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THE INTERNATIONAL SPECTRUM MANAGEMENT PROCESS AND SELECTED TECHNICAL BACKGROUND FOR SPACE SOLAR POWER

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ABSTRACT

The concept of space solar power (SSP) embodies a wide variety of technical challenges--as well as tremendous opportunities. This paper will provide background on the topic of international spectrum management, as well as technical background on the general topic of SSP, with special emphasis on the various conceptual issues, technologies and systems associated with wireless power transmission (WPT). Other technology areas that will be briefly characterized in terms of their relationship to spectrum management and WPT include: solar power generation; power management and distribution; structural concepts, materials and controls; in-space transportation; space assembly, inspection and maintenance; and others.

A number of broad issues will be addressed, including health and safety factors; environmental considerations (both terrestrial and in space environments); and general consideration of scenarios under which SSP applications might be realized. The paper will conclude with a summary of the major topics associated with the application of wireless power transmission and the international spectrum management process.

INTRODUCTION

The concept of space solar power (SSP) embodies a wide variety of technical challenges--as well as tremendous opportunities. This paper will provide background on the topic of international spectrum management, as well as technical background on the general topic of SSP, with special emphasis on the various conceptual issues, technologies and systems associated with wireless power transmission (WPT). Other technology areas that will be briefly characterized in terms of their relationship to spectrum management and WPT include: solar power generation; power management and distribution; structural concepts, materials and controls; in-space transportation; space assembly, inspection and maintenance; and others.

A number of broad issues will be addressed, including health and safety factors; environmental considerations (both terrestrial and in space environments); and general consideration of scenarios under which SSP applications might be realized. The paper will conclude with a summary of the major topics associated with the application of wireless power transmission and the international spectrum management process.

BACKGROUND

The emergence of effective and widely-varied use of the electromagnetic (EM) spectrum is one of the hallmarks of the 20th century. Because of the physics of EM wave generation, propagation and reception, it is impossible to envision large-scale use of the spectrum without risking potential interference with its use by others. This fact became abundantly clear with the development following the 1950s of Earth-orbiting satellites and globe-spanning satellite-based telecommunications systems. **Figure 1** provides a summary perspective into electromagnetic (EM) spectrum definitions, allocations and physical limitations associated with EM propagation from space to the Earth.

SPACE SOLAR POWER FOR TERRESTRIAL MARKETS

There is a real and growing need for new large-scale, base load power generation options during the 21st century. Space solar power satellites (SPS) are one such option. First invented in 1968 by Dr. Peter Glaser, of Arthur D. Little, the concept is elegant: solar power, generated in space, can be "transported" using a microwave beam (or other electromagnetic (EM) beam) to a receiving antenna on the ground. **Figures 2 and 3** illustrate the primary elements of a large-scale space solar power satellite delivering power to a terrestrial market grid. Figure 2 illustrates a recently-developed concept, the Integrated Symmetrical Concentrator (ISC) in geostationary Earth orbit (GEO), with a smaller supply vehicle in the foreground. Figure 3 illustrates one concept for a large rectifying antenna (a "rectenna")

Unlike ground-based solar power options, SPS can generate energy almost continuously—thus avoiding the very costly requirement to provide massive energy storage systems which limits the application of these systems in providing base load power at present. However, there are significant technological and infrastructure-related challenges that must be better understood and overcome if SPS are ever to be realized.

The concept of the SPS was studied in some detail by the US Department of Energy (DOE) and the national Aeronautics and Space Administration (NASA) in the late 1970s. However, needed technologies to achieve technical and economic viability were too far from realization for work to continue at that time. Also, the market for global energy (including an understanding of greenhouse gases and their effects on climate) did not then warrant the development of major new base load power options.

More recently, global demand for energy has soared at the same time that scientific studies of climate change effects have yielded significant concerns about the long-term effects of fossil fuel-based power generation. At the same time, a wide range of potential space applications of SSP technologies and systems has emerged—providing increasing non-terrestrial market justification investments in these important areas.

