the current budget, meaningful human space flight could not be achieved because the program's budget did not increase as originally envisioned.[30,31] Even NASA's large-scale projects sometimes met with cost issues.

Notwithstanding current situations, a U.S. researcher, citing principles listed in Table 4, proposes renewed thinking to make space innovation really come true. In addition to the adoption of next-generation electric propulsion systems such as ion engines and the exploitation of tether satellites that consist of main spacecraft and cables called tethers, he proposes to deploy gossamer bimorph membranes in the space environment rather than to develop highly rigid structures that can withstand the launch environment, or to use coherent cooperation among many spacecraft in order to implement large-aperture antennas. Table 5 describes detailed methods to implement the principle of "Replace structures with information" in Table 4, where he proposes to exploit formation flight approaches rather than truss structures that are, though necessary during launches, virtually unnecessary in the space environment, and to deploy large yet lightweight mirrors on orbit with plastic-wrap-like bimorph membranes rather than those with rigid structures.

3-2 Ideas for Space Innovation

(1) A Space Elevator

If implemented, a space elevator could dramatically change space activities. The space elevator, the original idea of which was conceived by a Russian scientist named Konstantin Tsiolkovsky, is now studied as an application of tether satellites: the space elevator's center of mass circles in geostationary orbit while its tether part spins once per orbital revolution.[32,33,34] In addition to the elevator's merit that it can exploit Earth's rotation energy to launch payloads, the space elevator could use the excess energy dissipated by a descending payload to ascend another payload if linear motor cars could be used there, and the elevator is expected to lower launch costs significantly when compared with conventional chemical propulsion rockets.[34]

A Russian engineer named Yuri Artsutanov

Table 4 : High-Leverage Principles to Pursue in Space Concepts
"Don't fight the space environment – use it to advantage."

1.	Replace structures with information
2.	Adopt distributed space systems. Use coherent cooperation among many spacecraft to implement coherent sparse apertures.
3.	Use adaptive gossamer membranes to make large yet lightweight, filled apertures.
4.	Fabricate large gossamer membranes in the benign space environment.
5.	Transport energy and information, rather than mass, through space.
6.	Use spectrally matched multiple bandgap cells and films for high-efficiency solar power.
7.	Replace chemical combustion in propulsive devices with electromagnetic and electrostatic forces and plasmas.
8.	Exploit electromagnetic, dynamic, and static properties of long tethers.
9.	Beam power to remote or difficult to access locations.
10.	Service, repair, and upgrade large and complex spacecraft.
11.	Leverage the moon's shallow gravity well to mine, manufacture, and transport materials and devices from the moon to Earth orbit and Earth.
12.	Exploit the explosion in machine computing, visualization, and artificial intelligence.
13.	Utilize designer materials, especially nanomaterials.
14.	Exploit nanotechnology, MEMS, and NEMS (nanoelectromechanical systems)

Source: Reference[5]

Table 5 : Concept Principles "Replace Structures with Information"

- No truss structures - precision stationkeep all elements (formation flying)
- Initially shapeless primary mirror
- Limp plastic-wrap-like piezoelectric bimorph membrane
  - Uninflated, unsupported, free
  - Adaptive throughout its surface
  - Shaped into a precise figure by electron beam only when in space
- Liquid crystal second-stage corrector to take out remaining errors
- An extremely lightweight, inexpensive, easy-to-build system

Source: Reference[5]

published his space elevator study result in 1960.[32,33,34] Studied in his paper is a structure that may replace conventional rockets in the future, whose one end is anchored to Earth and whose center of mass circles above the equator in geostationary orbit.[36] On the tower's lower side below its center of mass and closer to Earth, the gravitational force is superior, which is proportional to the inverse of the square of a distance from Earth's center while on the upper side above the center of mass, the centrifugal force is superior, which is proportional to a distance from Earth's center; therefore, the space elevator is a structure in tension where the gravitational and centrifugal forces balance at its center of mass located at about 42,166 kilometers from Earth's center (upper part of Figure 7). He envisages a vehicle similar to a linear motor car as transport to go up and down the space elevator and a solar power facility at the first stop at an altitude of 5,000 kilometers to provide electricity to the vehicle. Electric power supply to the vehicle is said to be unnecessary above the second stop located at an altitude of geostationary orbit because the centrifugal force would move it upward. He imagines that the final stop is located at an altitude of about 60,000 kilometers where laid out are facilities such as greenhouses, observatories, solar power stations, workshops, and fuel depots as well as launching-landing structures for interplanetary rockets. He asserts that interplanetary rockets, unlike rockets launched from Earth, could leave the structures without requiring powerful engines because the rockets there already had attained required interplanetary travel speed.

During the cold war when Artsutanov published his paper, such information could not be transferred from the East to the West, and U.S. researchers independently studied space elevator concepts. Jerome Pearson, one of such U.S. researchers, published his technical paper in a professional journal in 1975, where he stated problems standing in the way of building a space elevator were (1) buckling due to its self weight, (2) material strength, and (3) dynamic stability, and showed his analytical study results. He stated that the first problem above could be solved by building a structure not in compression but in tension, and that the space elevator's total length, if no counter weight were placed at the elevator's outer end, would be about 144,000 kilometers (cf. the distance between Earth and its Moon is about 384,000 kilometers); further, he stated that the second problem above could be solved by changing the tether's cross-sectional area exponentially with the sum of the gravity and centrifugal force potentials as a variable.[34] While existing skyscrapers such as Chicago's Willis Tower and New York City's Empire State Building in the U.S.,

