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URSI White Paper on Solar Power Satellite (SPS) Systems

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PREFACE

URSI (International Union of Radio Science) White Papers are documents issued by URSI scientific experts on controversial subjects involving aspects of Radio Sciences. They may be proposed to the URSI Board of Officers by an URSI Member Committee, an URSI Commission, an URSI Standing Committee, an URSI Working Group, or in response to a request to URSI by another body.

Where the issuance of a White Paper is determined to be necessary, the appropriate mechanism for preparing it is agreed to between the URSI Secretariat and the URSI Board of Officers. Once a draft URSI White Paper has been prepared, the URSI Secretariat forwards this to the members of the Board of Officers and to the URSI Member Committees and Commissions for review. All comments received by the URSI Secretariat are then either incorporated directly into the White Paper, if appropriate, or forwarded to the author(s) for consideration. The URSI Secretariat acts as a liaison throughout this process. The final version of the URSI White Paper is then sent to the members of the URSI Board of Officers for approval. Finally, the White Paper is distributed to ICSU, appropriate scientific unions and bodies, and is published in the *Radio Science Bulletin*.

The White Paper is the responsibility of URSI. However, it does not necessarily reflect all the views of individual URSI Member Committees nor Commissions.

1. Executive Summary

As a consequence of an ever-increasing world-wide energy demand and of a need for a “clean” energy source, the Solar Power Satellite (SPS) concept has been explored by scientists and engineers in the United States, Japan, and Europe. Several candidate systems have been proposed but so far neither constructed nor tested in space

In a typical SPS system, solar energy is collected in space by a satellite in a geostationary orbit. The solar energy is converted to direct current by solar cells, and the direct current is in turn used to power microwave generators in the gigahertz frequency (microwave) range. The generators feed a highly directive satellite-borne antenna, which beams the energy to the Earth. On the ground, a rectifying antenna (rectenna) converts the microwave energy from the satellite to direct current, which, after suitable processing, is fed to the terrestrial power grid. A typical SPS unit - with a solar panel area of about 10 km², a transmitting antenna of about 2 km in diameter, and a rectenna about 4 km in diameter - may yield an electric power of about 1 GW. Two critical aspects that have motivated research into SPS systems are the lack of attenuation of the solar flux by the Earth’s atmosphere and the twenty-four-hour availability of the energy, except around midnight during the equinox periods.

Among the key technologies involved in the SPS are microwave generation and transmission techniques, wave propagation, antennas, and measurement and calibration techniques. These radio science issues fall within the scientific domain of the International Union of Radio Science (URSI). URSI's ten Scientific Commissions (Appendix) cover a broad range of aspects involved in an SPS system, ranging from the technical aspects of microwave power generation and transmission to the effects on humans and the potential interference with communications, remote sensing, and radio-astronomy observations.

This has led URSI to organise an open forum for the debate of radio-science aspects of SPS systems and related technical and environmental issues. The present white paper is intended to draw attention to these aspects of SPS systems. It is not URSI's intention to advocate solar power satellites as a solution to the world's increasing energy demands or to dwell on areas outside of its scientific domain, such as the whole issue of space engineering to launch, assemble, and maintain an SPS system in space, the economic justification, and public acceptance. URSI is well aware that, if a practical SPS system is feasible, the realisation of such a system is far in the future. Many of the required technologies currently exist, but some of these must be substantially advanced and other must be created.

Microwave power transmission is an important technology for SPS systems, since its overall efficiency is one of the critical factors that determines the feasibility of such systems. Ideally, almost all energy transmitted from the geostationary orbit should be collected by the rectifying antennas on the ground. In that respect, an overall dc-to-microwave-to-dc power efficiency in excess of 50% is needed (see section 2.4), which requires the development of suitable microwave power devices, accurate control of the antenna beam is essential, and measurement and calibration are important issues. Even if these technologies can be successfully developed, there remains the challenging task of combining the outputs of thousands or even millions of elements to form a focused beam. Proper safety measures have to be developed to be certain that the transmitted microwave beam remains within the rectenna's area. Maintenance of the space systems may be very difficult and expensive in the harsh environment of a geostationary orbit. Ensuring long-term stability of huge structures in space in the presence of solar radiation pressure and tidal forces is an unsolved problem.

The influence and effects of electromagnetic emissions from an SPS, and, in particular, the microwave power transmission, are radio-science issues that concern URSI. Atmospheric effects on the microwave beam, and linear and non-linear interactions of the microwave beam with the atmosphere, ionosphere, and space plasmas are among the numerous issues that must be investigated and evaluated. Undesired emissions, such as harmonics, grating lobes, and sidelobes from transmitting antennas and rectennas, must be sufficiently suppressed not only to avoid wasting power but also to avoid interference with other radio services and applications and with remote sensing and radio astronomy, in accordance with the provisions of the Radio Regulations of the International Telecommunication Union (ITU). The evaluation of possible effects on

human health and incorporation of appropriate safety measures are essential for legal operation and public acceptance of this power-generation technique.

Finally, the paper identifies specific radio-science issues requiring further studies. It is stressed that only some of these questions can be solved by laboratory work, simulations, and system analysis. Testing of elements of such large systems in space is mandatory before a possible demonstration SPS unit can be considered and broad international consensus is likely to be required before an SPS demonstration system can be launched.

2. Solar Power Satellite Systems

2.1 SPS Concept

A solar power satellite is a very large-area satellite in an appropriate orbit (see section 2.6), which would function as an electric power plant in space. The satellite would consist of three main parts: a solar energy collector, to convert solar energy into dc electric power; a dc-to-microwave converter; and a large antenna array to beam the microwave power to the ground. For the production of 1 GW of dc power the solar collector would need to have an area of 10 km², and would consist of either photovoltaic cells or solar thermal turbines. The dc-to-microwave converter could be realised as either a microwave tube system or as a semiconductor system, or as a combination of both. For transmitting the power to the ground, frequency bands around 5.8 or 2.45 GHz have been proposed, which are within the microwave radio windows of the atmosphere. The antenna array to transmit the energy to the ground would require a diameter of about 2 km at 2.45 GHz, and its beam direction would have to be controlled to an accuracy of significantly better than 300 m, corresponding to 0.0005 degree, or less than 2 arc seconds (for a geostationary orbit of the satellite).