As a result, in the past several years, SSP and SPS have received renewed attention. A number of major studies have been conducted in several countries, including the "SSP Fresh Look Study" (1995-1997) and the "SSP Exploratory Research and Technology (SERT) Program" in the US. One key result from these efforts has been the emergence of a variety of technological options for one of the essential functions of an SPS: wireless power transmission (WPT). 1970s technology options were limited largely to electron tube devices (e.g., Klystrons, Magnetrons, etc.) and radio frequencies (RF) in vicinity of 2.45 GHz. By the 1990s, a much wider range of technologies had become available, including earlier approaches as well as solid state devices for RF beam generation and new, solid state options for visible light solutions (i.e., lasers). However, each of these solutions has significant impacts on overall system design, as well as on overall international planning for spectrum utilization. As a result, a careful consideration of the questions of WPT and spectrum management are needed.

THE INTERNATIONAL SPECTRUM MANAGEMENT PROCESS

The International Telecommunication Union (ITU) was originally formed as the "International Telegraph Union" in 1865 at Paris, France. However, the rapid development of electromagnetic (EM) wave theory and technology in the late 19th century led to the rapid emergence of radio frequency (RF) applications. By 1906, the first International Radio Conference was held in Berlin, Germany, to promote international coordination of these applications. This conference produced the first "Convention and Radio Regulations", and was followed in subsequent years by the creation of several separate international committees to promote spectrum coordination. By 1932, these international conferences changed the name of the older umbrella organization to the "International Telecommunications Union (ITU) and forged the first single ITU convention.

Following World War II, there was an immediate need to substantially revise and strengthen pre-war mechanisms for international cooperation and coordination; spectrum management was no exception. During the 1940s and 1950s, a series of "Plenipotentiary Conferences" authorized by individual governments as well as technical specialist radio conferences were held. During this period the seat of the Union was transferred to Geneva, Switzerland (1948), and earlier committees were merged into a new, more integrated structure. By 1992, the modern ITU had emerged, governed by a new convention and constitution and possessing the basic structure that continues at present. The Union today comprises some 187 countries, and is governed by four implementing documents: (1) the Constitution and Convention (renewed every 4 years), (2) Radio Regulations, (3) Telegraph Regulations, and (4) Telephone Regulations. As a technical organization, the ITU concerns itself with the use of the EM spectrum below 3000 GHz (i.e., the RF portion of the electromagnetic spectrum—see Figure 1).

International Spectrum Management Structure

The ITU is recognized by participating nations as the sole Agency for formulation and coordination of international telecommunications regulations and policy. **Figure 4** sketches the overall organizational structure for international spectrum management efforts. The structure of the ITU comprises three main sectors: Radio Communication, Telecommunication Standardization, and Telecommunication Development. In addition, the ITU is headed by an international "Pleni-potentiary Conference," which meets every four years to set the operational framework for the Union.

Between those meetings, the forty-three members of the ITU Administrative Council (elected by the Plenipotentiary Conference), act on their behalf. The Council manages the resources of the ITU and establishes agendas and dates for ITU conferences. However, the technical work of the ITU is conducted primarily through the three sectors (mentioned above), the Directors of which are also elected by the Plenipotentiary Conference.

Periodically, the members of the ITU meet as a body in a World Radiocommunications Conference (WRC). These conferences are a major focus of ongoing ITU and related national EM spectrum management activities (see below).

Spectrum Management Process

The process of spectrum management is very much national as well as international. The use and management of the EM spectrum affects an enormous aspects of modern civilization, ranging from global communications, to national security, to industrial competitiveness and innovation. Because of the breadth of these interrelationships, the international management of spectrum is conducted through a sometimes ponderous series of national entities and organizations—in addition to the global superstructure of the ITU. **Figure 5** summarizes as an example the U.S. processes and interfaces that feed into international spectrum management efforts.

Several activities are of particular importance. One of these is the Interdepartmental Radio Advisory Committee (IRAC), which advises the US National Telecommunications and Information Administration (NTIA) on telecommunications policy, technical and other matters affecting the Federal agencies. It comprises representatives from several dozen Federal agencies, as well as observers from still others.

