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14. ABSTRACT Space Solar Power – delivering solar energy economically from space to markets on Earth – is one of the few new systems concepts that has the potential to make a dramatic difference for the future of energy, the environment and the global economy. There are a wide variety of ongoing activities in the US and internationally related to advancing the field of space solar power (SSP), including workshops and studies by the US Department of Defence, studies of future flight experiments and demonstrations by NASA and others, and emerging interest in new directions for the US civil space program. This paper presents the results of a high-level survey of recent developments in the US, and related international activities. The paper identifies prospective directions for this field, and concludes with thoughts concerning a roadmap for future progress in the field of SSP.					
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The Proceedings of the Panel Discussions on the Space Solar Power Systems

The 27th ISTS in Tsukuba, Japan
on 10 July, 2009

Theme : Space Solar Power Systems
 Date : 2009/07/10 12:30 - 14:00
 Place : Hall 200
 Coordinator : Nobuyuki Kaya (Prof. Kobe University, Japan)
 Chair : John Mankins
 (Artemis Innovation Management Solutions, LLC, USA)
 Panelist : Paul Jaffe (Naval Research Laboratory, USA)
 Chit Hong Yam (ESA, Europe)
 Dallas Bienhoff (Boeing Company, USA)
 Nobuyuki Kaya (Prof. Kobe University, Japan)

Humankind is now in danger of a big energy crisis. Because oil and coal as fuels for power generators are anticipated to run out from the Earth approximately fifty years after. We are investigating new energy sources, for example, solar power generators, windmills, heat pumps and so on. However, these are too irregular and small generators to work as basic and steady power sources instead of the nuclear power stations. On the other hand, the Space Solar Power Systems (SSPS) looks an unique and hopeful candidate for electric power stations to satisfy ever-increasing energy demand on the Earth without destroying the environment. Electric power generated by huge solar paddles of the SSPS at the geosynchronous orbit is transformed into microwave, which is transmitted from a large antenna to the ground. Solar cells on the ground can supply nothing in rainy and cloudy days, though they can generate electric power in the sunshine. While, the SSPS can constantly generate electric power in space, where there are no rain and no cloud, except a short eclipse by the Earth. The efficiency of the power generation in space by the solar cells is estimated ten times higher than on the ground. The power density of the transmitted microwave is designed to be a low power density enough to bring no interference with the telecommunication and to give no critical effects on the ecological system on the Earth. Therefore, the SSPS would be a clean substitute for the nuclear power stations without destroying the environment.

International interest on the SSPS has increased dramatically during the past decade. This interest has been expressed through a variety of research and development efforts including studies and technology development in the U.S. and ongoing R&D in Japan, recent studies and ongoing studies in Europe, more recent studies in the U.S., for the first time under the leadership of the Department of

Defense (DOD), as well as interest in other space-faring countries of importance, such as India and China. The current status of these studies including the IAA study on the SSPS will be reported and discussed by the panelists.

Acknowledgement: We appreciate for the support from Asian Office of Aerospace Research & Development (AOARD) of Air Force Office of Scientific Research (AFOSR) for the panel discussion on the Space Solar Power Systems.



27th International Symposium on Space Technology and Science
in Tsukuba, Japan

July 2009

A Survey of US Activities in the Field of Space Solar Power

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Keywords: Space Solar Power, Solar Power Satellites, Wireless Power Transmission, Space Technology

ABSTRACT

Space Solar Power – delivering solar energy economically from space to markets on Earth – is one of the few new systems concepts that has the potential to make a dramatic difference for the future of energy, the environment and the global economy. There are a wide variety of ongoing activities in the US and internationally related to advancing the field of space solar power (SSP), including workshops and studies by the US Department of Defence, studies of future flight experiments and demonstrations by NASA and others, and emerging interest in new directions for the US civil space program. This paper presents the results of a high-level survey of recent developments in the US, and related international activities. The paper identifies prospective directions for this field, and concludes with thoughts concerning a roadmap for future progress in the field of SSP.

1.0 Introduction

Overall, U.S. activities indirectly related to space solar power (SSP) have generally declined during the past several years due entirely to drastic reductions in the advanced technology research and development (R&D) conducted by the National Aeronautics and Space Administration (NASA). However, despite this overall decline, there has been increasing activity and interest in the U.S. directly related to SSP. Foremost among these activities was the 2007 study of space-based solar power (SbSP) conducted for the Department of Defense (DOD) National Security Space Office (NSSO). The following paper provides a summary of these activities.

Figure 1 is an illustration of a new concept for SSP that was identified in 2007 by a U.S. firm, Managed Energy Technologies LLC.

There have also been a number of significant international SSP efforts in which the U.S. has participated. In particular, these include participation in the 2004 independent review by

Kobe University of the 2002-2004 European Space Agency (ESA) solar power satellite (SPS) study.

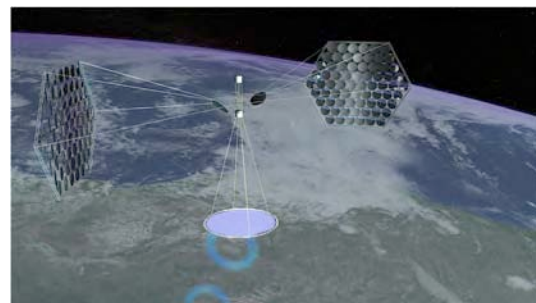


Figure 1 Integrated Modular Sandwich SPS Concept identified by Managed Energy Technologies LLC (2007); illustration by Kris Holland (Mavic Studios)

2.0 Overview of U.S. SSP Activities

The following section provides a brief summary overview of recent U.S. SSP activities (including both those activities that are focused on SSP, and those that are indirectly related to

SSP). The discussion is organized into four sections:

- (1) U.S. government organizations;
- (2) U.S. industry (large and small enterprises);
- (3) U.S. academic and non-profit organizations; and,
- (4) U.S. participation in international efforts.

2.1 U.S. Government Organizations

The principal U.S. government organizations that have had activities related to SSP/SPS in recent years are NASA, the DOD (particularly the USAF and the USN), and several of the national laboratories.

Within the DOD, the most significant activity was a preliminary assessment of the SSP concept for the National Security Space Office (NSSO), performed during Spring and Summer 2007. Following this study, there have been two workshops organized by the USAF, one examining requirements for energy by the DOD, and the second that examined a relatively narrow range of options for implementation of the SPS concept (both meetings were during 2008). Another important and recent activity is an effort by the Naval Research Laboratory (NRL) to demonstrate a modular SPS element of the sandwich panel type (started in Fall 2009, and planned to require a total of about 24 months to complete).¹

As noted above, within NASA the level of SSP-relevant R&D was reduced drastically during 2005-2009. Nevertheless, numerous relevant competencies continue within the U.S. space agency, and during 2008 there was a significant examination of the possibility of a WPT demonstration being performed on the International Space Station (ISS).

¹ An SPS system concept of the sandwich type (described in greater detail elsewhere) involved the close physical integration of power generation and wireless power transmission (WPT) system elements within the overall SPS platform.

2.2 U.S. Industry

The major aerospace firms in the U.S. are conducting a considerable level of activity that is relevant to achieving space solar power, including the Boeing Company, Lockheed Martin Corporation, and Raytheon. A number of these firms participated in the planning exercise conducted by the NASA Johnson Space Center during 2008 that examined a specific concept for a WPT demonstration from the ISS.

In addition, there are a variety of smaller firms in the U.S. that are developing SSP-relevant technologies, as well as several companies that have focused specifically (or largely) on the goal of SPS. The latter group includes Managed Energy Technologies LLC, The Space Island Group, and Solaren Corporation. Of these, Managed Energy Technologies was noteworthy in 2008 by conducting, with Kobe University, Texas A&M University, and others, a solar-powered wireless power transmission (WPT) demonstration between the peaks of Haleakala and Mauna Loa – a distance of 148 kilometers.

In 2009, there were several significant events. First, the Solaren Corporation signed a power purchase agreement with a California firm, Pacific Gas & Electric (PG&E) to deliver energy to that state's market. Also, Managed Energy Technologies worked with Kobe University to perform a WPT demonstration (using Professor Nobuyuki Kaya's retrodirective phased array technology) at a major IAA symposium on solar energy from space (discussed below).

