# How Safe Are Microwaves and Solar Power from Space?

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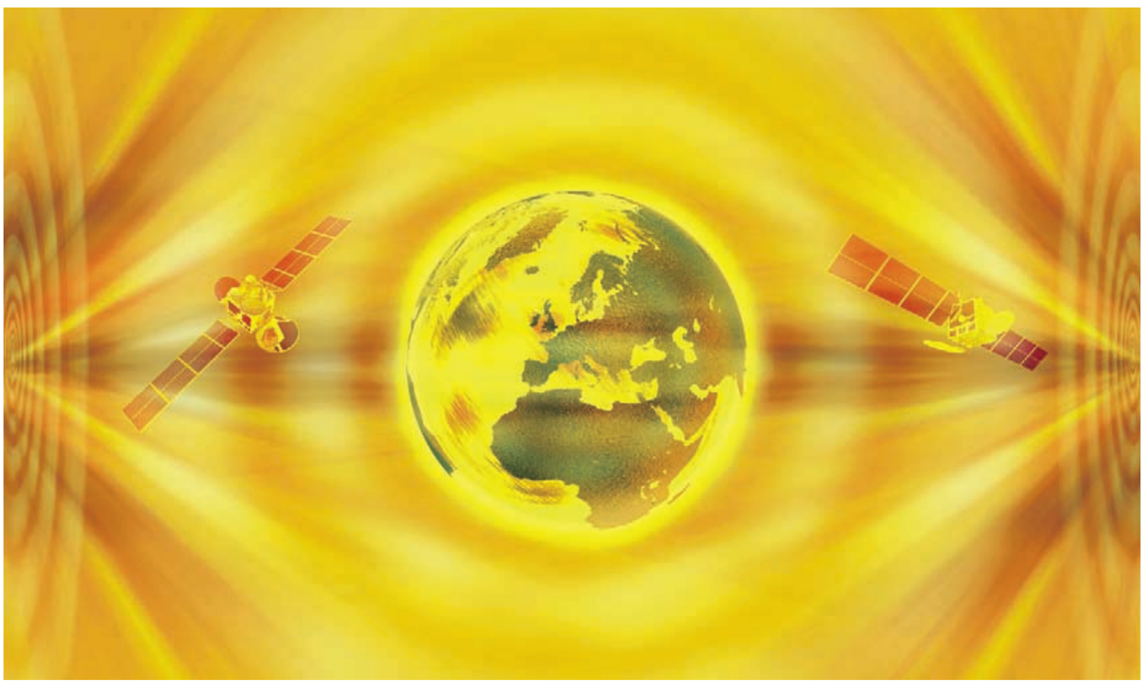


Over the last 50 years, mankind has become acutely aware of the conflict between the necessary facilities and resources for energy generation and the environment. In this new millennium, the idea of moving those facilities out to space may be appealing, but the price includes the acceptance of microwave beams as the link of that energy between space and Earth. Is this technology safe? This can be translated to: what are the environmental effects of microwave beams, and are they acceptable?

Since the first proposal of the 5-GW solar power satellite (SPS) in 1968, by Glaser, there has been extensive study [1] of many proposed systems to generate solar power in space or on the moon and to transmit such power to Earth using microwave beams. Scientists, engineers, and governments in the United States, Europe, the Soviet Union, and especially in Japan have contributed. The plenary session of the 2001 Asia-Pacific Radio Science Conference (AP-RASC 2001) was devoted to the SPS, and it was announced that Japan has the goal of deploying an SPS system by 2040 [2].

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## Background

A key aspect of any power/energy system is *efficiency*, so it was natural that the manufacturers of the most efficient devices for generating and amplifying microwave energy, i.e., magnetrons and related crossed-field amplifier tubes (CFAs), would get involved with the SPS. Hence, Brown, of Raytheon, joined with Glaser to develop microwave technology, including the rectenna, necessary for the realization of the SPS idea. As part of my work on power applications and safety standards at Raytheon, I also became involved in the environmental assessment of the microwave aspects of SPS systems.