Radio Communication Study Groups

Other primary ITU elements of importance in consideration of WPT in the context of overall spectrum management are the several Radio Communication Study Groups of the ITU. There are eight such groups:

- Study Group 1- Spectrum Management Techniques
- Study Group 4 - Fixed satellite service
- Study Group 5 - radiowave propagation in non-ionized media
- Study Group 6 - radiowave propagation in ionized media
- Study Group 7 - Science services
- Study Group 8 - Mobile radiodetermination and amateur services
- Study Group 9 - fixed service
- Study Group 10/11 - Broadcasting services (sound and television)

Of these, Study Group 1 (Spectrum Management Techniques) has particular responsibility.

FACTORS AFFECTING SPACE SOLAR POWER SATELLITES

As mentioned in the introduction, there is an increasing global need for renewable energy resources. Power transmitted from space is one such option—albeit a highly technically challenging one. The technology for WPT has been and is being developed to transfer power efficiently from one location to another via radio frequency beam. However, no frequency bands have been specifically designated for this purpose, nor has a service definition been provided. Also, critical radio-communication services may operate or be planned to operate in bands useful for WPT; and the use of power beaming may have a significant impact on the operation of radio-communications systems.

As a result of the physics of EM beam propagation, there is a complex family of interrelations that links intimately decisions concerning one element of SPS design (and technology) and many others. Key factors include:

- Wireless Power Transmission (WPT) frequency;
- Operational Orbit (and hence the distance over which the beam will be transmitted)
- Transmitter Diameter, Receiver Diameter (and desired beam transmission efficiency); and,
- Power Level (to be transmitted and received, and related market demand factors)

Figure 6 summarizes this family of interrelationships by which spectrum issues affect and are affected by other SSPS system and subsystem technology choices.

The eventual economic viability (or non-viability) of power from space will depend directly on the efficiency with which the WPT function can be performed. Hence, factors associated with power beaming are critical. However, the most suitable RF band for use in WPT will always be a function of the application in question. For the most part, consideration has been restricted to frequencies that are allocated as ISM (Industrial-Scientific-Medical) RF bands, however most frequencies above 2.45 GHz which coincide with regions of low atmospheric absorption are of potential interest for WPT. Examples include:

- 2.45 GHz
- 5.8 GHz
- 35 GHz
- 94 GHz
- 245 GHz
- Visible and Near-Visible Light (e.g., laser-generated)

Note that the preceding list represents a set of examples only. The actual choice of frequency is also tied to the overall RF system approach being considered; for example the choice between solid state devices and electron tube devices (e.g., magnetrons) is crucial.

In addition to spectrum management considerations, environmental effects and safety factors must also be well understood as WPT options are explored. **Figure 7** illustrates the general character of an RF wireless power transmission from an SSP systems at the ground, and indicates some of the issues associated with the transmission.

CONCLUSIONS

This paper has attempted to summarize the history and current practice of international electromagnetic spectrum management, and to highlight the ways in which EM spectrum decisions must play a critical role in the possible design and development of future space solar power satellites delivering power into terrestrial markets. These issues also come into play in the consideration of prospective sub-scale demonstrations of these technologies—as well as in the potential application of SSP and WPT technologies in nearer-term space applications.

In past discussions of WPT within the SSP and SPS community, some have argued for visible wavelengths versus microwave wavelengths based on the "open playing field" of the former over the latter—i.e., ITU regulation of EM spectrum ends at 3000 GHz. However, there have been discussions (e.g., at the WRC-2000 at Istanbul, Turkey) concerning the possible extension of the ITU regulatory regime to include all electromagnetic wavelengths. These discussions—stimulated by concerns of astronomy in the submillimeter to far-IR range above 3 THz—have arisen due to the potential application of higher frequencies for satellite-to-satellite links. This development illustrates the need for WPT technologists and advocates to be well aware and coordinated with ongoing ITU activities—including the upcoming Plenipotentiary Conference (to be held in 2002 at Marrakesh, Morroco) and WRC-2003 (venue still to be chosen).