In addition to the SPS orbiter, a ground-based power receiving site has to be constructed, consisting of a device to receive and rectify the microwave power beam, i.e. converting it back to dc electric power. This device is called a rectenna (rectifying antenna). The dimensions of the rectenna site on the ground depend on the microwave frequency and the size of the transmitting antenna. A typical rectenna site would have 4 km diameter for a transmitting antenna of 2 km² diameter at 2.45 GHz (see section 2.4). The peak microwave power flux density at the rectenna site would then be 300 W/m², if a Gaussian power profile of the transmitted beam was assumed. The beam intensity pattern would be non-uniform, with a higher intensity in the centre of the rectenna and a lower intensity at its periphery. For human safety requirements microwave power level has been set to 10 W/m² in most countries and the SPS power flux density would be constructed to satisfy this requirement at the periphery of the rectenna.

After suitable power conditioning, the electric output of the rectenna is delivered to the power network.

The combination of an SPS in orbit and the ground-based rectenna will be called an SPS unit in the following. On a global scale a very large number of 1 GW units may be necessary for a practical SPS system. More details about the SPS concept can be found in [1].

For the sake of completeness it should be mentioned that besides microwave power transmission very recently also laser power transmission has been suggested (Appendix D.9 in [1]). In such a scenario highly concentrated solar radiation would be injected into the laser medium (direct solar pumping) and transmitted to Earth. On the ground the laser light would be converted to electricity by photovoltaic cells. It is obvious that such a system would be fundamentally different from a “classical” SPS using microwave power transmission: In space there would be the light concentration system and the lasers instead of a photovoltaic cell array and the transmitting antenna, on the ground there would be a photovoltaic cell array instead of the rectenna. Since the technological challenges and problems for such laser-based systems have not yet been sufficiently explored, and since many subcomponents are on a low technology readiness level, it will not be treated in this White Paper.

2.2 Aim and Purpose of this White Paper

There are SPS-related issues that are highly controversial. Although several space agencies have pursued SPS studies and research (see next section), very critical papers have been published concluding that SPS is impractical and will never go into operation [e.g. 2]. A more pro-SPS reply to this criticism [3] is mainly based on economic issues as raised in [2]. Among the controversial issues is the question of the space engineering and technology that are necessary for the launch, the assembly and the maintenance of an SPS system, all of which are to a great extent not yet possible. Other heavily debated issues are related to economic justifications (in comparison with other power sources), to the question of whether SPS can provide a base-load “clean” power system on a global scale, to military applications, and to public acceptance. All of these issues are beyond URSI’s scientific domain and will therefore not be discussed in this White Paper. Social issues of SPS may perhaps be addressed by the International Council for Science (ICSU).

Instead, this White Paper will focus on the radio science aspects of SPS. Among the key radio science technologies involved in the SPS concept are microwave generation and transmission techniques, and antennas and beam control, and the very challenging task of protecting other services to the levels required by the International Telecommunication Union (ITU). Of the various scientific organisations or unions concerned with international development and applications of these technology areas, URSI has an important role to play because it covers most aspects of the above mentioned radio techniques. The scientific competence of URSI’s ten Commissions [see Appendix] encompasses aspects of microwave power generation (Commissions B, C and

D), calibration (Commission A) and transmission (Commissions G and H), the effects of electromagnetic emissions on humans (Commission K), the potential interference with communications (Commission C and E), remote sensing (Commissions E and F) and radio astronomy (Commission J) observations, and to some extent solar cell technology (Commission D). Thus, URSI could provide a continuing forum for development, discussion and debate on technical issues related to SPS systems.

In keeping with what has been said above, it is not the intention of this document to advocate SPS as a “clean” solution to the world’s increasing power demand (as is argued, for instance, in [1]). It is conceivable, however, that SPS, and, more generally, microwave power transmission, may be used in the future for special purposes. Among such possible scenarios are: bringing energy to remote areas on the globe that are difficult to otherwise access, sending energy from spacecraft to spacecraft, or providing energy to the dark side of the moon (in compliance with Recommendation ITU-R RA.479 recognising a shielded zone on the Moon). Possible spin-offs from SPS-related research have been considered elsewhere ([1], section 3.6).

A number of the issues related to radio science that are addressed here are also of relevance to the process that the International Telecommunication Union (ITU) has initiated towards an ITU-R Recommendation and/or Report on wireless power transmissions to be completed by 2010 at the latest [4].

Major technological problems still have to be solved, even before a demonstration project could be realised. On the other hand, the radio science aspects of SPS encompass many interesting scientific, engineering and technological challenges. To identify, to describe, and to discuss these items is the main aim of this White Paper.

2.3 History of SPS Research

The first concept of an SPS system was proposed by P. Glaser in 1968 [5], after a series of experiments on microwave power transmission [6]. Following this article, the United States conducted an extensive feasibility study in 1978-1980. The feasibility study was a joint effort of NASA and the Department of Energy. A reference model was proposed, known as the NASA/DOE reference model, in 1979 (Fig. 1, [7]). Research on SPS was suspended in the US in 1980, due to high estimated costs. Given a pre-set policy to re-evaluate SPS after an appropriate time interval, in 1997 the Fresh-Look-SPS concepts were published as an improved SPS reference system, which included the “Sun Tower” SPS concept (Fig. 1, [8]). This is a constellation of medium-scale, gravity-gradient-stabilised, microwave-transmitting space solar power systems. Each satellite resembles a large Earth-pointing sunflower, in which the face of the flower is the transmitting array, and the “leaves” on the stalk are solar collectors. The Sun Tower is assumed to transmit at 5.8 GHz from either a low Earth orbit or geostationary orbit, and to operate sun-synchronously at a transmitted microwave power level of about 200 MW. NASA states that due to its extensive modularity, the low-Earth-orbiting concept entails

the use of relatively small individual system components, which can be developed at a moderate price, ground-tested in existing facilities, and can be demonstrated in a flight environment during a sub-scale test.

An SPS system using mirrors for sunlight concentration on the solar cells, the Integrated Symmetrical Concentrator, was also proposed. It uses 24 or 36 plane mirrors of 500 m diameter for a concentration factor of 2 or 4 (Fig. 1, [9]).