Although the proposed systems vary much in various details like Earth orbit [geosynchronous Earth orbit (GEO), low Earth orbit (LEO), or on the moon], almost all have proposed the use of 2.45 GHz as the operating frequency, because this is in the industrial, scientific, and medical (ISM) band of 2.4-2.5 GHz and is low enough for the feasibility of high tube efficiencies approaching 90%. More recently, the U.S. National Aeronautics and Space Administration (NASA) has proposed the use of the 5.8-GHz ISM band for SPS systems, apparently in reluctant acceptance that the 2.45-GHz band has become compromised by its growing use by wireless systems, like Bluetooth, etc. It is unlikely that higher frequencies will be proposed because of the increasingly severe problems of attenuation in rain and clouds and diminishing efficiency.

Over the years, beginning with the first extensive NASA study of a GEO 5-GW reference system [3], the fear of microwave radiation has been the leading potential show-stopper. But is that fear justified? In my environmental assessment in 1986 [4], it was shown that potential exposure levels of the general public, which are limited to less than 0.1 mW/cm$^2$ (or 100 μW/cm$^2$), would be far below accepted safety limits around the world. We concluded, however, that radio frequency interference (RFI) is the more tangible environmental problem that should deeply concern engineers.

The new millennium has introduced increased pressure for finding new renewable energy sources. One factor is concern about global warming. Nuclear power seems to be one answer, but new concerns about terrorist attacks on Earthbound nuclear power plants have intensified environmentalist opposition to nuclear power. Will these new factors help conflicted environmentalists to accept the SPS, at least as the lesser of threats to the environment?

## A Global View of the SPS and the Environment

Figure 1 depicts a global view of the original SPS concept, that of a system generating 5 GW of microwave power stationed at GEO. In the original design, there would be 55 km$^2$ of glass-covered solar cells that are oriented normal to the sun, as well as a 1-km$^2$ microwave antenna, as shown in Figure 1. Because of this very large area, the SPS, in general, would appear as a very bright star in the relatively dark night sky. Even after specular reflections are minimized [3], the SPS in GEO would show an order of magnitude more light than Venus at its brightest. Thus, the SPS would be quite visible and might be objectionable, at least to those inclined against the spread of technology, especially if there are many such objects in the sky. Some astronomers already have objected [5], although more on the basis of radio interference than because of optical obstructions.

Of course, many lower-power and smaller systems, perhaps in LEO, would be less visible or not visible, in the case of LEO, which is not be illuminated at night by the sun. An interesting alternative, that of an SPS (or many SPSs) on the moon [6], would eliminate the large solar-cell arrays in space. Instead, the microwaves generated on the moon from solar cells would be beamed to reflectors that would then beam the energy to rectennas on the Earth. These reflectors would be much smaller than the original SPS solar arrays, perhaps of the order of a rectenna, or even smaller. Criswell [6] estimates that these reflector satellites would require less than 1% of the area required for the GEO SPS. This, however, is questionable since reflectors may introduce increased path loss. We note that power transmission