2.3 Academic and Non-Profit Organizations

There are several academic and non-profit organizations involved in SSP related activities in the U.S. For example, Dr. Peter Glaser of Arthur D. Little created in the U.S. the only international non-profit organization that is focused on SPS in the U.S. in the late 1970s; this organization, the Sunsat Energy Council (also known as the Space Power Association), continued to be active during 200-2009. Also, significant relevant R&D continued to be conducted by Texas A&M University (TAMU),

the Battelle Memorial Institute, through PNNL, and others.

2.4 U.S. Participation in International Efforts

Various individuals from the U.S. have participated in various international SPS activities over the years, including the International Astronautical Federation (IAF) annual space power symposium on at the International Astronautical Congress (IAC). In recent years, the most significant U.S. participation in international efforts related to SSP has been participation in, and co-leadership of a major international assessment of the SSP concept by the International Academy of Astronautics (IAA). This ongoing study was co- led by Managed Energy Technologies (cited previously) and Kobe University of Japan. The study will conclude during 2010 for the framing of an international roadmap for SSP, with results planned for presentation at the IAC in Prague, September 2010.

3.0 Future Directions

As yet, there continues to be no official U.S. program focused on developing SSP. However, key leaders in NASA and selected individuals in the DOD continue to be interested in the concept and since the election of President Barack Obama in November 2008, and his inauguration during winter 2009, there has been a great deal of policy discussion and legislation in the U.S. focused on increasing U.S. government investments in sustainable energy solutions.

The potential exists for a significant program in this area, depending on the course of future events. For example, NASA – which is at present examining a range of options for how best to contribute to U.S. green energy technology objectives might well engage on the topic of SPS. Also, it is possible that one or more of the commercial firms examining SSP will be successful in securing private sector funding.

At any event, the results of the IAA’s study of SSP, mentioned previously, will

certainly stimulated additional discussion and consideration of SSP and related R&D.

4.0 Summary

The past four years have been a period of general decline in U.S. space technology R&D activities related to SSP. However, during the same period, there has been an increase in activities directly related to SSP to levels that have not been evident since the late 1990s (and the NASA Fresh Look Study).

There is considerable evidence that U.S. and international activities directly and indirectly related to space solar power will increase during the coming several years. The ongoing concerns about climate change, the need for new “green” energy options, and the emphasis by the U.S. Administration on technology developments to resolve these issues all highlight this potential.

Glossary of Acronyms

DOD	Department of Defense
DOE	Department of Energy
ESA	European Space Agency
ETO	Earth-to-Orbit (Transportation)
GEO	Geostationary Earth Orbit
GW	Gigawatts
HRST	Highly Reusable Space Transportation
IAA	International Academy of Astronautics
IAC	International Astronautical Congress
IAF	International Astronautical Federation
IPC	(IAC) International Program Committee
ISS	International Space Station
ISTS	International Symposium on Space Technology and Science
JAXA	Japan Aerospace Exploration Agency
LEO	Low Earth Orbit

NASA	National Aeronautics and Space Administration
NRL	Naval Research Laboratory
NSSO	National Security Space Office
PNNL	Pacific Northwest National Laboratory
R&D	Research and Development
RLV	Reusable Launch Vehicle
SbSP	Space-based Solar Power
SEPS	Solar Electric Propulsion System
SPS	Solar Power Satellite
SSP	Space Solar Power
TAMU	Texas A&M University
USAF	United States Air Force
WPT	Wireless Power Transmission

Potential Pathways Forward” at the 59th International Astronautical Congress (IAC-08-C3.1.1; Glasgow, Scotland). September 2008.

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RECENT STUDIES OF SPACE SOLAR POWER AT THE US NAVAL RESEARCH LABORATORY

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ABSTRACT

Space solar power (SSP) is generally considered to be the collection in space of energy from the sun and its wireless transmission from space for use on earth. It has been observed that the implementation of such a system could offer energy security, environmental, and technological advantages to those who would undertake its development. A study conducted by the Naval Research Laboratory (NRL) sought to determine if unique, cost effective, and efficient approaches exist for supplying significant power on demand for Navy, Marine Corps, or other Department of Defense applications by employing a Space-Based Solar Power (SBSP) system. The study was initiated by and prepared for top NRL management in part as a result of the publication of the National Security Space Office's (NSSO) report "Space-Based Solar Power as an Opportunity for Strategic Security"¹. The NSSO report's recommendations included statements calling for the U.S. Government to conduct analyses, retire technical risk, and become an early demonstrator for SBSP. It should be noted that the principal objective of the NRL study differed significantly from that of the multitude of previous studies performed in reference to SBSP in that it focused on defense rather than utility grid applications. Interest generated by the NRL report has led to small-scale research funding of SSP-related technologies.

INTRODUCTION

The SBSP study group was formed at the behest of senior NRL leadership. The group first convened in May of 2008. It was comprised of a broad cross-section of expertise from around the laboratory, including specialists in spacecraft development, optics, solar cells, radar, electronics, and other disciplines. Over the course of approximately six months, the group surveyed the literature, debated, sought input from outside experts, and posited possible SBSP military scenarios and assessed the state of technology at the time as it applied to SBSP. The culmination of the study was the production of a report of the findings, "Space-Based Solar Power: Possible Defense Applications and Opportunities for NRL Contribution - Final Report"². This report was briefed to NRL leadership and underwent a public release process so as to make it generally available. It was cleared for public release in early 2009 and can be accessed at <http://www.nss.org/settlement/spp/library/2008-NRLSBSP-PossibleDefenseApplicationsAndOpportunities.pdf>

This paper summarizes the findings in the report and discusses some subsequent activities related to SBSP at NRL.

ACTIVITIES ASSOCIATED WITH THE REPORT

The study group heard from distinguished figures in the field of SBSP: John Mankins, widely recognized as one of the world's leading experts on SBSP and a former manager of NASA's Advanced Concepts Studies Office. He is also a creator of the TRL level grading system. Lt.

Col. Peter Garretson, one of the coordinators and authors of the NSSO report also briefed the group.

Several representatives from the NRL study group supported the Air Force Research Laboratory (AFRL)-sponsored Military Power Requirements Symposium in early July 2008. Members from the services were introduced to the SBSP concept and asked how it might provide useful and unique capabilities to meet their needs. Requirements and concepts were identified and considered in the formulation of this report.

A summary of preliminary findings from this report was also presented at the AFRL-sponsored State of Space Based Solar Power workshop in October 2008, held in Orlando, Florida, USA.

SUMMARY OF REPORT FINDINGS

Concept feasibility

The NRL SBSP Study Group concurred with the conclusions of the numerous previous studies of preceding decades that the SBSP concept is technically feasible but that there remain significant system risks in many areas. The Study Group also concurred that SBSP offers one of several possible solutions to the energy independence of the United States; and that alternative solutions (including terrestrial solar, nuclear, and wind) must be an integral part of the solution.

It was observed that safe power densities for wireless energy transmission may generally restrict military and other applications to large, relatively immobile receiver sites; and also that capital, launch, and maintenance costs remain significant concerns in the economics of fielding a practical SBSP system, an analysis of which was beyond the scope of the study.

Military Operations Scenarios

Specifically regarding military operation scenarios, a number of observations were made. SBSP systems employing microwave power transmission at frequencies below 10 GHz would be most suited to a limited number of bases and installations where the large area required for efficient power reception would be available. For applications requiring smaller apertures, millimeter wave or laser power transmission may be preferable, though tradeoffs among safety, increased atmospheric attenuation, and received power density would need to be addressed carefully. Direct power transmission to individual end users, vehicles, or very small, widely scattered nodes did not appear practical at the time the study was conducted, primarily because of the large inefficiencies and the possible risks of providing what amounts to a “natural resource”. Backup alternatives to SBSP would need to be considered for military installations in the event of failure, compromise, or military action as such a system may present the problem of a single point of failure.

Many specific military scenarios are given treatment in the report. They are summarized in Table 1.