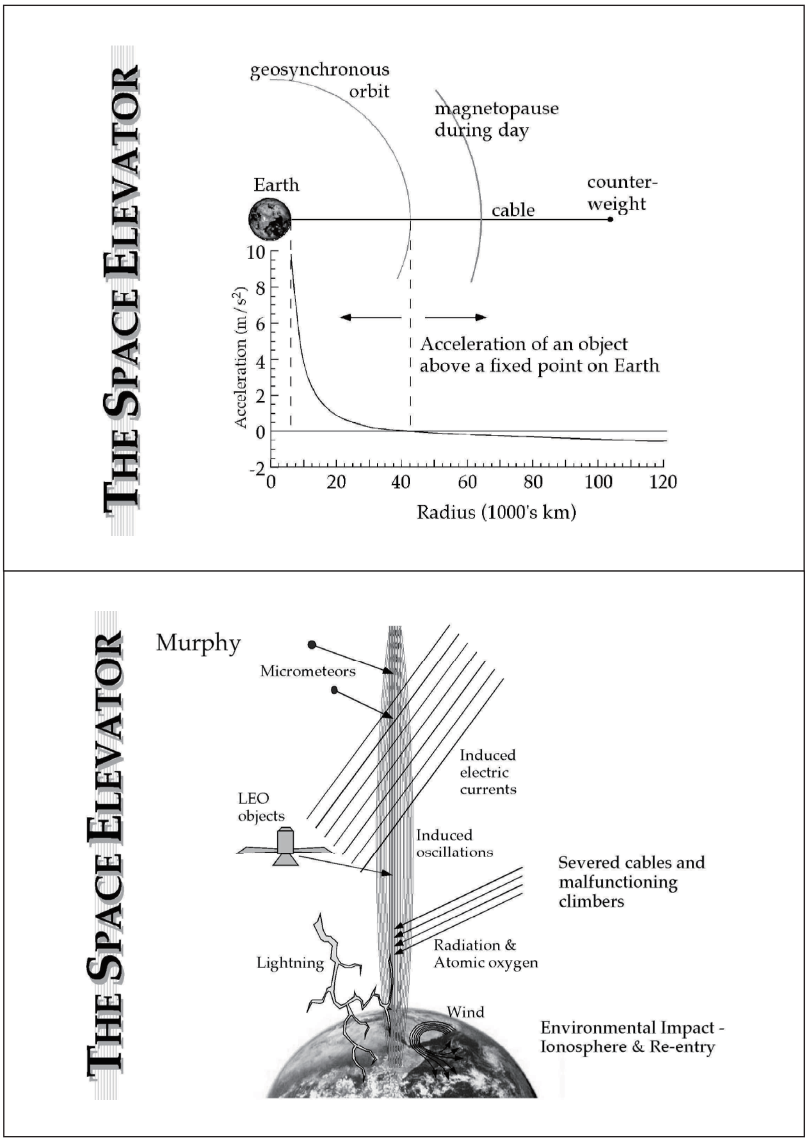

Figure 7 : A Space Elevator Concept

Source: Reference[35]

the Petronas Twin Towers in Kuala Lumpur, Malaysia, and Taipei 101 in Taiwan are about 400 to 500 meters high because they are compression structures, a gigantic space elevator would be theoretically possible by constructing it entirely as a structure in tension.

With regard to the third problem above, he analyzed the elevator's vertical vibration modes excited by the Moon's tidal forces and lateral vibration modes caused by payloads moving along it, assuming that they would be allowed to travel at a critical velocity for only a few hours, and he concluded that the elevator was dynamically stable.[34]

Table 6 shows the physical properties of typical high-strength materials as well as the ratios of their geostationary to ground tether cross-sectional areas when tapered exponentially (taper ratios) as described above (with regard to the characteristic speed, please refer to the MMOSTT section below). High strength and low density materials are required to achieve realistic taper ratios, and Mega-meter (Mm: 1 Mm=10^6 m) class CNT cables must be prerequisite. To construct lunar space elevators are said to be possible with currently available high-strength materials because the Moon's gravity is one sixth of Earth's.[37] Notwithstanding, there is a claim on CNT cables that their micro-scale strength is not scalable, and that their macro-scale strength would be substantially weaker.[38]

The space elevator's main characteristic as a space transportation system is that it could exploit Earth's rotation as a renewable energy source to launch payloads.[34] When launched by chemical propulsion rockets, payloads obtain the potential and kinetic energy, for example, required to circle Earth from the thermal energy produced by propellant

Table 6 : Physical Properties of Typical High-strength Materials

Material	Density (ρ:kg/m^3)	Tensile Strength (σ: GPa)	Characteristic Height[NOTE 7] ($h=\sigma/\rho g$: km)	Taper Ratio ($e^{0.776Re/h}$)[Note8]	Characteristic Speed[NOTE 9] ($V_c=(2\sigma/f\rho)^{1/2}$: km/s)	
SWCNT[NOTE 1]	2266	50	2250	9.0	4.7	3.8
T1000G[NOTE 2]	1810	6.4	361	9.2×10^5	1.9	1.5
ZYLON PBO[NOTE 3]	1560	5.8	379	4.7×10^5	1.9	1.6
Spectra 2000[NOTE 4]	970	3.0	315	6.5×10^6	1.8	1.4
M5[NOTE 5]	1700	5.7	342	1.9×10^6	1.8	1.5
M5 (planned)[NOTE 5]	1700	9.5	570	5.9×10^3	2.4	1.9
Kevlar 49[NOTE 6]	1440	3.6	255	2.7×10^8	1.6	1.3

NOTE 1: Single-wall carbon nanotube
NOTE 2: TORAY carbon fiber
NOTE 3: TOYOBO aramid PBO fiber
NOTE 4: Honeywell extended chain polyethylene fiber
NOTE 5: Magellan honeycomb polymer
NOTE 6: TORAY and DuPont aramid fiber
NOTE 7: Or breaking height. The term “g” is acceleration by Earth’s gravity, and is equal to about 9.8 m/s^2
NOTE 8: Re is Earth’s radius, and about 6,378 km
NOTE 9: The safety factor, f is two in the left column and three in the right.

Source: Reference[34,37]

combustion. On the other hand, with regard to space elevator launches, ascending payloads were imparted Earth’s rotation energy via the elevator, and they would have already acquired the energy necessary to circle geostationary orbit when they reached to a geostationary orbit altitude. The space elevator’s outer top would circle at the same angular velocity as that of the elevator’s center of mass, and the outer top’s speed would reach about 10.93 kilometers per second. A payload released from the top could fly inward to Mercury whose distance from the Sun is 0.39 astronomical units (AUs: one AU is an average distance between the Sun and Earth, and is about 150 million kilometers) or outward to Saturn whose distance from the Sun is 9.6 AUs within the solar system. Furthermore, if the elevator’s net centrifugal force could accelerate a payload from the geostationary orbit altitude where the elevator’s center of mass would be, to the elevator’s top, the payload could obtain the radial velocity of about 10.1 kilometers per second in addition to the above transverse velocity, and could fly outward to solar system bodies beyond Saturn. Hammer throws by the space elevator, which would rotate in the equatorial plane in sync with Earth’s rotation, could be terrific. As ancient Romans’ roads laid by the Roman Empire were ground transportation infrastructure at that time, the space elevator might become future space traffic infrastructure.

One of the biggest problems in constructing the space elevator is the enormous amount of material required. Assuming that high-strength material of a taper ratio of 10 and U.S. space shuttle launches are used, the number of launches for the construction is unrealistic 24,000.[34] Because of this unrealistic number of launches, an alternative method is also studied for constructing the space elevator, which might remind us “Kumo no ito (the Spider’s Thread),” a Japanese short story.[39,40] The idea is first to launch a satellite into geostationary orbit to deploy thin thread upward and downward from there, then to send upward one climber after another being powered by microwave or laser beams from the ground to add one thread after another to gradually strengthen the space elevator’s structure.

In addition to deterioration and damages caused by winds, lightning, radiation, atomic oxygen, space debris and micro meteorites, there would be possibilities that the space elevator, orbiting in the equatorial plane, would collide with low earth orbit (LEO) satellites that always cross the equatorial plane (lower part of Figure 7), and to establish a space traffic management (STM) system under international cooperation would inevitably become a must.[41] If collapsed, part of it would circle Earth, part of it would burn up in the atmosphere, and part of it would fall onto the ground.

Other examples of space elevator concept applications include a geostationary satellite whose lower end would be equipped with sensors and circle in low earth orbit. If such a satellite were implemented, high-resolution imaging from a fixed point over the equator would become possible.