GLOSSARY OF ACRONYMS

EELV	Evolved Expendable Launch Vehicle
EM	Electromagnetic
FCC	(US) Federal Communications Commission
GEO	Geostationary Earth Orbit
GHz	Gigahertz
IRAC	Interdepartment Radio Advisory Committee
ITU	International Telecommunication Union
kg	kilograms
kW	kilowatts
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LCC	Life Cycle Cost
LOX	Liquid Oxygen
MW	Megawatts
NASA	National Aeronautics and Space Administration
NTIA	(US) National Telecommunications Information Agency
PV	Photovoltaic
RF	Radio Frequency
RFI	Radio Frequency Interference
s	seconds
SPS	Solar Power Satellite
SSP	Space Solar Power
THz	Terahertz
W	Watts
WPT	Wireless Power Transmission
WRC	World Radiocommunications Conference

SELECTED BIBLIOGRAPHY

(US) Department of Commerce, "The US and the ITU in a Changing World," OT Special Publication 75-6 (US Chamber of Commerce, Office of Telecommunications; Washington, D.C.). December 1975.

Feingold, Harvey, et al, "Space Solar Power — A Fresh Look at the Feasibility of Generating Solar Power in Space for Use on Earth" (SAIC). April 2, 1997.

National Aeronautics and Space Administration, "Structure of the International Telecommunication Union", Viewgraph Presentation (Washington, D.C.). August 1997.

National Aeronautics and Space Administration, "Interfaces: National and International in Radio Frequency Spectrum Management", Viewgraph Presentation (Washington, D.C.). August 1997.