Table 1. Military Operations Scenarios Summary

Military Operations Scenario	Rationale for SBSP	Feasibility		Notes	Earliest operational capability	Rough magnitude cost
		Technical	Economic			
Forward Operating Base Power	Reduce fuel convoys	Possible	Possible	Probably best SBSP defense app	>5 years	\$10B+
Provide power to a ship or other large seaborne platform	Refuel from space	Possible	Possible	Almost certainly requires lasers and high power densities	>5 years	\$10B+
Bistatic radar illuminator	Improve imaging	Possible	Possible	Feasible but expensive	>5 years	\$10B+
Provide power to a remote location for synthfuel production	Reduce infrastructure	Possible	Possible	Requires transportation architecture that consumes synthfuel	>5 years	\$10B+
Power to Individual End Users	Reduce battery mass	Unlikely	Unlikely	Power inefficient, severe beam control & safety challenges	>10 years	?
Power for Distributed Sensor Networks	Cover large area	Possible	Unlikely	Power inefficient	>5 years	\$10B+
Space solar power to non-terrestrial targets						
Satellite to satellite power transmission	Fractionate spacecraft	Possible	Possible	Significant technical issues, questionable utility	>2 years	\$50M+
Space to UAV for dwell extension	Prolong dwell times	Possible	Possible*	*if used in conjunction with FOB power	>5 years	\$10B+
Terrestrial Wireless Power Beaming Applications Apart from SBSP						
Ship to shore power beaming	Increase flexibility	Possible	Possible	Attractive defense application, requires more study	>1 year	\$10M+
Ground to UAV for dwell extension	Prolong dwell times	Demonstrated	Possible	May be unnecessary in light of recent UAV tech advances	>1 year	\$10M+

Relevant Research Areas

As the report was created with NRL management as the primary audience, attention was called to existing research efforts and capabilities that could be employed in the pursuit of SBSP development. NRL has world class competencies in many of the engineering core areas necessary for SBSP risk reduction: thermal management, space structures, space robotic assembly, photovoltaics, RF amplifier technology, energy storage and management, propulsion, spacecraft and system engineering. Research applied to the areas in which NRL has core competencies would yield substantial technological dividends for SBSP as well as

other space and terrestrial applications. NRL's Naval Center for Space Technology (NCST) offers a unique and credible facility for developing and deploying spaceborne SBSP demonstrators. NCST has previously flown many experimental integrated systems and technology demonstration missions, including many cutting-edge solar power generation experiments. NCST also has a proven record of transitioning experimental systems to operational assets.

Table 2 shows specific NRL research areas of relevance to SBSP and previous related projects.

Table 2. High Priority NRL Contribution Research Areas

Technology Area	NRL Precursors	Recommended research
Space Structures	Superstring longeron truss	Beam walker & rolled-up beam deployment mechanism development and demonstration
Space Robotic Assembly	Satellite for the Universal Modification of Orbits (SUMO), Front-End Robotic Enabling Near-Term Demonstrations (FREND)	Co-operative robotics, smart skin technology, space robotic structure assembly
Space Subsystem Development	W-band transponder, Frangibolt deployment mechanism, atomic clocks for spaceflight, etc.	Photovoltaic RF-conversion antenna module research, a.k.a "sandwich" module
Thermal Management	Two-phase heat pipes, diamond substrate heat management	SBSP detailed component alternatives thermal analysis, e.g. the "sandwich" module
Photovoltaics	TacSat-4 solar cell experiment	Photovoltaic collector and concentration experiments
RF amplifier technology	Multiple beam klystrons, coupled-cavity and helix traveling wave tubes	Phase-controllable, light weight, high-efficiency, multipactor-resistant microwave sources in the 2kW to 15kW range
Propulsion	High Performance Xenon Flow System, Electric Propulsion Demonstration Module (EPDM), Advanced Tether Experiment (ATEX)	Long duration electric propulsion for large structures, LEO to GEO transfer propulsion, stationkeeping, LEO electrodynamic tethers
Spacecraft Engineering	Clementine, TacSat-1, TacSat-4, WindSat, Upper Stage, Interim Control Module, etc.	In-orbit robotic construction demonstration, SBSP-related technology free-flyer experiments
Energy Management & Storage	Spacecraft power subsystems, Sodium Sulfur Battery Experiment (NaSBE)	SBSP flight power architecture, Large capacity ground load-leveling storage capabilities

Recommended Course Forward

The report recommended that members of the NRL SBSP Study Group, in collaboration with all NRL interested scientists, should: (1) proceed to maintain meaningful and continuing engagement with the wider SBSP community and its efforts, both nationally and internationally, and (2) pursue sponsors to mount compelling demonstrations related to space-based solar power, with continued attention to military-specific opportunities.

It also advised that NRL leadership should consider continuing and expanding funding for energy technologies (generation, transmission, storage, etc) including, as appropriate, funding for SBSP component technologies and experimentation.

The study concluded that SBSP concepts and technologies are inherently viable, require further development, and are integral to many national security applications for energy independence and military superiority. Compelling research and collaboration opportunities exists for qualified organizations like NRL. Leadership needs to focus these efforts to construct a SBSP capability with true benefit and value.

A summary of some demonstration concepts and the technology areas advanced is shown in Table 3.

Table 3. Summary of Demonstration Concepts

Demonstration Concept	Technology Advanced	Cost range
Ground-based demonstration of robotic assembly of space structures	SS&A	\$2M-\$20M
A large structure robotic construction demo in space	SS&A	\$80M-\$400M
An international collaboration LEO free-flyer demonstrator hosting one or more SBSP technology demonstrations and experiments	PV, WPT, SS&A	\$40M-\$1B
Microwave power beaming from the International Space Station, using its existing solar arrays (currently being pursued by NASA)	WPT	\$40M-\$80M*
Demonstrations employing high altitude vehicles	PV, WPT	\$5M-\$30M
Earth to LEO microwave power beaming	WPT, SS&A	\$80M-\$300M
Laser or microwave terrestrial power beaming demonstrations	WPT	\$1M-\$50M
SSA = Space Structures and Assembly PV = Photovoltaics WPT = Wireless Power Transfer *shuttle or other launch provided		

CONCLUSION

The NRL SBSP study has been followed with increased engagement by NRL scientists and engineers with the broader SBSP community, as per the report's recommendations. Additionally, a small scale research effort with possible applicability to SBSP has been funded and will commence in FY10. It has been preceded by a related student project that successfully completed in August 2009. The larger recommendation to pursue sponsors for compelling SBSP demonstrations remains, and could materialize as smaller efforts show success.

¹ *Space-Based Solar Power As an Opportunity for Strategic Security*, Phase 0 Architecture Feasibility Study, National Security Space Office, Release 0.1, 10 October 2007.

² *Space-Based Solar Power: Possible Defense Applications and Opportunities for NRL Contribution - Final Report*, Naval Research Laboratory, 23 November 2008.



Solar Power from Space: Status and Perspectives

Presented by

Chit Hong Yam (a.k.a. Hippo)