(2) MMOSTT

An idea named Moon & Mars Orbiting Spinning Tether Transport (MMOSTT) is also an application of the tether satellite concept like the space elevator.[42,43] A tether satellite, about 100 kilometers long and weighing about 20 tons, would orbit in low earth orbit over the

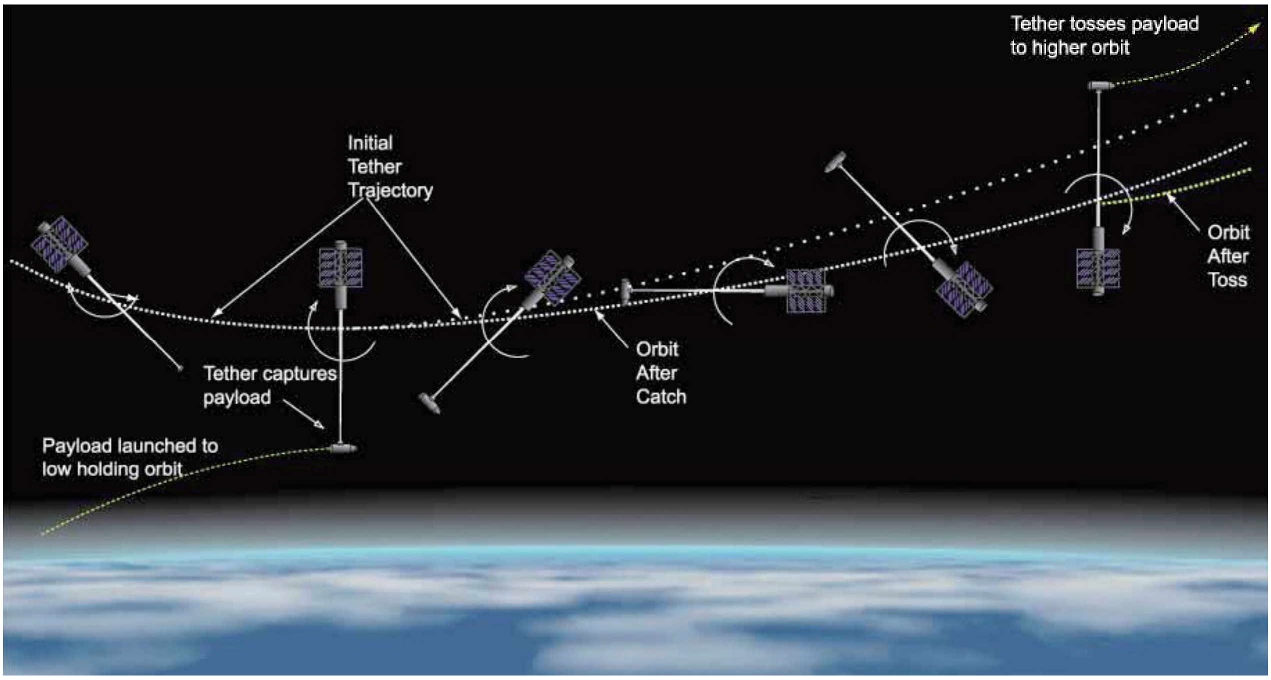

Figure 8 : MMOSTT's Concept of Operation

Source: Reference[43]

equator while rotating around its center of mass with its control station on one end that would also serve as a counter weight. MMOSTT would receive payloads from hypersonic planes and other vehicles flying at an altitude of about 300 kilometers, and would launch them to geostationary transfer orbit (GTO), lunar transfer orbit (LTO) and other higher energy orbit by imparting part of its energy to them (Figure 8). An upper stage, which would be usually discarded after mission and become space debris, of a launch vehicle that would put MMOSTT into orbit would be connected to the control station to increase its counter weight mass. MMOSTT's other end would house a payload grapple assembly. When seen from a payload, the payload grapple assembly would descend very rapidly from above and then ascend promptly, and the assembly would have to capture it in a very short time period. MMOSTT, so to speak, would conduct trapeze and hammer throw actions in orbit.

The energy lost due to capturing and releasing a payload could be recovered by generating along-track thrust through the interaction between currents generated by the solar panel and running through the tether's conducting part, and Earth's magnetic field; thus, MMOSTT would theoretically require no propellant.[42,43] As long as current technologies were used, a chemical propulsion rocket would be required to launch MMOSTT into orbit; however, it could thereafter be a space transportation system solely using renewable solar energy.

Tether material strength is also an important design parameter for MMOSTT like the space elevator.[42, 43] To optimize its weight, its tether cross-section must change exponentially: the ratio of the tether mass to the payload mass (M_T/M_P) is exponentially proportional to the square of $\Delta V/ V_c$, where ΔV is the velocity imparted to the payload and V_c is the characteristic velocity of the tether material, which depends on its strength and density (Table 6). To transfer a payload into GTO or LTO, the velocity increment of about three kilometers per second is required; therefore, it is said that MMOSTT, imparting velocities twice to give the required velocity increment, could be realized with currently available high-strength materials such as Spectra 2000.[43]

(3) Sail Propulsion

The propellant exhaust velocity of an ion engine, a kind of electric propulsion systems, is ten times higher than that of a chemical propulsion system, and can achieve the same amount of velocity change as that of the chemical system only using one tenths of propellants consumed by the chemical system; hence, ion engines have been used for such missions as solar exploration like Japan's "HAYABUSA" (MUSES-C) asteroid explorer, which require large velocity changes, and geostationary communications satellites, for which long mission lives are required.[44] The ion engine (1) first converts solar energy to electric power, and (2) then generates thrust by ionizing propellants, and then accelerating and exhausting them through the electric field; thus, it generates thrust from solar energy in two stages.

On the other hand, sail propulsion techniques, which would convert solar energy directly into thrust and therefore would not need propellant, have been studied for a long time.[45] One is the solar sail that, using solar radiation pressure due to photons' particle properties, reflects solar light to generate thrust. Another is the magnetic sail that, utilizing the interaction between solar wind plasma and the magnetic field generated by an onboard superconducting magnetic coil, deflects the plasma to generate thrust.

For the solar sail, the key is how to produce lightweight thin film membranes.[45] Below is the maximum acceleration to be attained from the solar radiation pressure (p_{rad}), where S is the area of the solar sail, and ρ is the film's area density.

(Radiation pressure force to the sail) / (the sail's mass)
$= (S \times p_{rad}) / (S \times \rho) = p_{rad}/\rho$

The radiation pressure in the space environment near Earth is about 5×10^{-6} Pa, and if we could assume that the thin film membrane whose area density were about 0.01 kg/m^2 could be manufactured, the acceleration of 5×10^{-4} m/s^2 similar to that of ion engines could be attained.[45] To obtain thrust of 1 N, or about 0.1 kgf, since the area, $S=0.2\times10^6$ m^2 (thrust/ p_{rad}=1 N/(5×10^{-6} Pa)), a 450 meter by 450 meter sail would be required, and the sail's mass would be about 2,000 kg.[45]

Because the solar sail would inevitably require large area membranes, but could generate quite small thrust, the Japan Aerospace Exploration Agency (JAXA), a Japanese independent administrative agency, has been studying the solar power sail (Figure 9) that is a hybrid propulsion system using both solar sail and ion engine techniques.[46] With part of its 50 meter diameter sail being covered with thin film solar cells, it is to provide electric power to its ion engines and other onboard equipment, and Jupiter and other solar system body exploration missions are under study.