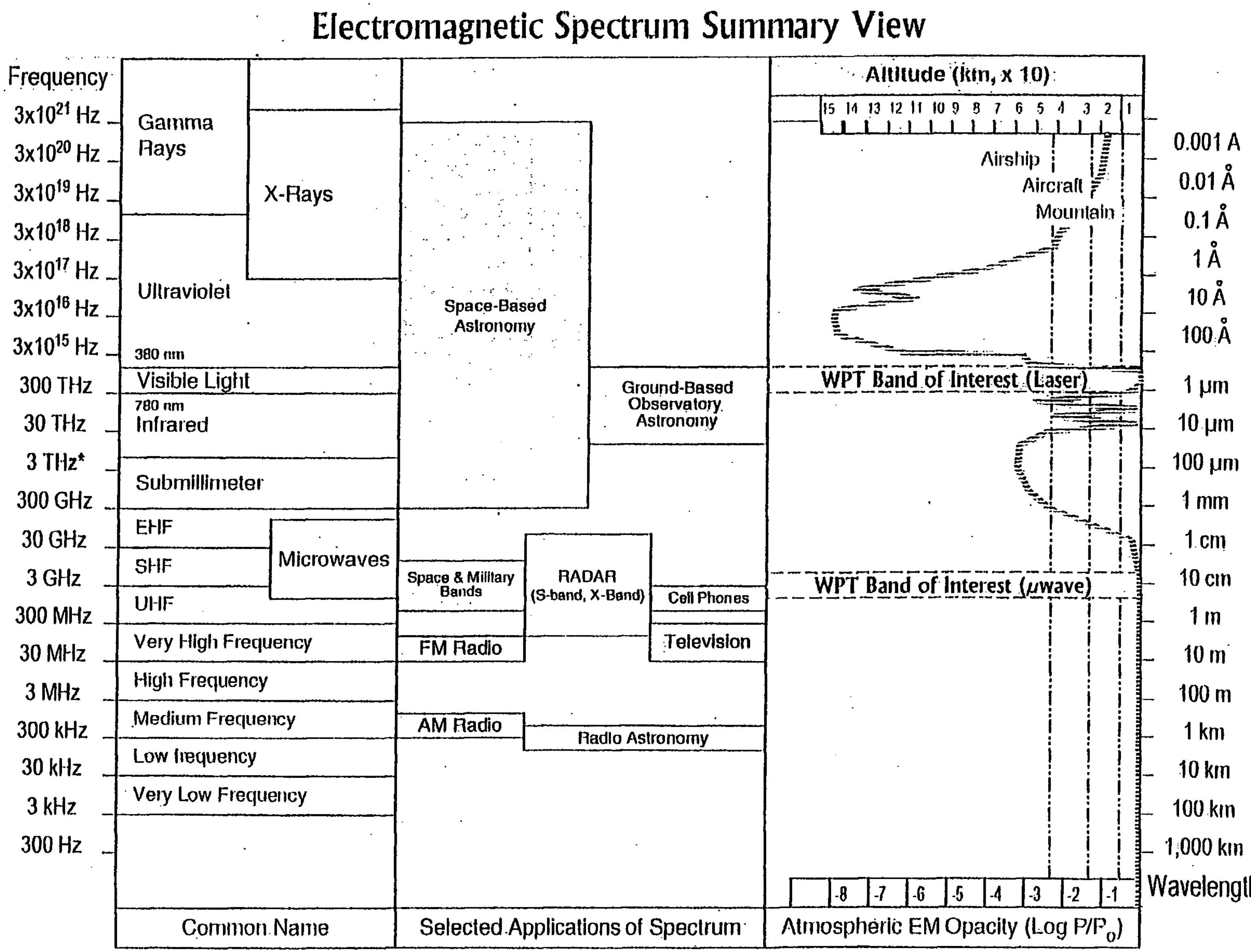

Figure 1 Summary overview of the electromagnetic (EM) spectrum and allocations
(*Note: 3 THz (3000 GHz) is the current upper limit of the ITU Regulatory Regime)

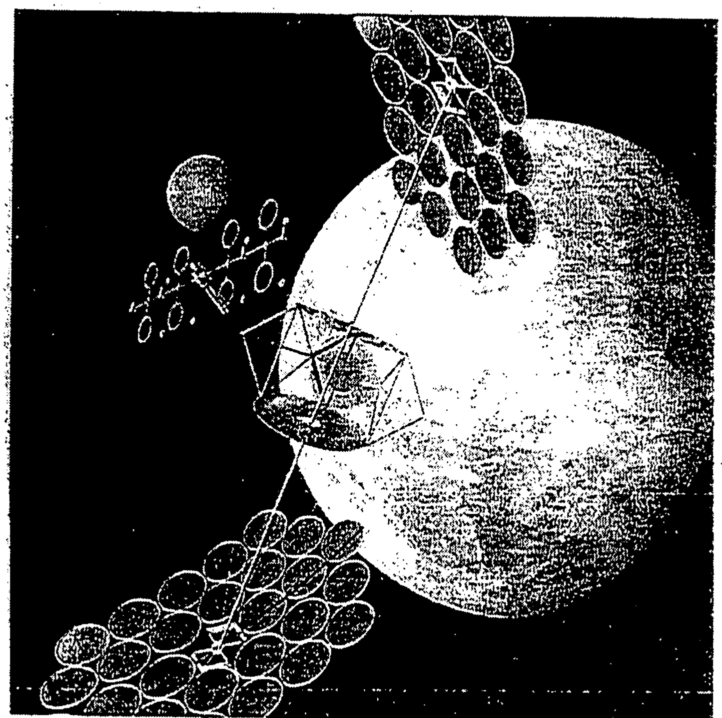

Figure 2 Illustration of a recently solar power satellite (SPS) concept—the Integrated Symmetrical Concentrator (ISC) concept—operating in geostationary Earth orbit