The European Space Agency (ESA) proposed a Sail Tower SPS (Fig. 1, [10]) the design of which is similar to that of NASA's Sun Tower SPS, but uses thin-film technology and an innovative deployment mechanism developed for 150 m × 150 m solar sails. The power generated in the sail modules is transmitted through the central tether to the antenna, where microwaves at 2.45 GHz are generated in mass-produced inexpensive magnetrons. The energy emitted would be 400 MW. In 2003, the Advanced Concepts Team (ACT) of ESA initiated a three-phased, multiyear program related to solar power from space (including laser power transmission concepts) [11]. In addition, a European Network on Solar Power from Space was established. It provides a forum for all relevant and interested European players in the field of SPS, including industry, academia and institutions.

Japanese scientists and engineers started their SPS research in the early 1980s. They conducted a series of microwave power transmission experiments, such as the world's first rocket experiment with powerful microwave transmission in the ionosphere [12,13], experiments on the ground [14], computer simulations [15], theoretical investigations [16], and system studies for a demonstration experiment [17]. After a conceptual study phase, two Japanese organisations have recently proposed their own models. JAXA (Japan Aerospace Exploration Agency) proposed an SPS 5.8 GHz-1 GW model (Fig. 1, [18]), which is different from the NASA/DOE model. It is based on a formation flight of a rotating mirror system and an integrated panel, composed of a photovoltaic cell surface on one side and a phased microwave array antenna on the other side. Formation-flying mirrors are used to eliminate the need for rotary joints. The Institute for Unmanned Space Experiment Free Flyer (USEF) proposed a simpler model (Fig. 1, [19]). The USEF model is a tethered SPS, which is composed of an integrated panel similar to JAXA's, but suspended by multi-tether wires emanating from a bus system above the panel.

The leading group in Japan in basic SPS-related research is based at Kyoto University. Many projects on microwave power transmissions have been conducted and several important papers have been published [e.g. 12-16]. This White Paper is, to a large extent, based on an extensive review of SPS issues prepared by an URSI Inter-Commission Working Group [1] under the leadership of the Kyoto group.

International collaboration was established at a Japan-US SPS workshop [20], an International Conference on SPS and Microwave Power Transmission [21], by the International Astronautical Congress (IAC) Space Power Committee, and by an URSI Inter-Commission Working Group.

[figure will be inserted in final version]

Artist's impressions of various current SPS models: NASA/DOE SPS Reference Model (top left), Sun Tower (NASA, top center) [8], Integrated Symmetrical Concentrator (top right) [9], JAXA 2003 Free Flyer Model (middle left) [18], Tethered-SPS (USEF, middle right) [19], and Sail Tower (ESA, bottom) [10].

More details about the different proposed models are available in [1].

2.4 A coherent set of numerical values

From the various concepts of SPS mentioned in the previous section a set of typical numerical values was extracted which should form the basis of the discussion in this White Paper.

Assuming an SPS unit to generate 1 GW effective power on the ground, the characteristic efficiencies are summarised in Table 1. The figures are given for a 2.45-GHz unit, corresponding values for a 5.8-GHz unit are not fundamentally different.

Quantity Efficiency References
solar power to dc power efficiency 13 % [1], section 2.4.1.2
dc power to rf power efficiency 78 % [1], section 2.4.1.2
RF collection efficiency 87% [1], section 2.4.1.2
RF power to dc power (rectenna) 80 % [1], section 2.3.6,1 (average of 70 and 90%). Total efficiency 7 %

Table 1: Efficiencies for SPS processes (for 2.45 GHz)

Therefore in order to generate 1 GW at the ground one needs to collect about 14 GW in space. Since the solar radiation power flux is equal to 1.37 kW.m⁻² one needs a solar panel area of approximately 10 km². The transmitted RF power is $14 \times 0.13 \times 0.78 = 1.44$ GW. Taking into account the RF collection efficiency of 87%, the RF power received at the ground level is $P = 1.25$ GW. The efficiency of the microwave power transmission (dc - microwave - dc) is the product of the efficiencies given in lines 2-4 of table 1, i.e. 54%. (Actually 54.18% was demonstrated and certified in a NASA laboratory test [22]).

In order to define the rectenna characteristics a reasonable value for the power flux at the centre of the rectenna system has to be assumed. Different values have been proposed: between 230 W.m⁻², 1000 W.m⁻² and even 4200 W.m⁻² ([1], table 2.3.2). Here a conservative value of 300 W.m⁻² (which is less dangerous from a biological point of view, see [1], section 4.3) is adopted for the central power flux. Assuming a Gaussian distribution of the power at the ground and assuming further that the power flux at the edge of the rectenna is equal to 10 W.m⁻² (for safety reasons which are discussed in [1], section 4.3), one arrives after a simple calculation at a radius of the rectenna of $r_r \sim 2$ km. If L is the altitude of the geostationary orbit ($L = 36000$ km) and if r_t is the radius of the transmitting antenna one has approximately $r_r / L = \lambda / (2 \cdot r_t)$ where λ is the RF

wavelength ($\lambda = 0.12$ m at 2.45 GHz); therefore $r_t = 1080$ m. The assumed sizes are summarised in Table 2.

Quantity Size solar cell array 10 km² area transmitting antenna on satellite 2 km diameter (for 2.45 GHz) rectenna 4 km diameter (independent of frequency in the above estimate)

Table 2. Size of considered SPS components

The last number to be introduced is the desired pointing accuracy of the transmitting antenna. In most projects one assumes that the allowed displacement of the centre of the beam is a small fraction of the diameter of the rectenna system. In ([1], section 2.1.1), the adopted value of this displacement is 300 m so that the required pointing accuracy for a geostationary power station is 0.0005. It should be noted that the above estimate for the rectenna size does not take into account any safety margin due to the pointing accuracy of 300m.

2.5 Economic Issues

As already stated in section 2.2, economic-related issues are outside of URSI's scientific domain. Some important aspects are therefore touched on only briefly in this section, and with some figures quoted from the available literature.

There are four main factors that determine the energy production costs of an SPS system: photovoltaic module efficiency and costs, mass-specific power production (W/kg) of the solar modules and the transmission system, microwave power transmission efficiency, and launch costs. The target is an efficiency of about 50% for the total microwave power transmission dc-microwave-dc conversion (see section 3.1) and a specific power output of 1 kW/kg for the whole microwave power transmission system. The published SPS cost estimates are based on a launch cost of USD150/kg ([1], section 2.1.4). All these assumptions lead to an estimated power-generation cost of an SPS system of approximately 0.1-0.2 dollar per kWh [23]. These estimates remain controversial. For example, present-day launch and space assembly costs are greater than two orders of magnitude higher than the desired USD150/kg (present day launch costs of USD10,000/kg, [242]). While NASA expects the launch costs to decrease by a factor of 100 by 2025 and by a factor of 1000 by 2040 [253], ESA is less optimistic. In a corresponding ESA report the power generation costs for a 500 GW SPS system were estimated to be USD0.40/kWh, assuming transportation costs of USD1,500/kg, and a mass specific power production of 0.2 kW/kg [264]. In the same report it was stated that transportation costs may be reduced to USD200/kg in the future.