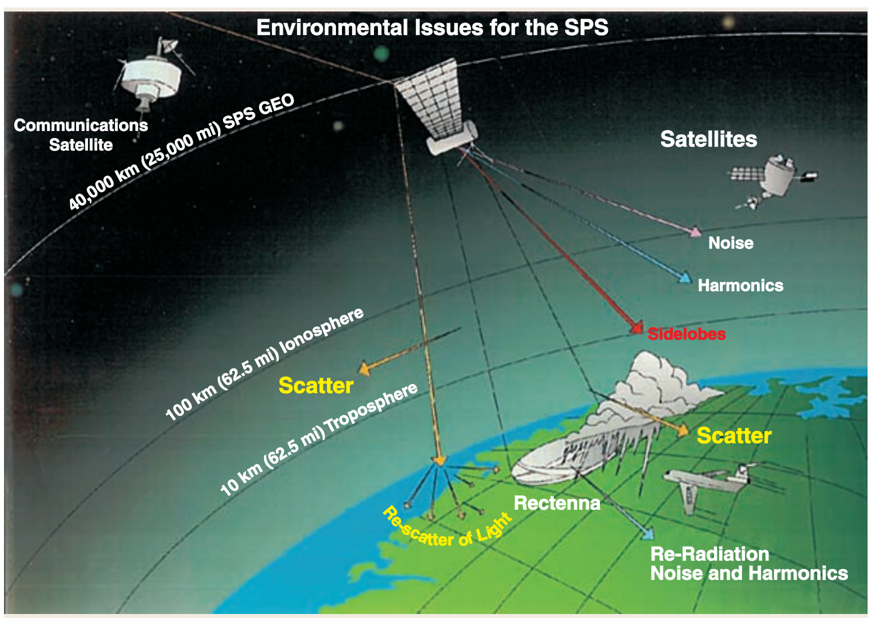


**Figure 1.** *A global view of the environmental issues of the SPS.*

experiments involving reflectors have not been reported. The relay satellites would be in high-inclination orbits around the Earth. Thus, the lunar SPS would entail moving points of light compared to the stationary bright light of the GEO SPS.

In fact, the SPS poses many environmental questions other than "microwave radiation" per se, but the proposed mitigation measures for these seem acceptable to most environmentalists. These include the issues of "space junk," optical pollution that could hinder astronomers, the health and safety of space workers in a heavy-radiation (ionizing) environment, and potential disturbance of the ionosphere and atmosphere. Studies [1], [3] either indicate that these problems are not significant, at least for the chosen parameters, such as microwave frequency, or that practical mitigation measures are available.

Some of these environmental issues derive from the massive construction phase for the GEO SPS, where many launch vehicles or shuttles (not shown in Figure 1) would be required to transport an estimated 50,000 tons of materials to GEO. Thus, a large expenditure of fuels and potential pollution are also associated with this expensive construction phase. Criswell [6] argues that these are greatly reduced in the lunar SPS version, at the cost of complexity of microwave power transmission (MPT) to Earth.

On the Earth, each rectenna for a full-power SPS would be about 12 km in diameter. This significant area poses classical environmental issues, but these could be mitigated by siting rectennas in environmentally insensitive locations, such as in the desert, over water, etc. The classic rectenna design [1], [3] would essentially be transparent to sunlight, permitting growth and the maintenance of vegetation under the rectenna. The rectenna area can compare favorably to many competing technologies, such as noisy and aesthetically disruptive wind farms.

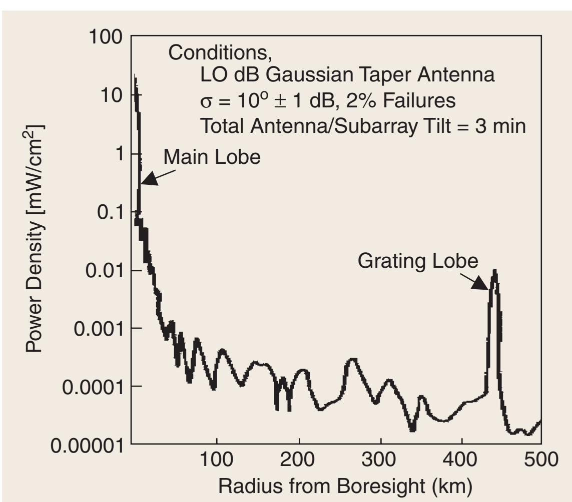


**Figure 2.** *Predicted ground-level microwave power density for one full-power GEO SPS as a function of distance from the rectenna.*

Figure 1 helps to illustrate the global pervasive problem of the microwave radiation, which entails both questions of safety from exposure of people and animals to such radiation and interference. The latter clearly relate to a host of satellites, aircraft, and Earth-based systems and equipment. The issues related to "microwaves" have been and continue to be the most pressing environmental issues.

## Microwave Exposure

In the last 100 years, we have allowed the level of electromagnetic (EM) energy in the environment to greatly increase as a consequence of broadcasting, radio communications, radar, mobile and cellular phones, and now even more new wireless systems and devices. These all play a key role in achieving a good quality of life in modern society. Furthermore, especially in the last 50 years, EM energy has been increasingly used for noninformation or power applications [7] like the over 400 million microwave ovens or medical procedures (diathermy, MRI, and hyperthermia) in the world. They all involve some incidental exposure to EM energy and, in the medical cases, substantial and deliberate exposure.