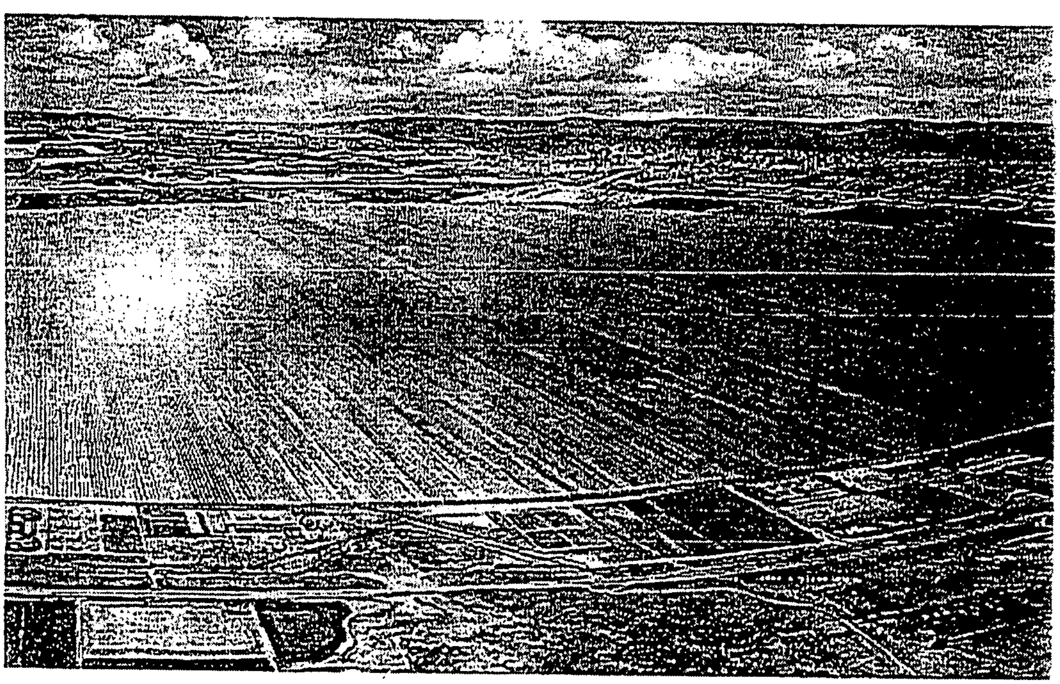

Figure 3 Depiction of a large SPS wireless power transmission receiving antenna (where the beam is transmitted at microwave RF frequencies)