A direct comparison of the output power from a space-based solar power unit with that from a terrestrial photovoltaic array with equal area is not straight forward. On one hand, a simple estimate of the energy output yields an advantage of about a factor 2.5 for the SPS:

1.37 kW/m² solar power flux in space * 0.07 overall SPS efficiency (Table 1) * 24 h =

2.3 kW/m²/day

terrestrial solar cell array:

5 kW/m²/day average insolation at a sunny place (Arizona,[294c])*0.17 solar cell efficiency =

0.85 kW/m²/day

A detailed economical comparison of the costs, on the other hand, turns out to be very complicating, depending on many factors, like launch costs, (see above), SPS concept, power consumption profile (base-load versus non base-load power supply systems), storage technology (for base-load power supply), terrestrial power transmission system (depending on the location of the terrestrial power plant), energy payback times, and others. ESA conducted several corresponding studies (including also terrestrial solar thermal plants) [e.g. 27,284a,b]. One of these came to the conclusion that (i) for a base-load power supply SPS systems above 5 GW and launch costs between 620 and 770 €/kg are required for SPS to be competitive with terrestrial plants, (ii) for non-base-load power supplies SPS systems above 50 GW and launch costs between 155 and 1615 €/kg would be required for SPS to reach a competitive level to terrestrial plants [284b]. More detailed results of these comparisons are presented and discussed in ([1], section 2.4.3, and Appendices E.5-E.7).

2.6 Key SPS Technologies

The most important key technology concerns the infrastructure to launch, assemble, transport, and maintain the SPS system. Since this topic is beyond URSI's scientific domain, it will not be dealt with here.

The key elements in the dc power generation for the SPS system are the solar cells. Thin-membrane (amorphous) silicon solar cells are expected to be the most suitable type for the SPS system, because of their good performance for a given weight, and because of conservation of natural resources, although their conversion efficiency is lower than the figures for Si-cells (17.3%, [7]) and GaAs-cells (20%, [7]). Mass production feasibility is also an important aspect in choosing the most suitable solar cell type. A sunlight concentrator would enhance the power output. Therefore, two types of power-generation systems have been studied: (a) a massive light-concentration type [9], and (b) a super-light-weight thin-membrane type [3025]. An increase of the total power conversion efficiency is greatly desired. It should be noted, however that solar cells in space deteriorate due to accelerated solar wind particles and solar radiation. For long-term space missions, radiation-hardened cells are already available, but at considerably higher costs than cells for terrestrial use.

The thermal design and control of the SPS system will also be of importance, particularly if sunlight concentration is applied. One method for thermal control of the generator is blockage of the infrared radiation from the sun, either by effective reflection or by band-elimination filters for infrared radiation.

The radio science and technology of an SPS system, such as the microwave power transmission, microwave power devices, rectennas, and beam control, will be discussed in detail in Section 3.

A very important detail of an SPS is the proper orbit in space. For most of the systems envisaged so far, a geostationary orbit has been proposed, but also a more remote orbit, an L2-halo orbit [3126], was considered. It is generally assumed that the SPS is assembled at a low Earth orbit, with a subsequent transportation to a geostationary orbit. All modern SPS concepts rely on robotic assembly and maintenance systems rather than human astronauts for the former task. For the latter suitable orbit transfer vehicles have to be developed to transport a very large structure from the lower to the higher orbit. Solar electric propulsion orbital transfer vehicles have been suggested for this purpose. Some corresponding prototype propulsion systems, like a magneto-plasdynamic thruster, a Hall thruster, and a microwave discharge ion engine have been tested ([1], section 2.3.1.2).

Other key issues of SPS technology are lifetime and maintenance. The limited lifetime of solar cells has already been mentioned, but a long-term radiation hazard also exists for any solid-state device on the SPS, such as, for instance, dc-to microwave converters. In addition, there is the problem of the long-term mechanical stability of the very large structures of the solar panels and the microwave transmitting antenna. The long-term influence of tidal effects and radiation pressure have to be examined. Both effects can in principle deform the structure as well as change its orientation. In particular, the radiation pressure exerts a force which is continuously changing in direction with respect to the line joining the satellite and the rectenna. This may pose serious problems concerning the control of the orbit and the orientation of the RF beam. The amplitude of this force is of the order of 100 N for a solar cell area of 10 km² ($2 * \text{solar radiation power flux} * 10 \text{ km}^2 / \text{velocity of light}$). Regarding maintenance, the present-day experiences for low-Earth orbits with the Hubble space telescope and the International Space Station indicate that maintaining and servicing a much larger system in a much higher orbit may be very difficult and much more expensive than for low Earth orbits. A completely new approach to space maintenance may be required to maintain assets at geostationary orbit. Currently, progressive replacement is the only viable option.

3. SPS Radio Technologies

3.1 Microwave Power Transmission

Wireless communication uses radio waves as carriers of information. In the microwave power transmission system, however, radio waves would be used as carriers of energy. In principle, the energy-carrying microwaves would be monochromatic waves without any modulation. The microwave power transmission would use power densities

at the surface of the transmitting antenna that are three or four orders of magnitude higher than the corresponding levels in wireless communication systems, and up to 25 orders of magnitude higher than power densities received by the radio astronomy and remote sensing services.

The main parameters of the microwave-power-transmission system for the SPS system are the frequency, the diameter of the transmitting antenna, the output power (beamed to the Earth), and the maximum power flux density. In addition to the system parameters described above, the weight per unit power of the microwave devices is also of importance ([1], section 3.2).

Efficiency is very important for the microwave power transmission system. Assuming the SPS transmitting antenna to rectenna propagation path is optimum, the following efficiencies will be important: dc-to-radio frequency (RF) conversion, RF-to-dc conversion, and beam-collecting efficiencies. Conversion efficiencies higher than 80% for both RF-dc and dc-RF conversions are necessary to make the cost of the SPS system reasonable (see section 2.4).