on behalf of

Leopold Summerer

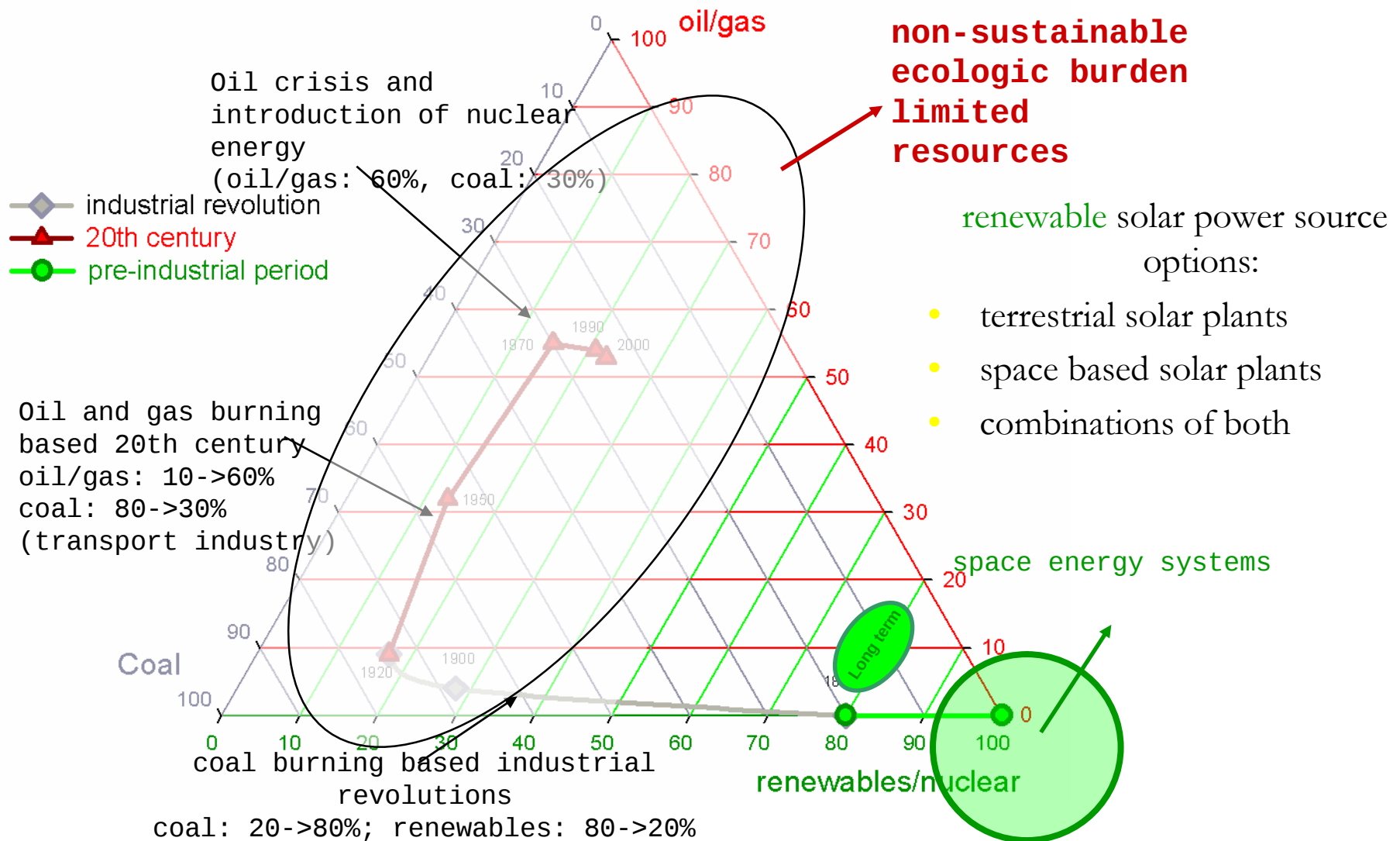
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ESA DG-PI
Advanced Concepts Team
<http://www.esa.int/act>



- Motivation
- ESA SPS Activities
 - Validation phase – comparison with alternatives
 - Maturation of key SPS technologies
 - Furoshiki 1
 - Research collaboration
- Conclusion

Motivation



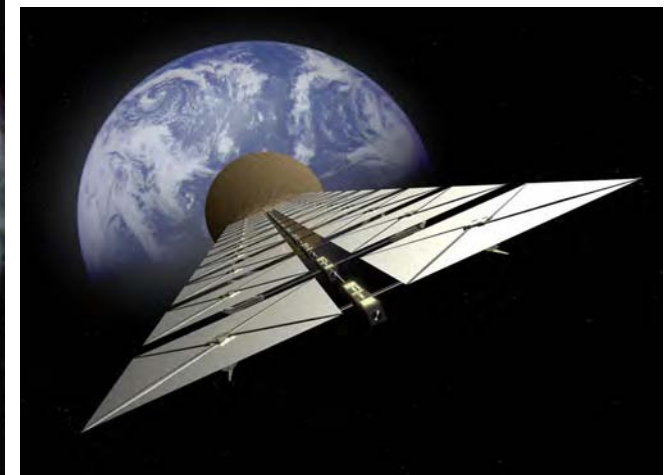
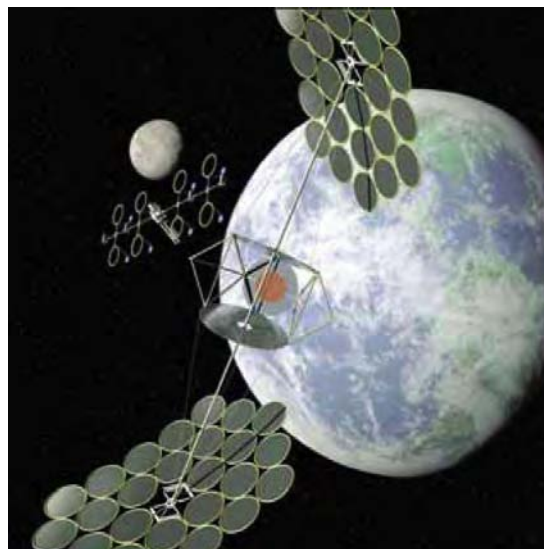
Source: International Institute for Applied System Analysis & World Energy Council, *World Energy Perspectives 1998*



The solar power satellite (SPS) concept generates an electrical power on the order of several hundreds to thousands of MW. It converts solar energy to electrical energy using photovoltaic panels and transmits this energy back to the ground using microwave or laser wireless power transmission.

Some superficial advantages of space-based plants over terrestrial ones:

- 11 800 kWh/m²
 - ~1000-2600 kWh/m² on Earth
- Production 24h/24 (in GEO)
 - ~8/24 hours on Earth
- No meteorological influences
 - microwave power transmission
- Reception close to consumer centers





- Energy systems for space applications:

- sustainable
- clean
- energy efficient
- closed cycle energy carriers

- Space as *driving force* for future terrestrial energy systems

- photovoltaic's
- fuel cells
- hydrogen as “transport fuel”
- energy saving in s/c

- space systems as *fore runners* of terrestrial applications

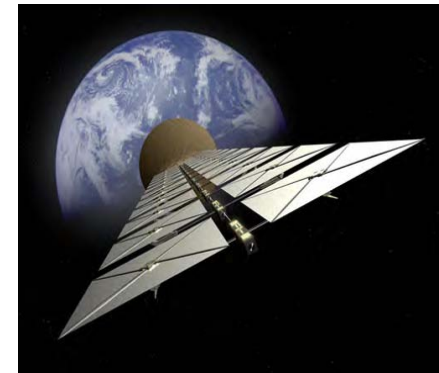
- 20 years lead time

100 kW
(~2010)

x 2 000

SPS?

Intern. Space Station



SPS “Solar tower”



European SPS Programme Plan

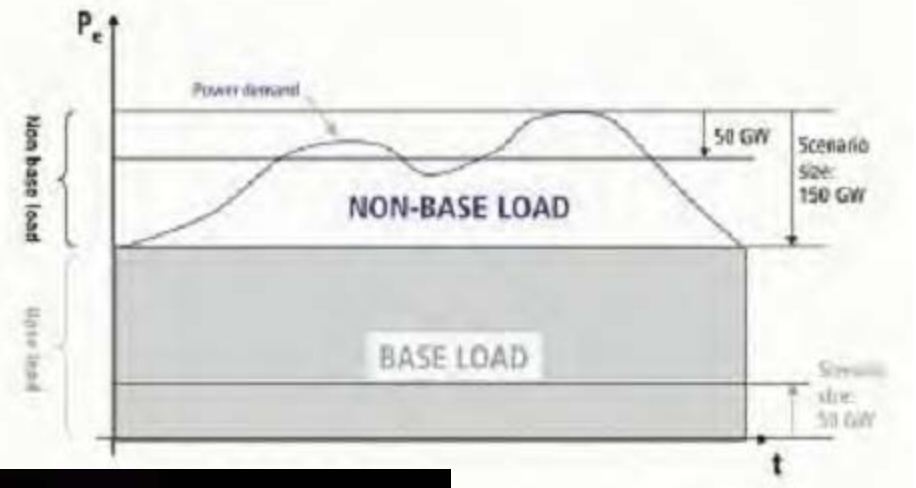
Early identification within the Advanced Concepts Team in 2002

- **General *validation phase***
 - Comparison of space and terrestrial solar power plants as key element for the general validation of space solar power
- ***Opening*** of the SPS research activities
 - ESA's Advanced Concepts Team studies into SPS system
 - Collaboration with universities / Experiments
- ***Integration*** into the larger energy community
 - SPS Workshops



Comparison: Space - Terrestrial

- base and peak/non-base -load power supply
- solar power only
- European scenario
- power levels from 0.5 to 150 GW
- timeframe: 2020/30
- launch costs as open parameter
- energy payback time
- Two industrial consortia chose different reference systems





Consortium 1 (LBST-lead):

- Multiple solar thermal tower units distributed throughout the Southern European sunbelt region
- Solar Thermal Tower Option
- Generation
 - Unit size of 220 MW covering an area of 14 km²
 - Capacity factor of 73%
 - Current electricity costs from this configuration (0.042 €/kWh) exp. to fall to 0.03 €/kWh by 2020/30
- Transmission
 - No significant additional transmission capacity for scenarios up to 100 GW, above which HVDC technology is used
- Storage
 - Local compressed hydrogen storage system