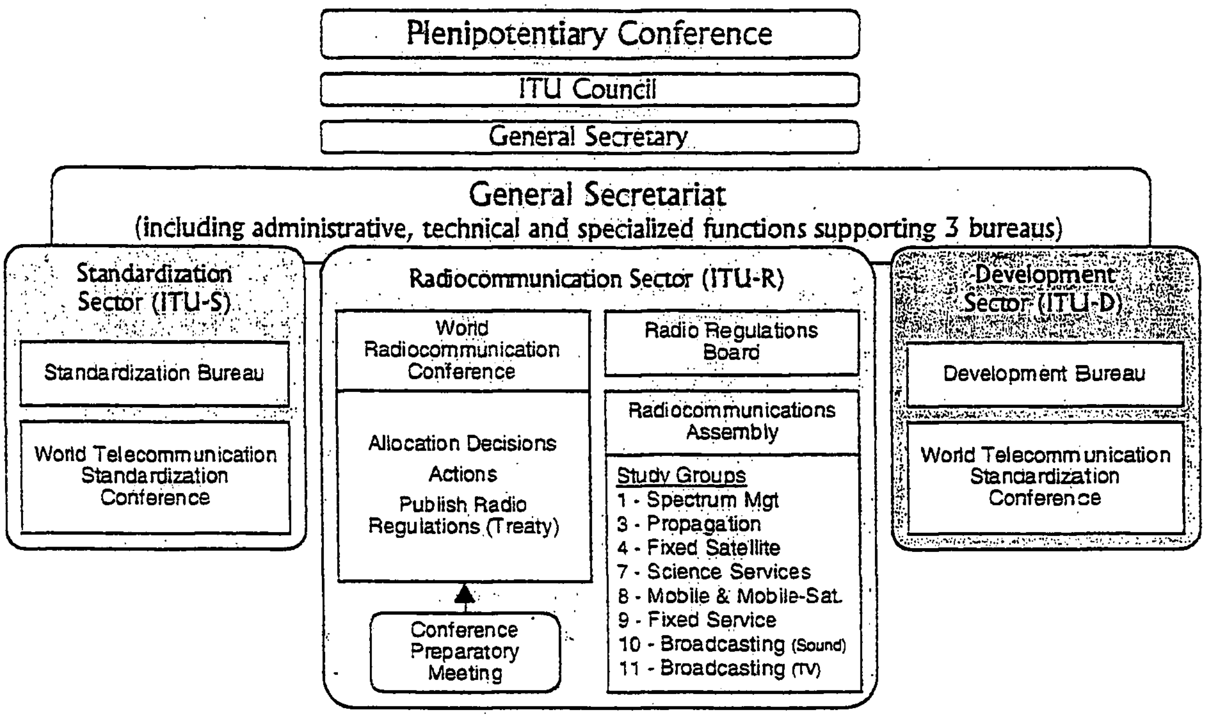

Figure 4 International Telecommunication Union (ITU) — Structure 1993

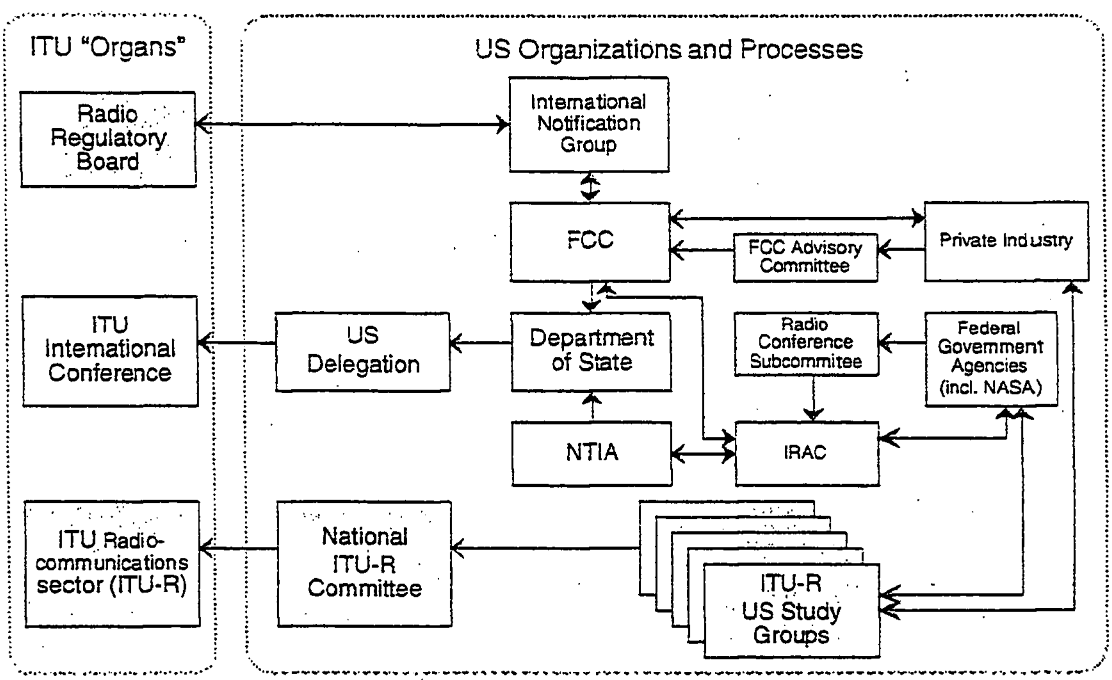

Figure 5 US Example: National interfaces and process to the international management of the electromagnetic spectrum