Under JAXA's current plan, a small-scale technology demonstrator named "IKAROS" (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) will be launched in 2010 together with the

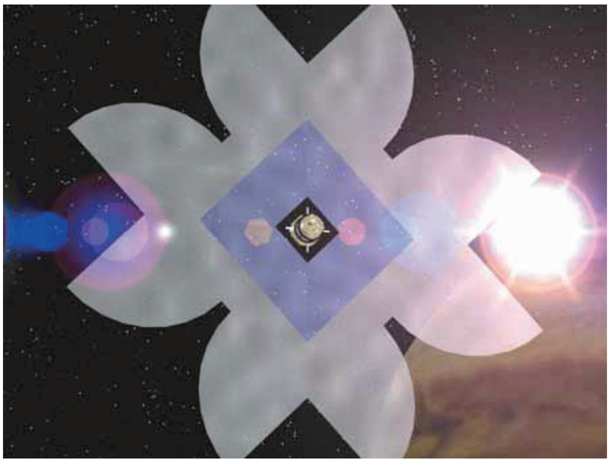

Figure 9 : A Solar Power Sail Concept

Source: JAXA[46]

"AKATSUKI"(PLANET-C) Venus Climate Orbiter. This mission is to demonstrate (1) the large membrane deployment, (2) the solar power generation, (3) the solar sail acceleration, and (4) the solar sail navigation (Figure 10).[47] IKAROS, with no ion engines onboard, will fly to Venus by only solar sail propulsion.

Since the dynamic pressure of solar wind plasma near Earth is about $7\text{x}10^{-7}$ Pa and is much smaller than that of solar radiation pressure, one could imagine that the sail using the solar wind plasma would require a much larger sail.

A U.S. researcher studied a magnetic sail, which could withstand the solar wind's dynamic pressure and wide open its sail to travel the solar system.[48] If the magnetic sail could magneto-hydro dynamically (MHD) interact with the solar wind like Earth's magnetosphere does, he showed that the magnetic sail could generate the acceleration (F/M) as described below, where ρ and V are the solar wind's density and velocity, respectively, and where R_m, ρ_m, I and j are the magnetic sail's radius, density, and electric current and its density running through the superconducting coil. μ is the permeability of free space and is equal to $4\pi\text{x}10^{-7}$.

$$F/M=0.59(\mu\rho^2V^4\ R_m/I)^{1/3}(j/\rho_m)$$

If we take the solar wind's typical values, $V=5\times10^5$ m/s and $\rho=(8.35\times10^{-21}\ kg/m^3)/R_s^2$, where R_s is the magnetic sail's distance from the Sun measured in the astronomical unit (AU), and if we assume for the superconducting coil that R_m=31.6 km, ρ_m =5000 kg (similar to copper oxide's density), $j=10^{10}$ A/m^2 and the diameter φ=2.52 mm, then the magnetic sail

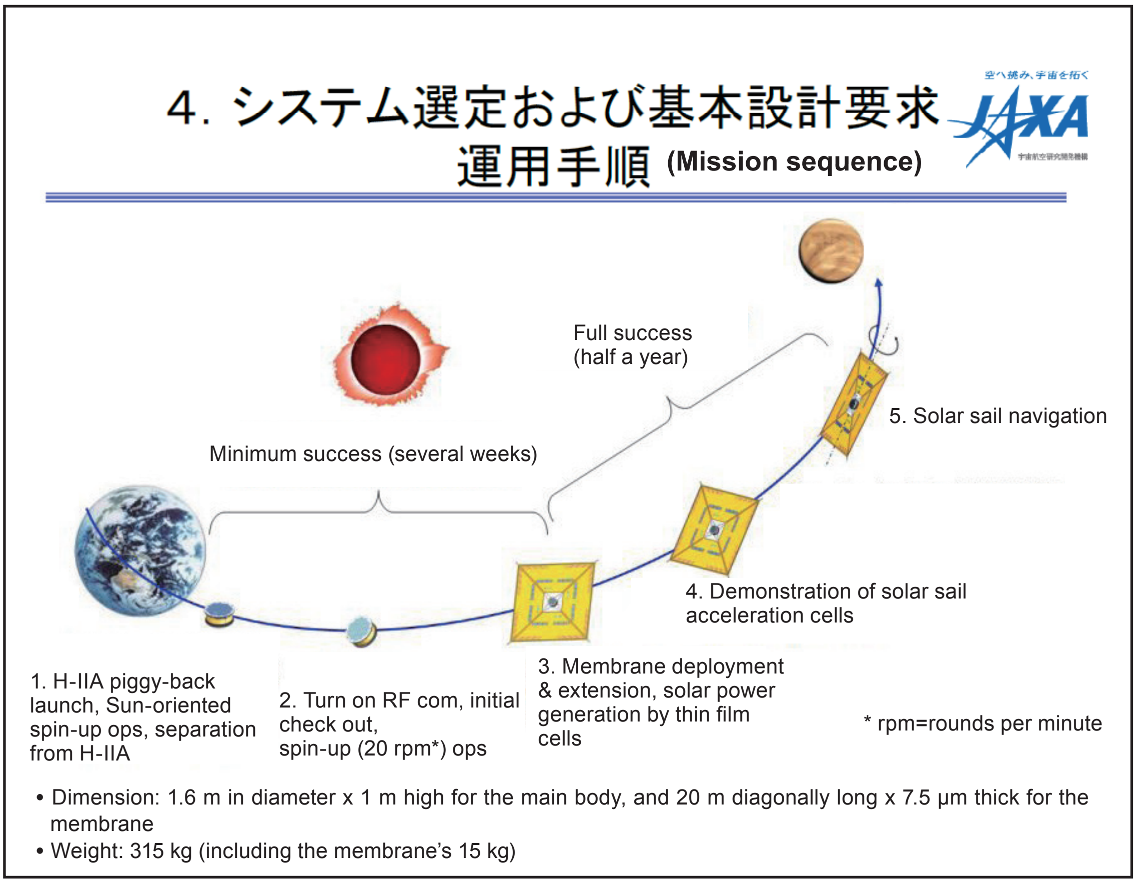

Figure 10 : Small Solar Power Sail Demonstrator "IKAROS"

Source: JAXA[47]

weighing about five tons (I is about 50 kA, and the magnetic density (B_m) is about 10^{-6} T) would have the self acceleration of 0.017 m/s^2 near Earth.[48] Although the magnetic sail would be quite large, it would be as good as the solar sail as far as self acceleration performances are concerned.

On the one hand, some could argue that to deploy such a large superconducting coil in space would be unrealistic; however, on the other hand, research results were published, which stated that if charged particles were injected into a 10 kilometer radius magnetic field created by a 10 centimeter radius coil, the field could be enlarged and efficiently interact with the solar wind, resulting in a realistic space propulsion system (Figure 11).[49,50] This concept is called a magneto-plasma sail, and was once regarded as promising because the sail was thought to generate large thrust even though it would have to inject charged particles, thus requiring propellant onboard.

Later some argued against the research results, stating that the results were based on a false assumption that injected particles would behave magneto-hydro dynamically, and that the strength of such a magnetic field could not withstand the solar wind's dynamic pressure and the wind would flow through the sail.[51] One might say that because the concept was based on a false assumption, it was a virtual physical phenomenon which could be realized in a virtual world like that of the movie "Matrix."
We might still need a strong enough magnetic field to open a large sail that could withstand the solar wind.