Validation Phase - Terrestrial Systems



Consortium 2 (EcoFys-lead)

- Solar-Trough system in a non-populated region of Egypt
- Generation
 - 225 €/m² of effective trough collector
 - 800 €/kW for the power block and 30 €/kW for the thermal storage
- Transmission
 - Relatively long power transmission lines (HVDC) lines
 - Capacity of 5 GW per line (today) exp. to increase to 6.5 GW by 2020/30
 - Operations/maintenance at 1% of total investment
- Storage
 - Utilisation of local topography for pumped hydro-storage system



Validation Phase - Space Plant Types



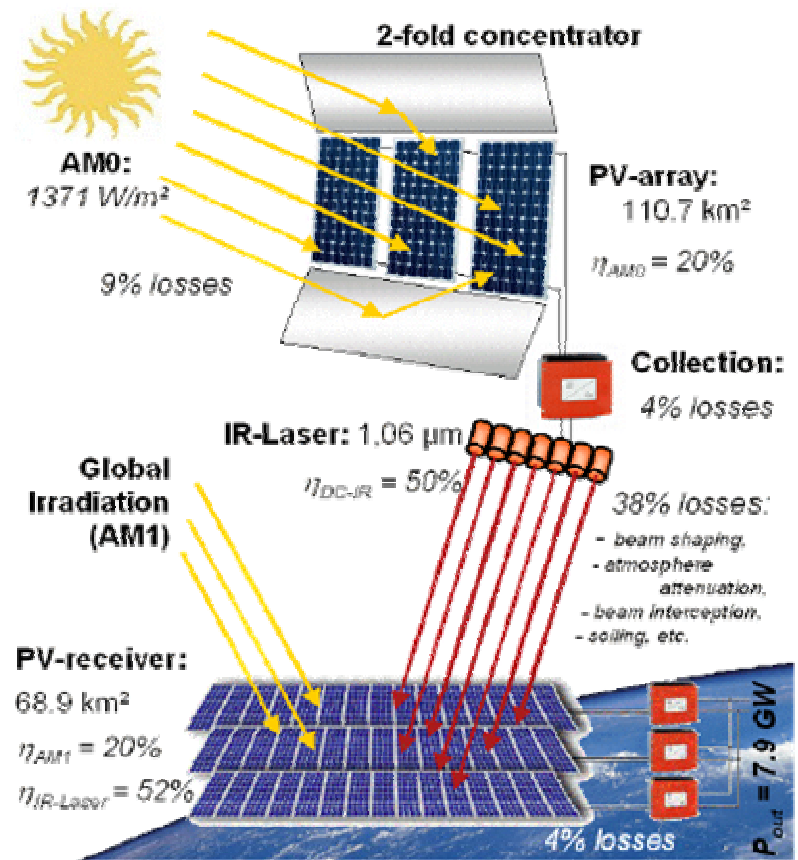
- Terrestrial receiver sites in North Africa and South Europe
- Due to the restrictions of European scenarios, only GEO systems were considered
- Analysis mainly based on technical assumptions of the European Sail tower concept, NASA Fresh look and follow-on studies and Japanese concepts

•LBST

- 500 MWe level: Solar tower concept in GEO
- 5-500 GWe level: Solar Disc concept in GEO
- 5.8 GHz microwave WPT

•EcoFys

- GEO platform
- 2 fold concentrating thin-film cells (110 km²)
- IR laser (1060 nm, 50% eff)
- PV receiver for laser and solar radiation
- 3 SPS / Ground receiver, 25 GWe



Conclusions of Validation Phase



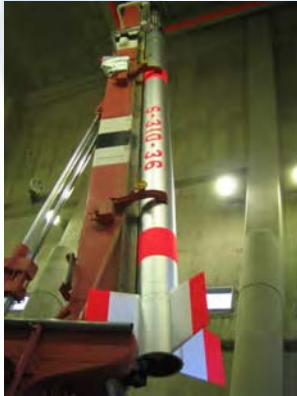
- Terrestrial plants advantageous over space plants until several tens of GWe.
- Both options have relatively low energy payback times of only few years.
- The integration of SPS into terrestrial solar power plants in order to reduce the substantial need for energy storage is very promising – especially since terrestrial solar power plants are likely to be operational earlier than space power plants.
- Economic comparison to terrestrial alternatives for European scenarios:
The higher the power level the better for the space system (>20-50 GWe)
- Integration of SPS into terrestrial solar power plants not straight-forward
- Preliminary data show little to no advantage for European only based concepts
- Very small scale solar power plants for space exploration (e.g. lunar exploration) offer an interesting test bed for the development and testing of the system, especially using wireless power transmission via laser.
- Results of European work was then peer reviewed first at the ESA-organised SPS conference in Granada and then during a Japanese Peer review process led by Prof. Kaya.



European SPS Programme Plan

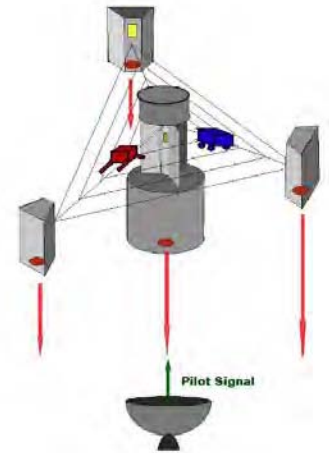
Early identification within the Advanced Concepts Team in 2002

- General *validation phase*
 - Comparison of space and terrestrial solar power plants as key element for the general validation of space solar power
- **Opening of the SPS research activities**
 - ESA's Advanced Concepts Team studies into SPS system
 - Collaboration with universities / Experiments
- *Integration* into the larger energy community
 - SPS Workshops



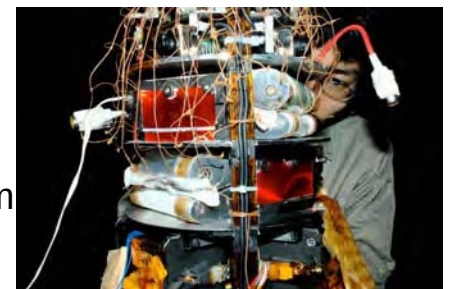
Furoshiki 1

The ACT contributed together with the robotics lab of the Vienna university of technology to a JAXA sounding rocket experiment, demonstrating the deployment and stabilisation of a large net in microgravity conditions with small satellites (Univ. of Tokyo) and wireless power transmission technology - retrodirective antenna (Univ. of Kobe).



European contribution:

- After the deployment of a 130 m² net by three daughter satellites detached from the mother section, two tiny robots, RobySpace Junior 1 and 2 got their signal to detach from and leave their launch configuration box in the mother satellite and tried to crawl on the free floating net in a controlled manner each towards one daughter section.
- The net deployed perfectly, the retrodirective antenna system worked and at least one of the two robots has left his garage and crawled on the free floating net.



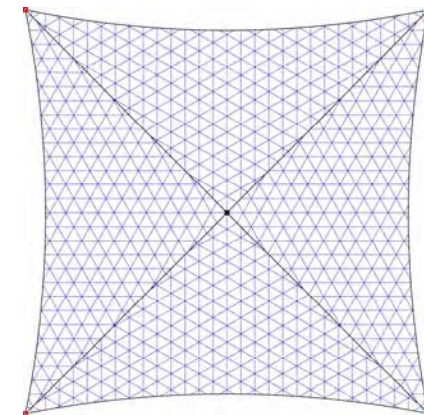


Post Furoshiki 1

- The ACT undertook two collaborative studies with KTH Stockholm and the University of Glasgow on varying topics based on large scale space webs.
- KTH examined the deployment of a large web in space
- Univ. of Glasgow studied the stability of a large web while robots moved on the web surface
- Investigation of two dynamical phenomena related to centrifugally deployed space webs
- Swarm assemble studies
- Power transmission systems
- System architecture research



RobySpace



Deployment of a large web

Conclusions



- Solar power is likely to play an increasing important role in the world's future energy mix.
- Many solar power plants have been constructed in southern Europe and plans to develop very large scale plants have recently been announced together with substantial political support (Desertec).
- ESA has currently no concrete plan for a larger SPS program, but the concept is considered important to develop the key enabling technologies to higher technology maturity.
- The Advanced Concepts Team works on a research level for the maturation of concept and key technology related to SPS
- Continued integration into the larger energy community:
IAA study group, URSI white paper SPS workshops.
- Hopeful of continued close and mutually beneficial cooperation.