Various types of transmitting antennas have been considered, such as slotted waveguide antennas, dipole antennas with reflectors, or microstrip antennas. The most suitable antenna type depends on the chosen microwave generator and amplifier, but also on weight. A possible concept seems to be the Active Integrated Antenna technique, combining the dc power generation, microwave conversion, and radiation and control in one multi-layered plate [3227].

As mentioned in section 2.4, the diameter of a transmitting antenna array of a 1 GW SPS system would be about 1 km. The average microwave power flux density at the array of the SPS would then be 1000 W/m² on the surface of the transmitting antenna. For the SPS system, a phased antenna array is planned, in order to obtain high-efficiency beam collection under the condition of fluctuating SPS attitudes. Depending on the frequency of the microwave power transmission, e.g. 2.45 GHz or 5.8 GHz, the number of antenna elements per square meter would need to be of the order of 100 or 400, where the power delivered by a single element is 10 or 2.5 W, respectively ([1], section 3). Thus the total number of elements could be of the order of several hundred millions (this number can be substantially reduced if single klystrons of more than 1 kW output power are used to feed one antenna element). Such a large phased array has neither been developed nor constructed up to now, even on Earth. It is uncertain if simple scaling of already realised arrays is possible or whether it may lead to unexpected problems.

Hence, realising the SPS system will require overcoming many engineering challenges, such as phased arrays with an RF-dc conversion efficiency higher than 80%, a phase-shifting system with very low root-mean-square errors for accurate beam control, phase synchronisation over millions of elements, and very-low-cost mass production of these elements.

3.2 Microwave Power Devices

Many possibilities have been proposed for the microwave generators, such as microwave vacuum tubes (klystrons, magnetrons, travelling wave tube amplifiers), semiconductor transmitters, and combinations of both technologies. These types of generators have been compared with respect to their efficiency, output power, weight, and emitted harmonics ([1], section 2.3.4.2). The dc-to-RF conversion efficiency for microwave vacuum tubes can be as high as 65% to 75%; the power of a single tube can be more than 100 kW. For semiconductor transmitters, the best achievable efficiency is 40%, the power from a single transmitter being below 100 W. Better efficiencies may be possible with new devices such as wide-bandgap devices, using GaN, which have significant power output, in particular at microwave frequencies of 2.45 GHz and 5.8 GHz ([1], section 2.3.4.2 (4)).

Compared to semiconductor technologies, a microwave tube has higher efficiency, lower cost, and a smaller power-to-weight ratio (kW/kg), even if one includes the power source, the dc-dc converter, the cooling system, and all the other elements needed to drive the system. Some of the SPS concepts are based on a microwave power transmitter with microwave tubes, such as klystrons and magnetrons. For example, a new concept for a microwave transmitter has been developed, called a phase-controlled magnetron, which satisfies both the requirements of high efficiency and beam controllability [3328]. A hybrid tube-semiconductor system is also a possible solution currently under investigation [3428a].

For the high-efficiency power transmitters, a design that generates a low amount of harmonics, and low-loss phase shifters, are particularly important and would need to be developed. Manufacturability would be one of the important considerations in the implementation of particular technologies for the microwave power transmission system. Since the SPS requires huge investments, even in electronic parts, the availability of particular materials and the manufacturability need to be examined. From a manufacturing point of view, recent semiconductor technologies could be useful for SPS systems. However, their reliability in space would need to be investigated. For the microwave power transmission technology, the reduction of the weight per unit of generated power would also be of importance to ensure a reasonable cost for given performance.

In any case, thousands of microwave tubes or millions of solid state amplifiers and oscillators have to be phased and controlled, which is a large technical challenge.

3.3 Rectennas

The rectenna (located on the Earth) receives the microwave power from the SPS and converts it to dc electricity [e.g. 3529]. The rectenna is composed of an RF antenna, a low-pass filter, and a rectifier. It is a purely passive system (apart from a low power pilot beam, see section 3.4) and needs no extra power. A low-pass filter is necessary to suppress the microwave radiation that is generated by nonlinearities in the rectifier. Most rectifiers use Schottky diodes. Various rectenna schemes have been proposed and the maximum conversion efficiencies anticipated so far are 91.4% at 2.45 GHz [360] and 82% at 5.8 GHz [3720]. However, the actual rectenna efficiency will also depend on various other factors, such as the microwave input power intensity and the load impedance.

The single elements of the rectenna can be of many types, such as dipoles, Yagi antennas, microstrip antennas or even parabolic dishes.

The rectenna array, with a typical radius of approximately 2 km, is an important element of the radio technology, for which high efficiency is essential. The efficiency depends on the input power, and the input power flux density is not constant over the entire rectenna site for the SPS system. Further research would be required into rectennas that maintain high efficiency under various input power conditions. Recently, development has started on a low-power (only 100 μ W or less), high-efficiency rectenna system for the perimeter of the rectenna site [382]. Studies and experiments have also been performed for a hybrid technique [393].

3.4 Control and Calibration

Another important issue concerning the space-based microwave antenna is the necessarily high precision of the control of the beam direction. This is important for two reasons: to maximise the energy transferred to the Earth; and to limit radiation in undesired directions, to avoid adverse effects on existing telecommunication, passive radio-detection systems, and biological systems. This goal may be achieved with the concept of a retrodirective array in which the rectenna sends a pilot signal to the SPS in order to indicate its position before the power beam is transmitted. This pilot beam is then used to direct the power beam back along exactly the same path as the pilot beam: in the retrodirective direction. The effect of this is to automatically remove perturbations to the direction of the propagating beam, assuming that the perturbing factors along the propagation path do not change during the round-trip transit time. For this to work, retrodirective beam-forming techniques have to be developed in order to suppress sidelobes and to maximise the transmission efficiency. In addition, control measures have to take the delay of commands into account, which is a considerable fraction of a second for an SPS in geostationary orbit.

Emergency procedures should be defined and have to be applied when the beam direction is not contained within the predefined angle of 0.0005° . Ordering an interruption of the RF transmission may be a possible solution, but the detrimental effects

that could be caused by a sudden interruption of the dc to RF conversion onboard the satellite has to be evaluated, not forgetting that the load to the grid will also need to be managed carefully.