3-3 Possibilities Space Innovation Might Open

The Review of U.S. Human Space Flight Plans Committee proposed to develop a in-orbit refueling facility.[31] If compared with the situation of an isolated space flight heading from Earth to its destination without any refueling, such an in-orbit facility could ease the burden to space transportation systems, and their development and operations costs could be lowered. If two-stage-to-orbit space launch vehicles came true whose operations were similar to airplanes, their operations costs might become lower because they would not have expendable parts like the U.S. space shuttle's external tanks. Furthermore, If, for example, came true space transportation systems such as the solar power sail, MMOSTT and the space elevator that could use solar energy, Earth's rotation

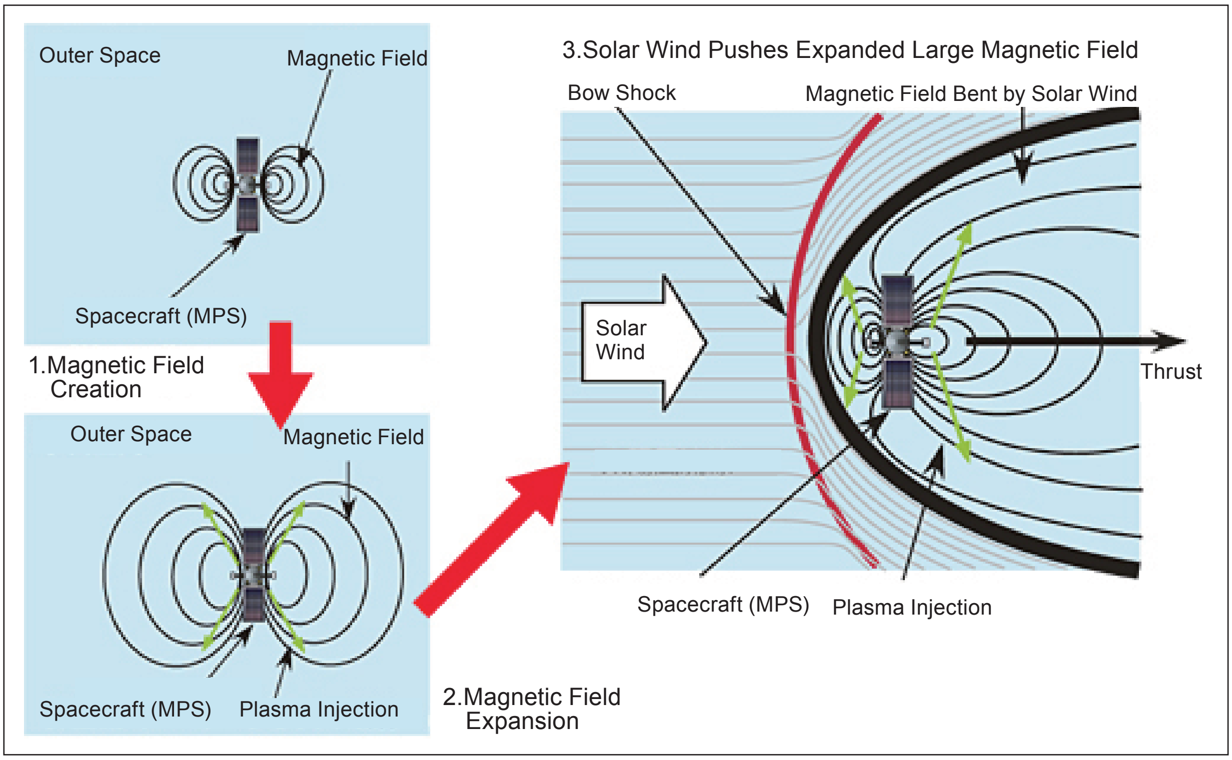

Figure 11 : Principles of How a Magneto-plasma Sail Works

Source: Reference[45]

energy and other reusable energy and that were totally different from chemical propulsion systems, their launch costs would be drastically reduced because they would consume a little or no propellants.

If launch costs were lowered, access to space could become easier; thereby, spacecraft design-life and reliability requirements might become lesser, and spacecraft development costs could be lowered. If lightweight and small satellites with thin-film or formation-flight technologies applied were realized, satellites with functions similar to bigger ones might be deployed with less launch costs. While a current spacecraft is to become space debris after its mission ends, a future spacecraft might be returned to Earth for reuse, or on-orbit maintenance, repair and improvement might be realized if launch costs could become lower drastically.

If lightweight and super-strong carbon nanotubes could be used with reasonable costs, higher-performance launch vehicles and lighter spacecraft could be realized.

For you information, collisions with spacecraft and space debris would pose serious problems to large space structures such as the space elevator and MMOSTT because of their large collision cross sections. Though not discussed in this paper, full-scale space debris measures and space traffic management (STM) established under international cooperation would become mandatory when space activities would become more active.[41] As a next step for the future, the U.S. Federal Aviation Agency (FAA) is studying, under its "NextGen" next generation air traffic control system study, how to deal with operationally responsive space (ORS) launches, which the U.S. Air Force is envisioning, in addition to airplanes.[52] Furthermore, the U.S. Defense Advanced Research Projects Agency (DARPA) issued a solicitation in September 2009 to request information on innovative approaches to remove space debris and solve problems imposed by the debris.[53]

4 The U.S.'s Approach to Create Innovation for Space Activities

All the ideas shown in Section 3-2 except the solar power sail were studied under the funding of the NASA Institute for Advanced Concepts (NIAC). In addition to them, also funded were such researches as one on a large yet lightweight telescope, the surface of which is a thin film bimorph membrane and the diameter of which is about 20 to 30 meters, to observe ex-solar planets and formation flying of such telescopes to form a virtual telescope whose diameter is several hundred meters,[54] and one on formation flying of numerous number of very small satellites in geostationary orbit to virtually form a large antenna of 30 to 40 kilometers in diameter to conduct very high resolution Earth observation.[55]

NIAC was an external entity formed in February 1998 under NASA's contract to the Universities Space Research Association (USRA) to infuse strategically advanced concepts into NASA's future missions.[56] Its objective was to create new innovative ideas for 10 to 40 year future missions rather than to provide technical assistance to on-going projects (Figure 12). It awarded to basic researches whose technology readiness levels (TRLs) were TRL 1 to 2.[57] It also conducted outreach activities to U.S. citizens and especially to young people to make them interested in science and technology.[56]

Former U.S. President George W. Bush announced an initiative in January 2004 for human space activities to go beyond the low Earth orbit limit and expand to the Moon and other solar system bodies like the Apollo program did in the 1960s to the 1970s, and NASA has started implementing this initiative. [58] However, on the contrary, NASA has met with a funding problem because its appropriated budget figures have not increased as envisioned, and because of this funding problem, the NIAC contract was terminated. NIAC ceased its activities on April 31, 2007.[59]