ACT Power Systems

European Space Agency

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Energy Systems

Ongoing Projects

Wireless Power Transmission for space applications

This sites contains basic information on activities within the Advanced Concepts Team on concepts related to solar power from space, an advanced and innovative way to tackle the issue of sustainable energy supply.

[Back to "Ongoing Projects"](#)

What are Solar Power Satellites?

Solar Power Satellites (SPS) are fairly large structures in space that convert solar energy, captured as solar irradiation, into an energy form that can be transmitted wirelessly (Wireless Power Transmission - WPT) to any remote location with a receiver station, either on Earth, to high altitude platforms, to other spacecraft or even to surfaces of the moon or other planets. This idea has a long history, for an overview see [this table](#).

Why go into space instead of building them on Earth?

The big advantage of space based solar power collection is the 24h availability: unlike the situation on the surface of Earth, in geostationary orbit there is no night and the sun is never shadowed by clouds, rain or fog. Since we are using energy day and night, the continuous power generation in space makes large and expensive energy storage devices superficial. But the final trade-off depends on many more parameters that are subject of the study started by the Advanced Concepts Team.

How is the power transmitted to Earth?

Currently the so-called reference design transforms solar power into electricity via photovoltaic cells in geostationary orbit around Earth. The power is then transmitted via electromagnetic waves at 2.45 GHz to dedicated receiver stations on Earth, "rectennas", which convert the energy back into electricity used in the local grid.

Currently visiting the ACTweb

Ariadna proposals submission countdown: 0d, 12h, 58m, 56s.

ISTS SBSP Panel Thoughts

Dallas Bienhoff

In-Space & Surface Systems, The Boeing Company

- 1) I will address five key points related to SBSP viability and close with the current Boeing position on SBSP
 - a) SBSP is technically possible – the technology works; electricity can be converted to radio waves or laser beams, transmitted great distances, captured, and converted back to electricity
 - b) SBSP is physically possible – hardware exists for each step; solar cells, laser diodes, klystrons, magnetrons, transmitting antennas, and receiving antennas.
 - c) SBSP is not yet operationally possible – we do not yet have the capability to launch massive quantities to GEO on a regular and frequent schedule; assemble Manhattan-sized space structures with or without people; control large structures to maintain required attitude and flatness; or safely handle megawatts and kilovolts in space.
 - d) Other non technical and non economic hurdles exist, including: environmental concerns related to microwave wireless power transfer; the concerns based on an “it’s a weapon” perspective, especially if WPT is by laser; the “Not In My Back Yard” reaction to large receiving antennas in “my” neighborhood; GEO slot and frequency allocation through the International Telecommunication Union; “landing” rights for the power beam from the FCC or its equivalent; and beam corridor approval from the FAA, or its equivalent.
 - e) SBSP is not yet economically viable at market conditions – hardware cost, transportation cost, assembly time, system performance (kW/kg), and operations cost drive SBSP electricity above the price for current terrestrial sources. However, I submit the economic hurdle may be the easiest to overcome. Any product or service **CAN** have a closed business case.
 - i) For this to happen in the open market the product or service must offer a better value than existing products at a similar price and cost less to produce than its market price;

- ii) Early niche markets may be willing to pay a sufficient premium for the convenience of WPT to cover its cost and provide a profit. Potential customers in this category include the Department of Defense, NASA, remote mining and drilling sites, and remote research sites.
 - iii) Policy or law can also be used to close a business case through direct subsidies to the provider or by directing customers to buy a product or service at a price greater than its cost. In a commodity market, like electricity, the impact to the end user can be limited by setting a maximum increase in the customer's utility bill and use that to define the appropriate combination of SBSP price and percent mix to close the SBSP business case for the provider. As an example, a utility may be directed to purchase up to 5% of its energy from a SBSP company at 10 times the current market price while limiting the consumers' electric bill increase to less than 2%.
 - iv) California, and other states, has already started down this path by requiring utilities to buy up to 20% of their electricity from renewable energy sources by 2010, 30% by 2017, and 33% by 2020. However, I am unaware of any limits on the price utilities must pay for this renewable energy or the allowable impact on the consumers' electricity bill.
- 2) Now, in light of the Solaren and Pacific Gas & Electric announcement in April, I need to caveat my comments. There are at least two companies (one utility and one supplier) that believe Space Based Solar Power can be profitably provided within the current renewable energy market price constraints. We will have to wait until 2016 to see if their belief is justified.
- 3) Current Boeing position with respect to SBSP business area
- a) Boeing is primarily a system and technology developer for customers: airlines, military, NASA, commercial satellite companies.
 - b) Boeing is not, in general, a new industry risk taker or investor
 - c) Boeing is always interested in new market opportunities, especially ones that have the potential for open-ended continuation and growth and ones that increase the market for existing products and their derivatives, such as solar cells, spacecraft, launch vehicles, launch services, orbit transfer systems and/or services, systems engineering, systems integration, etc.

- d) Boeing is assessing SBSP as we do any other opportunity to determine our ability to meet the customer's needs while increasing shareholder value, and the probability that SBSP can and will go forward. Given positive answers to these questions, and others, Boeing would likely become a provider for SBSP systems.

New Basic Plan for Space Policy

Nobuyuki Kaya

Kobe University, Japan

The Japanese Government has recently suggested the new Basic Plan for Space Policy based on the Basic Space Law established in May 2008 and as the Japan's first basic policy relating to space activities. The Basic Space Law aims to solve these existing issues and stipulates that the government formulates Basic Plan for Space Policy. This law aims to powerfully work in a comprehensive and systematic manner to "change space policy from R&D-driven to utilization-driven underpinned by high technological capabilities", to "utilize in the area of national security" beyond the generalized theory while maintaining an exclusively defense-oriented policy in accordance with the principle of pacifism enshrined in the Constitution of Japan, to promote "space diplomacy" and "research and development of the forefront areas" and at the same time to forge "improvement of industrial competitiveness" while aiming to become "environment-friendly".

Especially, the Space Solar Power Program in this basic plan for Space Policy is defined to realize the Solar Power Satellite in the near future. The following sentences are quoted from the new Basic Plan for Space Policy on the Space Solar Power Program. The pamphlet is attached to this paper.

Space Solar Power Program in this basic plan for Space Policy

H. Space Solar Power Program

As a program that corresponds to the following major social needs and goals for the next 10 years, a Space Solar Power Program will be targeted for the promotion of the 5-year development and utilization plan.

1) Social needs and goals for the next 10 years

(a) Resolving the global-level environmental issues (realization of low carbon society)

To respond to the demand of "realization of energy to support the low carbon society", renewable energy power (for example, solar power generation and wind-generated power) has been used on earth, but there are some stability issues, and the utilization of energy to overcome these issues has not been realized in space. In the future, research and development of the technology necessary to realize the solar power generation system in space for clean and stable energy utilization without any geopolitical influences, Japan will

aim to have prospects for practical application within the next 10 years, comparing with the progress of the renewable energy development on earth.

2) 5-year development and utilization plan

To realize the above goals, the following measures will be taken:

- Government will examine the system for the development of space solar power program from a comprehensive point of view in collaboration with related institutions, and also conduct demonstration of technologies for the energy transmission technology in parallel. Based on the result, Government will conduct ample studies, then start technology demonstration project in orbit utilizing "Kibo" or small sized satellites within the next 3 years to confirm the influence in the atmosphere and system check.

Basic Plan for Space Policy



~Wisdom of Japan
Moves Space~

Secretariat of Strategic Headquarters for Space Policy

1-11-28 Akasaka, Minato-Ku, Tokyo, 107-0052

TEL 03-5114-1935 / FAX 03-3505-5971

HP <http://www.kantei.go.jp/jp/singi/utyuu/index.html>

June, 2009

What is the Basic Plan

In view of the situation in which the role of the use and R&D of space has been expanding globally, the Basic Space Law was enacted in May 2008 to cope with challenges to Japan's space policy such as lack of a comprehensive strategy as a whole nation due to the absence of a policy headquarter.

The Basic Plan was decided as the first national comprehensive strategy by the Strategic Headquarters for Space Policy, which was established based on the Basic Space Law and chaired by the Prime Minister.