The centre of the microwave beam should be confined to a region within 0.0005° of the centre of the rectenna. This corresponds to less than one fourth of the 8-arc-seconds half-power beamwidth of a 1000 m diameter parabolic SPS antenna. Achieving such pointing accuracy and stability would currently pose a major technical challenge. The required beam-control accuracy of the SPS microwave power transmission system may be achieved using a very large number of power transmitting antenna elements, and by limiting the total phase errors over the antenna array to a few degrees. Technologies to achieve these goals are presently under study [186]. Beam-collection efficiency is as important as the beam-control accuracy and the efficiency depends on the power lost in sidelobes and grating lobes.

Measurement and calibration are important issues for the SPS and microwave power transmission systems, because the SPS-microwave power transmission system requires accurate beam control with a large phased array. Space is a harsh environment, with large temperature gradients, the solar wind, and ionising radiation (it should be noted that an SPS at geostationary orbit can well be located within the solar wind regime during a large geomagnetic storm and not within the magnetosphere as under quiet conditions). There are serious restrictions in simulating such physical conditions on a limited scale in a laboratory environment. The testing of large SPS antennas presents not only the usual difficulty of making accurate RF measurements over a substantial aperture, but also the unusual problems of devising tests that can accurately predict the performance of the antenna under the harsh mechanical and thermal conditions in the space environment. New methods of measurement and calibration would therefore need to be developed. Microwave measurements and calibration would be necessary for the evaluation of power, interference, and spurious emissions from the SPS and rectennas.

The proposed antennas, both the transmitting antenna and the rectenna, are expected to be so large that testing them in their entirety will pose significant challenges. Computer simulations can give accurate predictions of the performance of the antennas in terms of gain, beamwidth, and near sidelobes. However, the transmitting antenna can only be accurately tested once in orbit and to achieve this, special antenna measurement and calibration techniques would need to be developed.

4. Radio Science Influences and Effects of SPS

4.1 Interaction with Ionosphere and Atmosphere

Power loss due to normal atmospheric absorption over the distance from a geostationary orbit to the ground is assumed to be below 2%. In abnormal circumstances

significant departures might be expected when for instance the beam encounters scintillations in the ionosphere and rain cells in the troposphere, as explained in the following.

Very few groups have worked on the effects of powerful microwaves on the atmosphere and ionosphere, and the few studies presently available refer to potential effects via the heating of ionospheric electrons or via ionisation of the air. The expertise is limited, but it exists. However, at a time where new observations (transient luminous events, terrestrial gamma ray flashes) raised new questions about energy coupling between the atmosphere and the space environment [4034], studies are needed on all phenomena that may influence the atmospheric electrical conductivity and chemical composition.

In the process of SPS construction, large high-power electric propulsion systems would be needed to move the structures from a low Earth orbit to the geostationary orbit. They inject heavy ions perpendicular to the Earth's magnetic field (around equator). The injection can strongly disturb the electromagnetic environment surrounding the ion engine in the plasmasphere and the magnetosphere through interaction between the heavy-ion beam and the magnetospheric plasmas. Some of these effects are discussed in ([1], section 4.1.3).

As an ESA contract, a very thorough and systematic theoretical analysis of possible ionospheric effects was published [4134a]. It indicated several possible relevant effects but simultaneously stated that "the natural variability of the ionosphere, as well as the fundamental unpredictability of nonlinear effects certainly limit the accuracy with which the performance of SPS systems and their environmental impact can be estimated".

Radio waves passing through the ionosphere are, in principle, absorbed due to ohmic heating, i.e., wave energy heats the electrons. This effect is strongest in the ionospheric D and E layers, but the effect is assumed to be small for radio wave frequencies above 1 GHz, since the heating efficiency varies as the inverse square of the frequency. No ground-based measurements of electron heating by high-power microwaves are available in the GHz range; only theoretical estimates exist for a frequency of 3 GHz [4336]. They indicate that an electron temperature increase from 200 K to 1000K in the E layer may occur for a power flux density of 500 W/m². Test microwave injections from a sounding rocket have been carried out in Japan [121]. Although ohmic heating effects were not observed, plasma waves were excited by the injected microwaves. This is in agreement with several theoretical predictions that high-power microwaves may produce plasma instabilities in the ionosphere [e.g. 4134a]. Several types of such instabilities produce secondary electromagnetic waves, which could be a source of interference to other radio services. The instabilities may also result in additional electron heating and density irregularities which may have an effect on other radio waves propagating through the region. It is uncertain if the SPS microwave power flux density would be high enough to cause such effects or whether these effects could affect the SPS microwave transmissions.

Another problem may be defocusing of the microwave power beam due to naturally occurring electron density irregularities causing rapid signal-strength fluctuations (scintillations). This could have severe implications for the beam control described in Section 3.4, but, again, it is not known if this effect is important for the envisaged frequency of the SPS microwave beam. Theoretical considerations show that a 2.45-GHz SPS system would be more strongly affected than a 5.8-GHz system [4134a]. The effects of defocusing and scintillation on natural irregularities will be there for all power densities. What is uncertain is whether the high SPS power densities would enhance the effect through nonlinear interactions and feedback.

Some effects of powerful microwaves on the stratosphere have been studied, both theoretically and experimentally [4235]. These investigations have been carried out for a quite different purpose, namely to study the effects of ozone-destroying pollutants in the troposphere, and to create an artificial ozone layer in the stratosphere by high-power electromagnetic waves. The field strength necessary for this is much higher than the values that would be used by the SPS. Therefore, such effects on the atmosphere are not expected.

In the troposphere, refraction and scintillation effects on the beam (or even those induced by the high-power beam itself) need to be considered. Also, absorption and diffraction by atmospheric gases, aerosols, (water/ice) clouds and precipitation must be studied. Recommendation ITU-R P.619, for instance, states about interference from an SPS: “Using available data on likely harmonic content, it can be shown that - even at the 4th harmonic - the interfering signal at a distance of 50 km from the rain cell, can be comparable with the level of the received signal in the fixed satellite service. At the fundamental frequency however, direct radiation from the side lobes of the SPS to the terrestrial station will probably exceed the signal due to precipitation scatter.” In addition, two other effects have to be taken into account: beam attenuation and beam diffusion due to rain. As an example, for a cloud temperature of 0°C, and a path length under rain of 4 km, absorption at 5.8 GHz is 0.16 dB, 1.2 dB and 2.8 dB for precipitation rates of 10, 50, and 100 mm/h, respectively [4437]. Although rain rates of 100 mm/h are rare [1], it has to be stated that the last figure corresponds to a power loss of almost 50%. The beam diffusion at a -30 dBW level can be as large as 4-6 km in diameter for precipitation rates of 50-100 mm/h [4437].