NIAC received the total funding of about 36.2 million dollars during its activity period of about nine years. NIAC awarded about 70% of this total funding to external entities for their research activities, and spent about 30% for its own operations.[56] NIAC awarded research funding to (1) "Phase 1" projects which conducted concept studies each with a performance period of about six months and research funding of about 50,000 to 75,000 dollars and (2) "Phase 2" projects which conducted follow-on studies each with a performance period of no more than 24 months and research funding of no more than about 400,000 dollars. NIAC received 1,309 research proposals in total, and awarded 27.3 million dollars in total to 126 Phase 1 and 42 Phase 2 researches. Some NIAC researches, because of their potential for future missions, received additional research funding from the Department of Defense and other U.S. federal agencies. For your information, NASA's annual budget when NIAC operated was about 13 to 17 billion dollars.[31]

The U.S. National Research Council (NRC), considering the situation that although NASA had contracted to operate the virtual institute of NIAC before to create advanced concepts, NASA terminated the contract and consequently has lost opportunities to create innovative space ideas by external entities, published a report in 2009.[60]

In this report, the NRC recommended to reestablish a NIAC like institution, stating that NASA, currently being solely devoted to project developments, does not invest in advanced research and development for

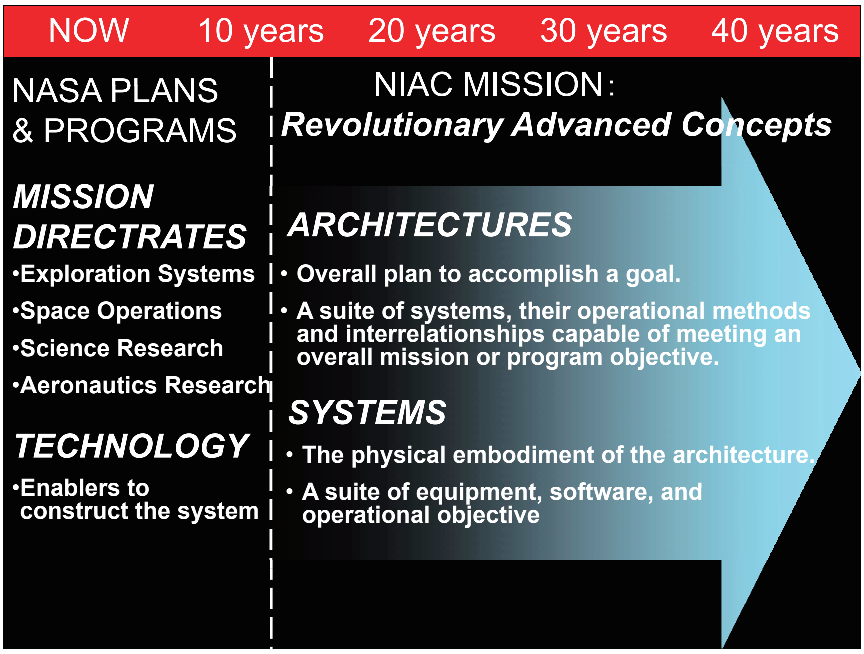

Figure 12 : NIAC's Mission

Source: Reference[56]

the future and that this situation would have negative consequences for future U.S. space activities.[60] However, to strengthen such an institution's potential to contribute to NASA's future missions, the NRC also made such recommendations as to include researches whose results could be infused into NASA missions in ten years, to extend Phase 1 and 2 performance periods and increase their research funding amounts, and to newly establish "Phase 3" projects each with a performance period of no more than about four years and research funding of no more than about five million dollars to fully demonstrate concepts' feasibilities. The NRC also recommended that it was necessary to more widely disseminate proposal solicitations and to strengthen reviewers including the discipline, age and gender aspects. To explore space innovation concepts requires not only to nurture researchers and engineers who can propose highly advanced concept proposals but also to establish functions to review and select such proposals.

5 Conclusion

"Anything one can imagine, other men can make real" is a saying of science fiction writer Jules Verne, and was aired in a Japanese TV advertisement before. Although our imagination may not always come true, there are some ideas that have made impact upon us when realized; for example, the industrial revolution brought about by the invention of steam engines and further the popularization of automobiles and airplanes have totally changed our society and life style.

As to space activities, while there is no argument against the importance of improving existing rocket and satellite technologies, efforts to create innovation for future space activities 10 years and beyond are also important because space technology has potential to tackle and solve global issues.

When space innovation would advance, what future would be open to us humans? Though very optimistic, Figure 13 shows an example of what effects could be brought as space innovation would advance.[5] If space system weights and costs could be reduced by several orders of magnitude not by several percent, what consequences such reductions would bring is out of our imagination. We might be surprised at the emergence of a good "black swan," an idea proposed by Mr. Nassim Nicolas Taleb.[61]

The U.S. Apollo program around the 1960s is said to have brought various advanced technologies such as fuel cells[62] and computers.[63] If space innovation described in this paper came true, what would be the effects such innovation would bring? The author hopes that Japan, as one of the developed nations, would engage in advanced research activities fully to be able to conduct its space activities with totally new ideas and without being caught with old ideas, and to create innovation for space activities to contribute more and more to our society and economy. We could

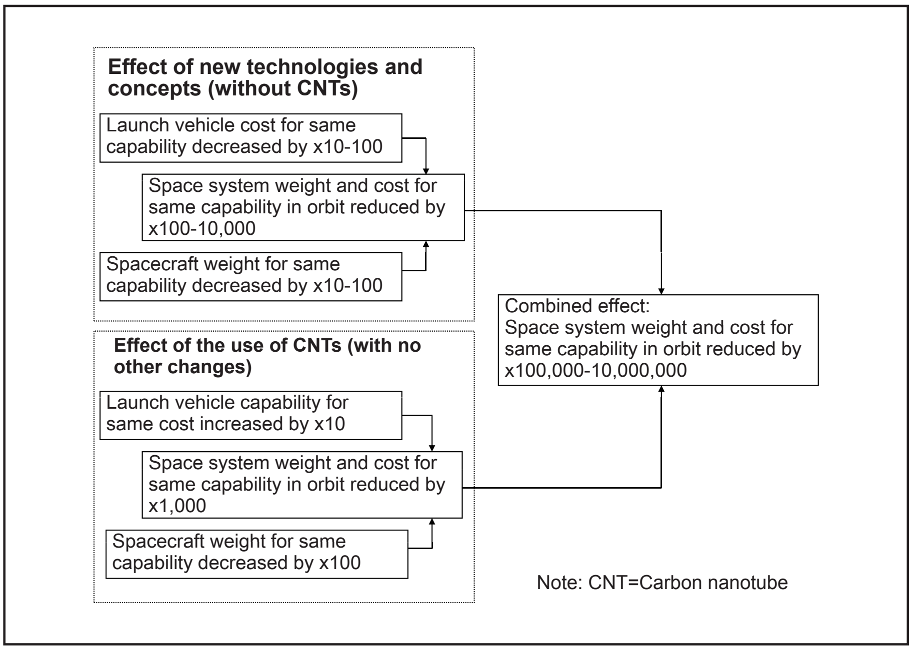

Figure 13 : Combined Effect of New Technologies, Concepts and CNTs

Source: Reference[5]

also expect that outreaching and educating our young people, Japan's next-generation with such advanced research activities could make them more interested in science and technology.