This Plan is a five-year-program, from FY2009 to FY2013, foreseeing the next ten years, describing the basic policy and the measures which the Government should take during this period.

A Special Committee for Space Policy, whose members are opinion leaders from various fields, chaired by Mr. Jitsuro Terashima, Chairman of Japan Research Institute, was established to make recommendations on the plan. Additionally we have received about 1500 public comments on this matter.

The Government will act comprehensively and systematically regarding this Basic Plan.



Special Committee on Space Policy (Member)

Setsuko Aoki	Professor, Faculty of Policy Management, Keio University
Toshio Asakura	Executive Managing Director, Chairman, Editorial Board, The Yomiuri Shimbun
Ryoko Fujimori	Vice President, NPO Weather Caster Network
Shinichi Kitaoka	Professor, Graduate Schools of Law and Politics, The University of Tokyo
Hideko S. Kunii	Chairperson, RICOH SOFTWARE, Inc
Terunobu Maeda	Chairman, Mizuho Financial Group, Inc.
Hiroshi Matsumoto	President, Kyoto University
Reiji Matsumoto	Manga Artist, President, Young Astronauts Club-Japan Chairman, National Council of Youth Organizations in Japan
Mari Matsunaga	Director, BANDAI Co., Ltd.
Fujio Mitarai	Chairman & CEO, Canon Inc.
Mamoru Mohri	Executive Director, National Museum of Emerging Science and Innovation, Astronaut
Atsuhiko Nishida	Former Director General, Institute of Space and Astronautical Science
Akira Sawaoka	President, Daido University
Etsuhiko Shoyama	Broad Director (Chairman), Board of Directors, Hitachi, Ltd
Jitsuro Terashima	Chairman, Japan Research Institute
Katsuaki Watanabe	President, TOYOTA MOTOR CORPORATION

Activities in the past and challenges in the future of our country

1. Use and R&D of space in Japan

From the beginning of the 20th century, the United States and the former Soviet Union played central roles in advancing the use and R&D of space.

Beginning with the Pencil Rocket created by Professor Hideo Itokawa, University of Tokyo, in 1955, Japan succeeded in launching a satellite in 1970, fourthly in the world, following the Soviet Union, United States and France.

Japan has developed several satellites and rockets, such as “Himawari” and the H-IIA rocket, participated in the International Space Station Program (ISS) and has played a significant part technologically among space advanced countries.



2. Insufficient use of Japan's space technology

However, because we have not made full use of space and have showed insufficient experience with rockets and satellites in Japan, our industrial competitiveness is not highly evaluated, compared with not only the space advanced countries but also late-starting countries such as China and India.

People point out that this is because Japan has concentrated on the R&D of space rather than the use of space.

The Government has decided to promote an appropriate space policy for better quality of life and large contribution to the international community. While keeping the R&D further developed, the Government intends to promote the use of space corresponding to social needs specifically, such as disaster relief, global environmental concerns, preservation and care of territorial land and search for the natural resources, and also take measures to enhance the strength of the space industry.

The Government will also promote further use of space for diplomacy and national security.



Six Basic Pillars

~For “Better Quality of Life” and “Contribution to the international community”~

1. Ensure a Rich, Secure and Safe Life

Our daily life depends on using space more effectively, such as for weather forecasts, telecommunications, a smooth supply of food and energy, car navigation systems and others. The Government will use as much of its potentiality as possible.

2. Contribute to Enhancement of Security

The use of space is extremely important in strengthening information gathering capability. The Government will promote the use of space in the field of national security, while maintaining our exclusively defense-oriented policy, in accordance with the principle of pacifism enshrined in the Constitution of Japan.

3. Promote the Utilization of Space for Diplomacy

The Government will promote using space to contribute to diplomatic efforts, such as providing imagery data to Asian neighbors in the event of disaster and providing necessary information to resolve the global warming and other global environmental concerns.

4. Create an energetic future by promoting R&D of the forefront areas

The Government will create the foundation stone of an energetic future by promoting space science, in which we have achieved world top class results by SELENE “Kaguya” and MUSES-C “Hayabusa”, a lunar exploration, human space activity and a space solar power program.

5. Foster Strategic Industries for the 21st Century

The Government will place the space industry among the strategic industries in the 21st century and enhance industrial competitiveness by promoting making space machinery smaller, serialized, commonized and standardized.

6. Consider the Environment

The Government will take measures considering both the global and the space environment, such as space debris issue.



Systems and Programs for Six Basic Pillars

【5 Systems for utilization】

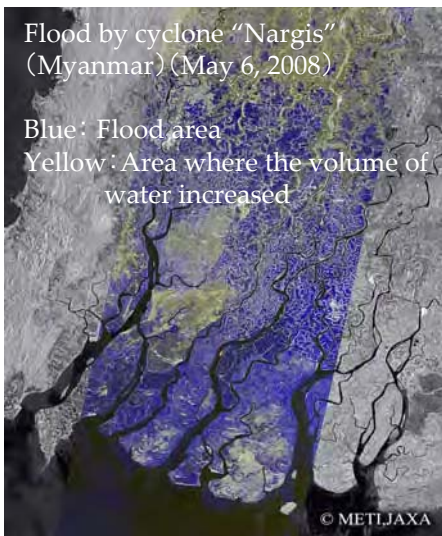
- A. Land and Ocean Observing Satellite System to contribute to Asia and other regions
- B. Global Environmental Change and Weather Observing Satellite System
- C. Advanced telecommunication Satellite System
- D. Positioning Satellite System
- E. Satellite System for National Security

【4 Programs of R&D】

- F. Space Science Program
- G. Human Space Activity Program
- H. Space Solar Power Program
- I. Small Demonstration Satellite Program



A. Land and Ocean Observing Satellite System to contribute to Asia and other regions



This system will enable us to;

- gather information within three hours, regardless of the weather and time of day, in the event of disaster, which is necessary for the efficient and effective disaster relief activities.
- search national resources and energy.
- observe deforestation and monitor World Heritage Sites



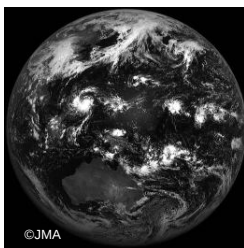
<Long term evaluation of change of the width of forest area (Rondonia, Amazon) >

B. Global Environmental Change and Weather Observing Satellite System

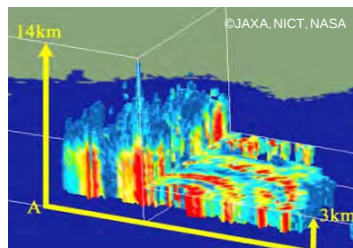
Although we use imagery data from MTSAT "Himawari" and other satellites for weather forecasts in our daily life, it is still insufficient to use them to deal with recent abnormal weather.

This system will enable us to;

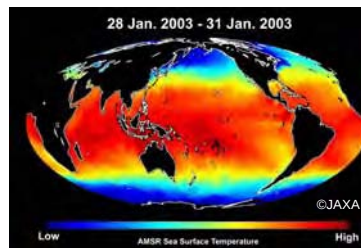
- forecast a very local and torrential downpour.
- forecast long-term weather by observing the sea surface temperature.
- grasp the distribution of greenhouse gases globally.



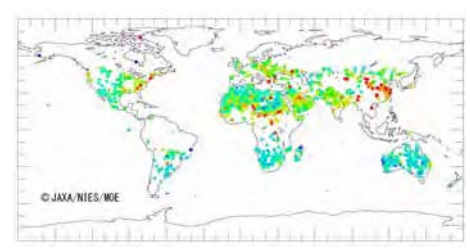
Imagery data of "Himawari"



Three-dimensional situation of rain of hurricane



Temperature of sea surface



Distribution of carbon dioxide

C. Advanced telecommunication Satellite System

The BS and CS are used in our daily life.

Although satellite-based cellular phone services have not spread in Japan so far, compared with usual cellular phone services, it is useful when the ground facilities are down in the event of a disaster.

The cellular phone system, which enables telecommunication both via ground facilities and via the satellites, is under R&D.