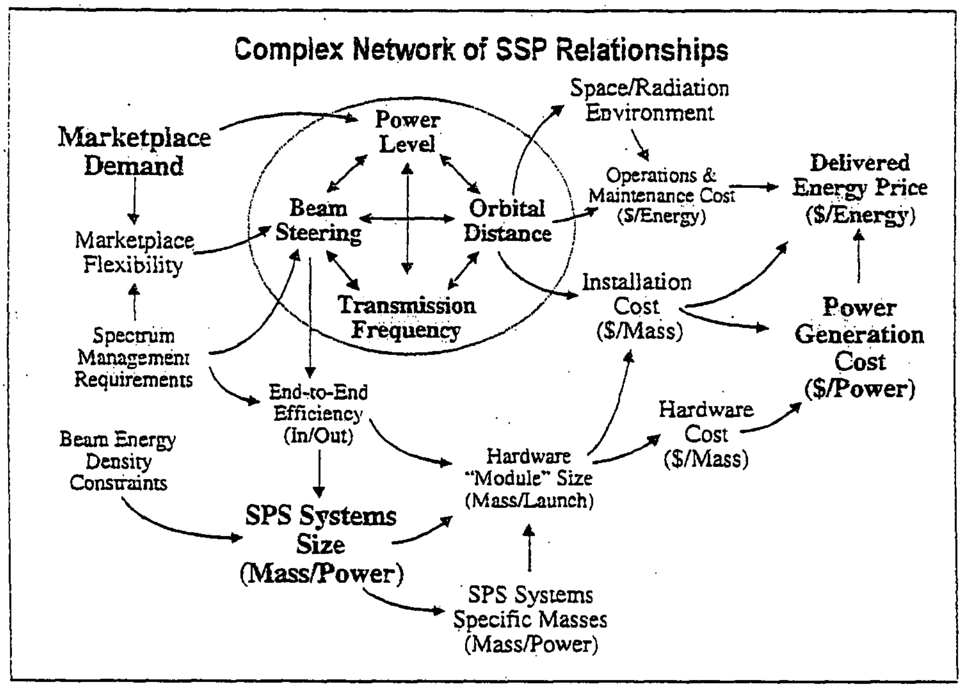

Figure 6 Complex network of relationships connecting SSPS technologies and systems back to questions of spectrum choices and management

- Wireless power transmission from a solar power satellite would typically involved a high power (but moderate power flux density) beam at the ground-based receiver, For SSP, power densities would vary greatly across an incoming beam; for example:
  - A 2.45 GHz, 5 GW beam would have power densities
    - Beam Center ~ 230 W/m2
    - Rectenna edge ~10 W/m2
    - Fence edge ~ 1 W/m2
  - A 5.8 GHz, 1.2 GW beam would have power densities
    - Beam Center ~ 100 W/m2
    - Rectenna edge ~1 W/m2
    - Fence edge << 1 W/m2
- US Standard Limit for microwave exposure
  - ≤ 100 W/m2
  - ≤ 6 minutes
- There is a continuing concern regarding the health & safety issues associated EM radiation
  - These must be treated seriously
  - At µwave frequencies, the only known physical effect on living tissue is thermal heating

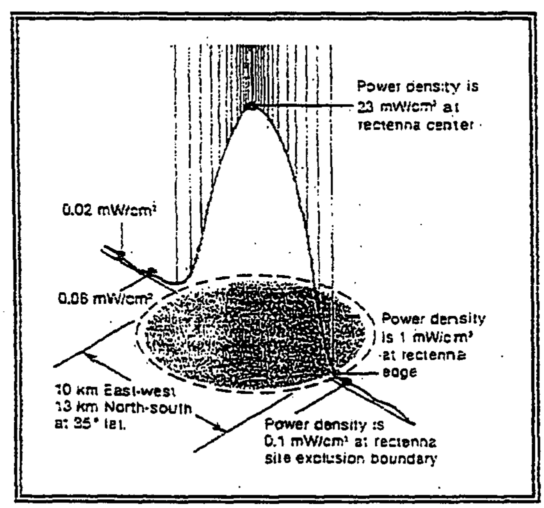

Figure 7 General characteristics and issues associated with wireless power transmission from a solar power satellite