References

[1] "Arthur C Clark: Predictions," BBC NEWS online, March 19, 2008 : http://news.bbc.co.uk/2/hi/technology/7304852.stm
[2] "The Technology Strategy Map 2009 - the nanotechnology field," the New Energy and Industrial Technology Development Organization (NEDO), cited on the NEDO HP on April 30, 2009 : http://www.nedo.go.jp/roadmap/2009/nano1.pdf (Japanese)
[3] "Tunguska at 100," Nature, Vol.453, Issue no.7199, June 26, 2008, pp.1157-159
[4] "The Tunguska Mystery," Luca Gasperini, Enrico Bonatti and Giuseppe Longo, Nikkei Science, pp.36-42 (Japanese: first published in Scientific American June 2008)
[5] "Advanced Space System Concepts and Technologies: 2010 - 2030+," Ivan Bekey, The Aerospace Corporation, ISBN 1-884989-12-8, 2003
[6] "America's Future in Space: Aligning the Civil Space Program with National Needs," Committee on the Rationale and Goals of the U.S. Civil Space Program, National Research Council, ISBN 0-309-14037-4, 2009 : http://www.nap.edu/catalog/12701.html
[7] "Electricity without Carbon," Nature, Vol.454, August 14, 2008, pp.816-823
[8] JAXA HP "Greenhouse gases observing satellite 'IBUKI' (GOSAT)" (Japanese): http://www.ard.jaxa.jp/research/hmission/hmi-ssps.html
[9] "Carbon capture plant backed by EU," BBC NEWS online, October 16, 2009: http://news.bbc.co.uk/2/hi/uk_news/england/south_yorkshire/8311286.stm
[10] JAXA HP "Space Energy Utilization (Solar Light Utilization)": http://www.ard.jaxa.jp/research/hmission/hmi-ssps.html
[11] "Space-Based Solar Power as an Opportunity for Strategic Security: Phase 0 Architecture Feasibility Study: Report to the Director, National Security Space Office: Interim Assessment," October 10, 2007: http://www.nss.org/settlement/ssp/library/final-sbsp-interim-assessment-release-01.pdf
[12] "A Sunshade for Planet Earth," NIKKEI Science, June 2009, pp.60-70 (Japanese: first published in Scientific American November 2008)
[13] "Responsible Leadership for a Sustainable Future," Japan's Ministry for Foreign Affairs HP: http://www.mofa.go.jp/policy/economy/summit/2009/declaration.pdf
[14] "The Geoengineering Option - A Last Resort Against Global Warming," David G. Victor, M. Granger Morgan, Jay Apt, John Steinbruner, and Katherine Ricke, Foreign Affairs, March/April 2009
[15] "Geoengineering the climate: Science, governance and uncertainty," the Royal Society, September 2009: http://royalsociety.org/displaypagedoc.asp?id=35217
[16] "Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change," Susan Solomon, Dahe Qin, Martin Manning, Melinda Marquis, Kristen Averyt, Melinda M.B. Tignor, Henry LeRoy Miller, Jr. and Zhenlin Chen (eds), Cambridge University Press: http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm
[17] "Radioactive forcing," a glossary of environmental words, the Environmental Information & Communication Network: http://www.eic.or.jp/ecoterm/?act=view&serial=2419
[18] "Transient Climate-Carbon Simulations of Planetary Geoengineering," H. Damon Matthews and Ken Calderia, PNAS, June 12, 2007, vol.104, no.24, pp.9949-9954: http://www.pnas.org/cgi/doi/10.1073/pnas.0700419104
[19] "Climate targets 'will kill coral'," BBC NEWS online, September 2, 2009: http://news.bbc.co.uk/2/hi/science/nature/8233632.stm

[20] "Technical Assessment: Satellite Power System Concept Development and Evaluation Program, Volume 1, Technical Assessment Summary Report," NASA Technical Memorandum 58232, November 1980: http://www.nss.org/settlement/ssp/library/NASATechnical%20Memorandum58232 - SPSTechnical%20 Assessment.pdf

[21] "Radiofrequency and Microwave Radiation Standards," the U.S. Occupational Safety and Health Administration: http://www.osha.gov/SLTC/radiofrequencyradiation/standards.html

[22] "How Safe Are Microwaves and Solar Power from Space?," John M. Osepchuk, IEEE Micowave Magazine, December 2002, pp.58-64: http://electricalandelectronics.org/wp-content/uploads/2008/10/01145676.pdf

[23] "Project Summary: Responses of Airborne Biota to Microwave Transmission from Satellite Power System (SPS)," the United States Environment Protection Agency, EPA-600/S1-84-001, September 1984 (searched from the site below):
http://nepis.epa.gov/Exe/ZyNET.EXE?ZyActionL=Register&User=anonymous&Password=anonymous&Client=EPA&Init=1

[24] "A Fresh Look at Space Solar Power: New Architectures, Concepts and Technologies," John C. Mankins, International Astronautical Federation IAF-97-R.2.03, 1997: http://www.nss.org/settlement/ssp/library/1997-Mankins-FreshLookAtSpaceSolarPower.pdf

[25] "Appendix C: US Activities (NASA Report) of the International Union of Radio Science (URSI) White Paper on Solar Power Satellite (SPS) Systems," 2007: http://www.ursi.org/WP/Appendices070529.pdf

[26] PowerSat's HP: http://www.powersat.com/

[27] "Earth & Space-Based Power Generation Systems - A Comparison Study: A Study for ESA Advanced Concepts Team," Blandow, V., Schmidt, P., Weindorf, W., Zerta, M., Zittel, W, Bernasconi, M., Collins, P., Nordmann, Th., Vontobel, Th., and Guillet, J., European Space Agency Contract No.17682/03/NL/EC, January 2005:
http://www.esa.int/gsp/ACT/doc/POW/GSP-RPT-SPS-0503%20LBST%20Final%20Report%20Space%20Earth%20Solar%20Comparison%20Study%20050318%20s.pdf

[28] "Peter Glaser Lecture: Space and a Sustainable 21st Century Energy System," Ongaro, F. and Summerer, L., 57th International Astronautical Congress, Paper IAC-06-C3.1.01, 2006:
http://www.esa.int/gsp/ACT/doc/POW/ACT-RPR-NRG-2006-IAC-SPS-Peter_Glaser_Paper.pdf

[29] DESERTECH Foundation's HP: http://www.desertec.org/index.html

[30] "Summary Report of the Review of U.S. Human Space Flight Plans Committee," September 8, 2009:
http://www.nasa.gov/pdf/384767main_SUMMARY%20REPORT%20-%20FINAL.pdf

[31] "Seeking a Human Spaceflight Program Worthy of a Great Nation," Review of U.S. Human Spaceflight Plans Committee, October 22, 2009: http://www.nasa.gov/pdf/397898main_HSF_Cmte_FinalReport_High.pdf

[32] "The Space Elevator: 'Thought Experiment', or Key to the Universe," Arthur C. Clark (First Published in Advances in Earth Oriented Applied Space Technologies, Vol.1, pp.39-48, Pergamon Press Ltd., 1981. Printed in Great Britain):
http://wiki.spaceelevator.com/Open_Wiki/Documents/Articles/The_Space_Elevator%3a_'Thought_Experiment'%2c_of_Key_to_the_Universe%3f

[33] "Audacious & Outrageous: Space Elevators," Science@NASA Headline News, September 7, 2000: http://science.nasa.gov/headlines/y2000/ast07sep_1.htm