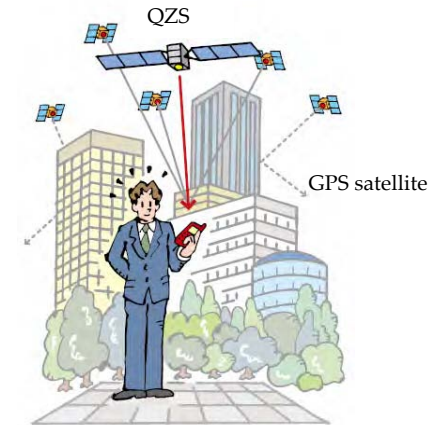
D. Positioning Satellite System

We use positioning satellites, which consist of GPS satellites of the United States, for car navigation systems and other services in our daily life.

The Government will promote highly accurate positioning and create new services such as personal navigation systems by combining our QZS and GPS.

The Quasi-Zenith Satellite (QZS)

This satellite enables highly accurate positioning service even in mountain districts and in city parts with building shadow, which will be always located at almost the zenith.



E. Satellite System for National Security

Chief example of the use of space for our national security purposes would be the Information Gathering Satellites introduced after the “Taepo-dong” missile launch by North Korea in 1998. However, the use of space in the area of national security has been limited compared with international standards.

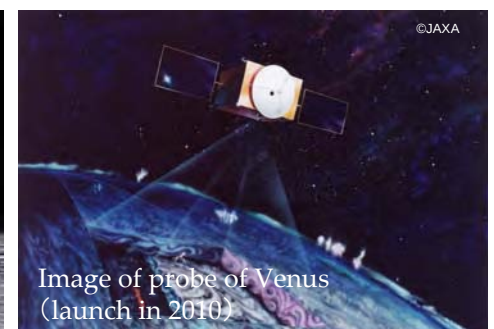
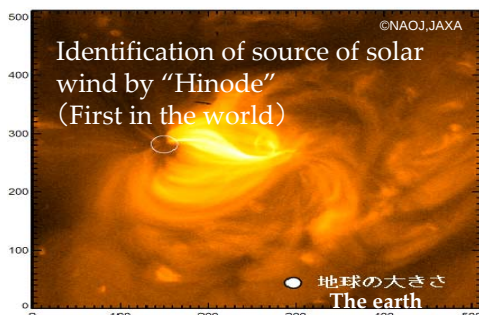
The Government will strengthen the information gathering capability and promote research in the field of early warning and signal information gathering, while maintaining our exclusively defense-oriented policy, in accordance with principle of pacifism enshrined in the Constitution of Japan.

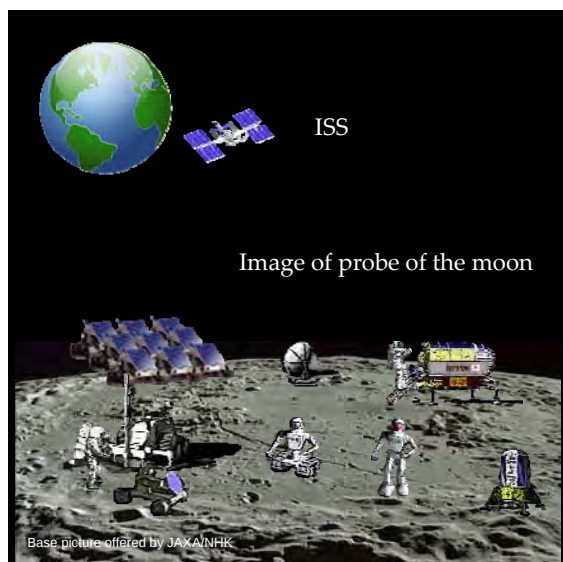
F. Space Science Program

We have achieved world top class results in the space science field, such as in space astronomy and solar system exploration.

(Landing of the MUSES-C “Hayabusa” on the Asteroid “Itokawa”, Identification of the source of solar wind by SOLAR-B “Hinode”, and so on)

The Government will continue to achieve world-leading scientific results, such as probes of Venus and Mercury, and the astronomical observations by X rays, and strengthen the cooperation with fields other than space science.





G. Human Space Activity Program

Japan has participated in the International Space Station Program (ISS) cooperating with the U.S., Canada, Russia and European countries, and has strived to accumulate fundamental technology.

Japan has contributed and will contribute to ISS by the Japanese Experiment Module “Kibo” and H-II Transfer Vehicle (HTV). The experiment of Kibo is expected to provide valuable results in such areas as medicine, which we cannot get on the ground.

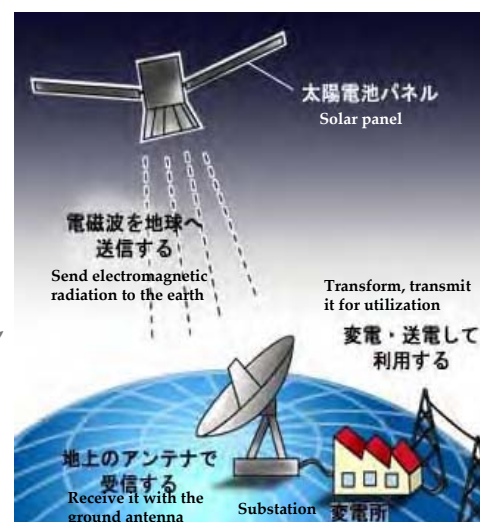
The Government is examining moon exploration with robots, aiming to achieve it around 2020, considering a manned exploration later.

H. Space Solar Power Program

This program will enable the new system to gather solar power in space and to transfer it to the ground for our use.

Although solar power generation in space has advantages in that it will not be influenced by the weather nor time of day, we have to consider its economy compared with generation on the ground, technological feasibility and safety.

Taking those into consideration, the Government will demonstrate it on the orbit with an actual satellite, such as a small-size satellite.



I. Small Demonstration Satellite Program



The space industry is a very important foundation stone to promote the use and R&D of space.

To enhance space industry, we have to expand skirts of the space utilization industry. The government will promote such new entry to this field as the medium and small-sized enterprises in Higashi-Osaka produced a ultra-small size satellite SOHLA-1 “Maido 1”.

The government will promote demonstration of new technology in space using small-size satellites, and will support the medium and small-sized enterprises and universities.

【Invest for the next generation】

The government will promote both training of engineers and researchers, and educating children and measures for public relations.



R&D Plan of satellites (outline of the attachment 2 of Basic Plan)

FY	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
A. Land and Ocean Observing Satellite System to contribute to Asia and other regions	ALOS "Daichi" (optical·radar)				ALOS2 (radar)			Series of ALOS, Series of ASNARO, 2-4 satellites for each continuously (total 4-8 satellites)		
	Terra(U.S.): sensor ASTER					ALOS3 (optical)				
			ASNARO (tentative name, optical)				ASNARO (tentative name, radar)			
	DRTS "Kodama" (Data relay)				Data Relay Satellite : 1-2 continuously					
B. Global Environmental Change and Weather Observing Satellite System	Aqua(U.S.): sensor AMSR-E		GCOM-W (precipitation)			GCOM-C (cloud, aerosol)		GCOM-W, GCOM-C, GOSAT 1 satellite for each continuously		
	GOSAT "Ibuki" (greenhouse gases)									
	TRMM(U.S.): sensor PR				GPM(U.S.): sensor DPR					
					EarthCARE(Europe): sensor CPR					
	Himawari6 (standby)	(standby)								
	(standby)	MTSAT "Himawari7"					(standby)			
						Himawari8				
C. Advanced telecommunication Satellite System	ETS-VIII "Kiku8"									
	WINDS "Kizuna"				1 satellite as for demonstration of next generation telecommunication					
D. Positioning Satellite System			Quasi-Zenith Satellite 1							
				Additionally 2-6 satellites more						
E. Satellite System for National Security	IGS(Optical1)									
	IGS(Optical2)									
	IGS(Optical3)									
			IGS(Optical4)				IGS(Optical5)			
	IGS(Radar2)							IGS(Optical)		
			IGS(Radar3)							
				IGS(Radar4)						
F. Space Science Program	Certification				Certification					
	MUSES-C "Hayabusa"									
	SOLAR-B "Hinode"									
			Planet-C(Venus)							
G. Human Space Activity Program	Utilization of "Kibo", one HTV every year									
	Planning for one year									
			Moon exploration							
H. Space Solar Power Program										
I. Small Demonstration Satellite Program	SERVIS-2									
		SDS-2								
Other satellites (commercial, other governmental)										
			Kompsat-3 ST-2							

※ Necessary fund is estimated to be JPY2,500B for the utilization, R&D of all satellites above, which should be shared by government and private sector.