4.2 Compatibility with Other Radio Services and Applications

It is assumed that typical SPS systems will use frequency bands around 2.45 GHz or 5.8 GHz. These bands are already allocated in the ITU-R Radio Regulations to a number of radio services, and are also designated for ISM (industry, science, and medical) applications such as microwave ovens and wireless LAN [4538]. It is

mandatory that unwanted emissions, such as carrier noise, harmonics, and spurious and out-of-band emissions of the microwave power transmission beams, are suppressed sufficiently to avoid interference with other radio services and applications, in accordance with the ITU-R Radio Regulations [4539]. This is a serious engineering challenge, given the huge disparity between SPS power levels and those of other radio services. Although the intended bandwidth of the SPS emissions is quite narrow - since an essentially monochromatic wave without modulation will be used - spurious and out-of-band emissions generated by microwave power transmission beams could substantially degrade the performance of other services and applications, even if received only indirectly. Of particular concern is interference with radio astronomical observations which have a protected band (4.9 - 5.0 GHz) near the envisaged SPS frequencies or their first harmonic. All possible measures need to be taken to protect these observations since if they cannot be protected, it would not be possible for an SPS to operate legally under the present ITU regulations. The same applies for measurements by the Earth-exploration satellite services (passive). The ITU has initiated work towards an ITU-R Recommendation on wireless power transmission [4], which may be relevant to interference an SPS could cause to other services.

The possibility of spurious emissions related to tube (e.g. magnetron) failure is a serious concern for radio astronomy and many other services. With, for example 10,000 magnetrons of 100 kW output for the microwave transmission, and assuming a mean time to failure of say, 30 years for these tubes, it is possible that the average failure rate could be one per day at some point in the life cycle.

Furthermore, the passive thermal radiation of the solar cells of a large number of SPS units is expected to make a substantial zone of the sky, centred on the geostationary orbit, unusable for astronomical observations at essentially all frequencies [4639]. This would occur even when the microwave transmission of the SPS towards the Earth was not operational.

In addition to this thermal radiation, the huge solar cell array will act as a broadband antenna for all radio noise created within the SPS (from switching, out-of-band contributions, etc.). Therefore such RF noise has to be minimised so as not to degrade operations of radio services and applications.

The apparent angular size of a solar cell array of 10 km² is close to 1 arc minute (somewhat larger than the angular size of Jupiter) and scattering of unwanted radiation in the atmosphere would extend the affected region substantially. This means that even optical astronomy would be affected in an extended region of the sky, particularly if a large number of SPS units were operational. The substantial loss of observable sky resulting from these wide band emissions (optical, UV, infrared and radio) needs to be carefully considered.

The requirements of spectral purity (a narrowband signal with very low spurious transmission) and high efficiency of the transmitter will be opposing constraints and

could be difficult to reconcile since high-efficiency, high-power transmitters have an inherent problem of non-linearity. This needs to be carefully assessed.

4.3 Microwave Power Transmission Effects on Human Health

A variety of environmental considerations and safety-related factors should continue to receive consideration because of public concerns about radio wave exposure [470]. Above the centre of the rectenna, the SPS power flux density will be considerably higher than the currently permissible safety levels for human beings. The corresponding exposure limits for IEEE standards at 2.45 or 5.8 GHz are 81.6 W/m² and 100 W/m² averaged over six minutes, and 16.3 or 38.7 W/m² averaged over 30 minutes [481]. The ICNIRP, the International Commission on Non-Ionising Radiation Protection, and Japan, both apply more stringent limits of 50 W/m² and 10 W/m² for 2.45 or 5.8 GHz respectively [492]. The latter level is equal to the power flux density at the perimeter of the rectenna site ([1], section 4.3).

Since during normal operation of the SPS established safety limits for microwave exposure are exceeded in an area around and above the rectenna, access would need to be carefully controlled to ensure environmental safety and health standards are maintained. Under normal operating conditions, the SPS microwave downlink will need to be monitored continuously to ensure the tightly tuned phased-array techniques and beam control are functioning correctly. Should there be a loss of control, beam defocusing techniques to disperse the power would need to be applied.

More details regarding the human health and bio-effects are discussed in ([1], section 4.3).

5. Radio Science Issues for Further Studies

The list of issues below is most likely not complete. Depending on the outcome of the questions addressed, other issues may come up. Again, the list is limited to issues of URSI's scientific domain.

- Can the exposure level of the microwave density at the perimeter of the SPS receiving rectenna site be adequately controlled to avoid exceeding the safety level fixed by international standards?
- What is the impact of rectenna operation on (i) biological systems such as human beings, birds, insects and plants, etc.; (ii) airborne vehicles such as airplanes; and (iii) other electric/electronic equipment and telecommunication networks?

- Can SPS operations be made safe by a precise control of the high-power beam using a pilot signal from the Earth, also taking the time delay of the signal into account?
- The influence of atmospheric refraction, beam defocusing and of absorption and diffraction by atmospheric gases, aerosols, clouds and precipitation have to be further examined. Are there other effects caused by the SPS power beam on the environment (magnetosphere, ionosphere, troposphere, etc.) that have not yet been explored?
- What is the impact of SPS electromagnetic emissions - both intended and unwanted (harmonics of the microwave frequency, unexpected and harmful radiation resulting from malfunctions), at microwave frequencies and other related frequencies - on telecommunications, remote sensing, navigation satellite systems, and radio astronomical observations? What actions can be taken to suppress this unwanted emission? Constraints imposed by the Radio Regulations of the International Telecommunication Union must be taken into account; new Recommendations and regulations probably have to be developed.
- How will reflections of sunlight from the huge satellite structure affect optical astronomical observations, and how will passive thermal emissions affect radio astronomical observations?
- What potential is there for damage to the SPS system from space weather?
- What are the consequences of long-term exposure to solar wind particles and solar radiation of solar cells and other solid state devices on the reliability and costs of SPS systems, taking maintenance and possible replacement into account?
- Will the SPS lead to congestion at the geostationary orbit and to interference with communication satellites?