[34] "The orbital tower: a spacecraft launcher using the Earth's rotational energy," Jerome Pearson, Acta Astronautica, Vol.2, pp.785-799, Pergamon Press Ltd., 1975: http://www.star-tech-inc.com/papers/tower/tower.pdf

[35] "The Space Elevator," Bradley C. Edwards, presented at the June 2001 NIAC Annual Meeting:
http://www.niac.usra.edu/files/library/meetings/annual/jun01/521Edwards.pdf

[36] "To the Cosmos by Electric Train," Yuri Artsutanov, July 31, 1960 (Russian to English translation. First published in the Young Person's PRAVDA):
http://wiki.spaceelevator.com/@api/deki/files/13/=Artsutanov_Pravda_SE.pdf

[37] "NIAC Phase I Study: Lunar Space Elevators for Cislunar Space Development," Jerome Pearson, Star

Technology and Research, Inc.: http://www.niac.usra.edu/studies/1032Pearson.html
[38] "On the Strength of the Carbon Nanotube-based Space Elevator Cable: From Nano- to Mega-Mechanics," Nicola M. Pugno, arXiv:cond-mat/0601668v1, January 30, 2006: http://arxiv.org/ftp/cond-mat/papers/0601/0601668.pdf
[39] "NIAC Phase I Study: The Space Elevator," Bradley C. Edwards, Eureka Scientific, Inc.: http://www.niac.usra.edu/studies/472Edwards.html
[40] "NIAC Phase II Study: The Space Elevator," Bradley C. Edwards, Eureka Scientific, Inc.: http://www.niac.usra.edu/studies/521Edwards.html
[41] "Cosmic Study on Space Traffic Management," International Academy of Astronautics (IAA), ISBN 2-9516787-5-4, 2006: http://iaaweb.org/iaa/Studies/spacetraffic.pdf
[42] "NIAC Phase I Study: Tether Transport System for LEO-MEO-GEO-Lunar Traffic," Robert P. Hoyt, Tethers Unlimited, Inc.: http://www.niac.usra.edu/studies/7Hoyt.html
[43] "NIAC Phase II Study: Moon & Mars Orbiting Spinning Tether Transport Architecture Study," Robert P. Hoyt, Tethers Unlimited, Inc.: http://www.niac.usra.edu/studies/373Hoyt.html
[44] "Japan's Space Capabilities for Lunar and Planetary Exploration," Science & Technology Trends Quarterly Review, No.30, pp.70-92, January 2009 (first cited in Science and Technology Trend, No.89, pp.20-36, August 2008 in Japanese)
[45] "The Challenge of Magnetoplasma Sail Propulsion for Deep Space Explorations," the Journal of Plasma and Fusion Research (JPFR), Vol.83, No.3, 2007, pp.281-284 (Japanese): http://www.jspf.or.jp/Journal/PDF_JSPF/jspf2007_03/jspf2007_03-281.pdf
[46] "On a Solar Power Sail Demonstration Program," ISAS News, March 2005 issue (No.288: Japanese): http://www.isas.jaxa.jp/ISASnews/No.288/mission-05.html
[47] "On Mission Plans of the 'IKARO' Small Solar Power Sail Demonstrator," Osamu Mori, September 9, 2009 (Japanese): http://www.jaxa.jp/press/2009/09/20090909_sac_ikaros.pdf
[48] "The Magnetic Sail: Final Report to the NASA Institute of Advanced Concepts," Robert Zubrin and Andrew Martin, Pioneer Astronautics, January 7, 2000: http://www.niac.usra.edu/files/studies/final_report/320Zubrin.pdf
[49] "NIAC Phase I Study: Mini-Magnetspheric Plasma Propulsion (M2P2), NIAC Award No.07600-010, Final Report," Robert M. Winglee, May 1999:
[50] "NIAC Phase II Study: Mini-Magnetspheric Plasma Propulsion (M2P2), NIAC Award No.07600-032, Final Report," Robert M. Winglee, November 2001: http://www.niac.usra.edu/files/studies/final_report/372Winglee.pdf
[51] "Fundamentals of the Plasma Sail Concepts: Magnetohydrodynamic and Kinetic Studies," G. Khazanov, P. Delamere, K. Kabin and T. J. Linde, Journal of Propulsion and Power, Vol.21, No.5, September-October 2005, pp.853-861: http://hsd.gsfc.nasa.gov/staff/bios/cs/KhazanovGV/AIAA-3737-130.pdf
[52] "Space Transportation Concept of Operations Annex For NextGen Version 1.0," the Federal Aviation Administration: http://www.faa.gov/about/office_org/headquarters_offices/ast/media/NextGen_ConOps_Space_Annex_final_v1.0.doc
[53] "DARPA Orbital Debris Removal," Solicitation No.DARPA-SN-09-68
[54] "NIAC Phase I Study: An Extremely Large Yet Ultra-lightweight Space Telescope and Array - Feasibility Assessment of a New Concept, NIAC Grant # 07600-006," Ivan Bekey, Bekey Designs, Inc., May 29, 1999: http://www.niac.usra.edu/files/studies/final_report/58Bekey.pdf
[55] "NIAC Phase I Study: Extremely Large Swarm Array of Picosats for Microwave / RF Earth Sensing, Radiometry, and Mapping, NIAC Research Sub-Award No.07605-003-029," Ivan Bekey, Bekey Designs, Inc., April 29, 2005: http://www.niac.usra.edu/files/studies/final_report/942Bekey.pdf
[56] "NASA Institute for Advanced Concepts 9th & Final Report 2006-2007," NASA Institute for Advanced Concepts: http://www.niac.usra.edu/files/library/annual_report/2006annualreport.pdf
[57] "R&D Activities for Aeronautics S&T in Japan, the United States and Europe," (Japanese), Takafumi

Shimizu, Science and Technology Trend, April 2009 (No.97), pp.19-34: http://www.nistep.go.jp/achiev/ftx/jpn/stfc/stt097j/index.html

[58] "The Vision for Space Exploration," the National Aeronautics and Space Administration, February 2004: http://www.nasa.gov/pdf/55583main_vision_space_exploration2.pdf

[59] NIAC HP: http://www.niac.usra.edu/

[60] "Fostering Visions for the Future: A Review of the NASA Institute for Advanced Concepts," Committee to Review the NASA Institute for Advanced Concepts, National Research Council, ISBN 0-309-14052-8, 2009: http://www.nap.edu/catalog/12702.html

[61] "The Black Swan: The Impact of the Highly Improbable," Nassim Nicholas Taleb, Penguin Books, 2008 (First published in the United States of America by The Random House Publishing Group 2007 and in Great Britain by Allen Lane 2007)

[62] "Apollo's Fuel-Cell Power Legacy," BBC NEWS online, July 16, 2009: http://news.bbc.co.uk/2/hi/science/nature/8154721.stm

[63] "Weaving the Way to the Moon," BBC NEWS online, July 15, 2009: http://news.bbc.co.uk/2/hi/technology/8148730.stm

Profile

Takafumi SHIMIZU
Fellow, Science and Technology Foresight Center
Monodzukuri Technology, Infrastructure and Frontier Research Unit
http://www.nistep.go.jp/index-j.html

Engaging in space development-related research. Responsible for space development and other frontier fields at the SFTC.

(Original Japanese version: published in December 2009)