Even if it is beyond URSI's scientific domain, the economics of SPS systems have to be examined by competent organisations, since the cost advantage is a crucial issue for the feasibility of the whole SPS concept.

Only some parts of these questions can be addressed by laboratory work, simulations, or system analyses. Tests of the large structures (solar cell arrays, transmitting antenna, mirrors) in space are mandatory. After successfully testing, launching a pilot SPS unit as an operational demonstrator project - presumably with broad international consensus - may be a suitable way to assess the remaining questions. However, before being considered for launch, even for such a pilot unit all concerns, such as the impact on communications, radio astronomy, Earth observations and bio-hazards must be addressed fully.

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8. APPENDIX: The ten Scientific Commissions of URSI and their Terms of Reference

1. Commission A - ELECTROMAGNETIC METROLOGY, Electromagnetic measurements and standards.

The Commission promotes research and development in the field of measurement standards, in calibration and measurement methodologies, and the intercomparison of such. Areas of emphasis are:

- (a) the development and refinement of new measurement techniques.
- (b) primary standards, including those based on quantum phenomena.
- (c) realization and dissemination of time and frequency standards
- (d) characterization of the electromagnetic properties of materials.
- (e) electromagnetic dosimetry.

The commission fosters accurate and consistent measurements needed to support research, development and exploitation of electromagnetic technologies across the spectrum.

2. Commission B - FIELDS AND WAVES, Electromagnetic theory and applications.

The interest of Commission B is fields and waves, encompassing theory, analysis, computation, experiments, validation and applications. Areas of emphasis are :

- (a) Time-domain and frequency-domain phenomena;
- (b) Scattering and diffraction;
- (c) General propagation including waves in specialised media;
- (d) Guided waves;
- (e) Antennas and radiation;
- (f) Inverse scattering and imaging.

The Commission fosters the creation, development, and refinement of analytical, numerical, and measurement techniques to understand these phenomena. It encourages innovation and seeks to apply interdisciplinary concepts and methods.

3. Commission C - RADIO-COMMUNICATION SYSTEMS AND SIGNAL PROCESSING.

The Commission promotes research and development in :

- (a) Radio-Communication and Telecommunication systems;
- (b) Spectrum and Medium Utilisation;
- (c) Information Theory, Coding, Modulation and Detection;
- (d) Signal and Image Processing in the area of radio science.

The design of effective radio-communication systems must include scientific, engineering and economic considerations. This Commission emphasises research into the scientific aspects, and provides enabling technologies to other areas of radio science.

4. Commission D - ELECTRONICS AND PHOTONICS.

The Commission promotes research and reviews new development in :

- (a) Electronic devices, circuits, systems and applications;

- (b) Photonic devices, systems and applications;
- (c) Physics, materials, CAD, technology and reliability of electronic and photonic devices down to nanoscale including quantum devices, with particular reference to radio science and telecommunications.

The Commission deals with devices for generation, detection, storage and processing of electromagnetic signals together with their applications from the low frequencies to the optical domain.

5. Commission E - ELECTROMAGNETIC NOISE AND INTERFERENCE.

The Commission promotes research and development in :

- (a) Terrestrial and planetary noise of natural origin, seismic associated electromagnetic fields;
- (b) Man-made noise;
- (c) The composite noise environment;
- (d) The effects of noise on system performance;
- (e) The lasting effects of natural and intentional emissions on equipment performance;
- (f) The scientific basis of noise and interference control, electromagnetic compatibility;
- (g) Spectrum management.

6. Commission F - WAVE PROPAGATION AND REMOTE SENSING (planetary atmospheres, surfaces and subsurfaces).

The Commission encourages :

- (a) The study of all frequencies in a non-ionised environment :
 - (i) wave propagation through planetary, neutral atmospheres and surfaces
 - (ii) wave interaction with the planetary surfaces (including land, ocean and ice), and subsurfaces,
 - (iii) characterisation of the environment as it affects wave phenomena;
- (b) The application of the results of these studies, particularly in the areas of remote sensing and communications;
- (c) The appropriate co-operation with other URSI Commissions and other relevant organisations.

7. Commission G - IONOSPHERIC RADIO AND PROPAGATION (including ionospheric communications and remote sensing of ionised media).

The Commission deals with the study of the ionosphere in order to provide the broad understanding necessary to support space and ground-based radio systems. Specifically, the Commission addresses the following areas:

- (a) Global morphology and modelling of the ionosphere;
- (b) Ionospheric space-time variations;
- (c) Development of tools and networks needed to measure ionospheric properties and trends;
- (d) Theory and practice of radio propagation via the ionosphere;
- (e) Application of ionospheric information to radio systems.

To achieve these objectives, the Commission co-operates with other URSI Commissions, corresponding bodies of the ICSU family (IUGG, IAU, COSPAR, SCOSTEP, etc) and other organisations (ITU, IEEE, etc.).

8. Commission H - WAVES IN PLASMAS (including space and laboratory plasmas).

The goals of the Commission are :

- (a) To study waves in plasmas in the broadest sense, and in particular :
 - (i) the generation (i.e. plasma instabilities) and propagation of waves in plasmas,
 - (ii) the interaction between these waves, and wave-particle interactions,
 - (iii) plasma turbulence and chaos,
 - (iv) spacecraft-plasma interaction ;
- (b) To encourage the application of these studies, particularly to solar/planetary plasma interactions, space weather, and the exploitation of space as a research laboratory.

9. Commission J - RADIO ASTRONOMY (including remote sensing of celestial objects).

- (a) The activities of the Commission are concerned with observation and interpretation of all radio emissions and reflections from celestial objects.
- (b) Emphasis is placed on :
 - (i) the promotion of technical means for making radio-astronomical observations and data analysis,
 - (ii) support of activities to protect radio-astronomical observations from harmful interference.

10. Commission K - ELECTROMAGNETICS IN BIOLOGY AND MEDICINE

The Commission is charged with promoting research and development in the following domains :

- (a) Physical interaction of *electromagnetic fields** with biological systems;
- (b) Biological effects of *electromagnetic fields*;
- (c) Mechanisms underlying the effects of *electromagnetic fields*;
- (d) Experimental *electromagnetic fields* exposure systems;
- (e) Assessment of human exposure to *electromagnetic fields*;
- (f) Medical applications of *electromagnetic fields*.

* (*frequency range from static to terahertz*)

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