It is true that public concerns over EM exposure, i.e., to frequencies below 300 GHz, have been substantial and have plagued the development and deployment of many technologies including radar, microwave ovens, computer terminals [visual display terminals (VDTs)], power lines, police radar, and now cellular phones and wireless base stations. These concerns often have been irrational and have triggered the use of the term "electrophobia." How else can one explain the banning of the use of handheld police radars of 10-mW power in the state of Connecticut, while allowing anybody, including children, to buy and use laser pointers of comparable power (5 mW) but of a radiation of much higher quantum energy. Despite continuing electrophobia, most people accept the idea that the modern EM environment is safe. Many studies [8] have shown that, including the whole spectrum, radio frequency (RF) environment levels are on the average of the order of 0.001-0.01 $\mu W/cm^2$ in suburbia, with levels exceeding 1 $\mu W/cm^2$ only near transmitter sources and higher levels up to 100 $\mu W/cm^2$ in a few places, like in high buildings in cities.

By comparison, public exposures from SPS systems would be similar or even less. The rectenna area for the classic 5-GW reference SPS system is about 12 km in diameter. In this area, the microwave beam has an incident power density of around 25 $mW/cm^2$ (25,000 $\mu W/cm^2$) in the center, dropping off rapidly at its edge to below 10 $\mu W/cm^2$. Based on the well-developed antenna theory (phased-array), the environmental levels drop down to around 0.1 $\mu W/cm^2$ in most places, except for isolated points of about a few kilometers in diameter, where theory predicts grating lobes (see Figure 2) of power density approaching 10 $\mu W/cm^2$—still far below accepted environmental safety levels—that are of the order of 100-10,000 μW/cm$^2$ in most places in the world. We see in Figure 2 that such grating lobes may be located several hundred kilometers from the rectenna, thus possibly in populated areas. Thus, even though these levels (10 μW/cm$^2$) are well below safety limits, they might undoubtedly provoke local "not-in-my-backyard" (NIMBY) type concerns that often plague attempts to site wireless base stations. Even inside rectenna areas, levels (approximately 25 mW/cm$^2$) are modest compared to high levels that exist high above the ground near high-power transmitter towers used for broadcasting, radar, etc.

If environmental SPS levels are comparable to levels existing from today's technology, is there reason for special concern? This can derive only from the much greater scope in area and total power. Thus, one might be concerned about the potential effects on workers, but, more importantly, on birds that might fly into the rectenna area and remain there for extended periods of time. Concern about human exposure can be dismissed forthrightly. Even though human exposure to the 25 mW/cm$^2$ will, in general, be avoided, modern studies [9] of human exposure at 2.45 GHz show that people easily tolerate such exposures for a period of at least 45 min. Specific research over the years has been directed towards effects on birds, in particular. Modern reviews of this research [10] continue to show only that some birds may experience some thermal stress, such as blue jays at 2.45 GHz, at high ambient temperatures. Of course, at low ambient temperatures the warming might be welcomed by birds and present a nuisance attraction (that, in turn may require new techniques for repelling birds from a given area—as in airports). At worst, more research is needed if the frequency of 5.8 GHz is used, at which frequency smaller flying creatures, like honeybees, might be affected. Past extensive research [1], [3] led investigators to conclude that there would be no adverse effect "on the flora or fauna of the region." They noted that rectenna design would allow 98% of the incident sunlight to reach the ground. Extreme environmentalists (see page 568 in [3]) have claimed that birds would be killed by the microwave beam, and that the ground under the rectenna would dry up. More rational environmentalists, such as those from the Audubon Society, recognize the more sensible view that any loss of birds is minor compared to those killed by wind farms for energy generation.

## What are the environmental effects of microwave beams, and are they acceptable?

Besides a favorable comparison of the microwave energy around the rectenna with other existing microwave and radiofrequency transmitters, it is instructive to compare these energy levels with energy levels in the environment at all frequencies of the spectrum, as depicted in Figure 3. We show various benchmarks as measured by power density, or equivalent far-field E- or B-field levels in this chart. We see that naturally occurring fields far higher than the microwaves near the rectenna are found at low frequencies, such as from lightning, and at

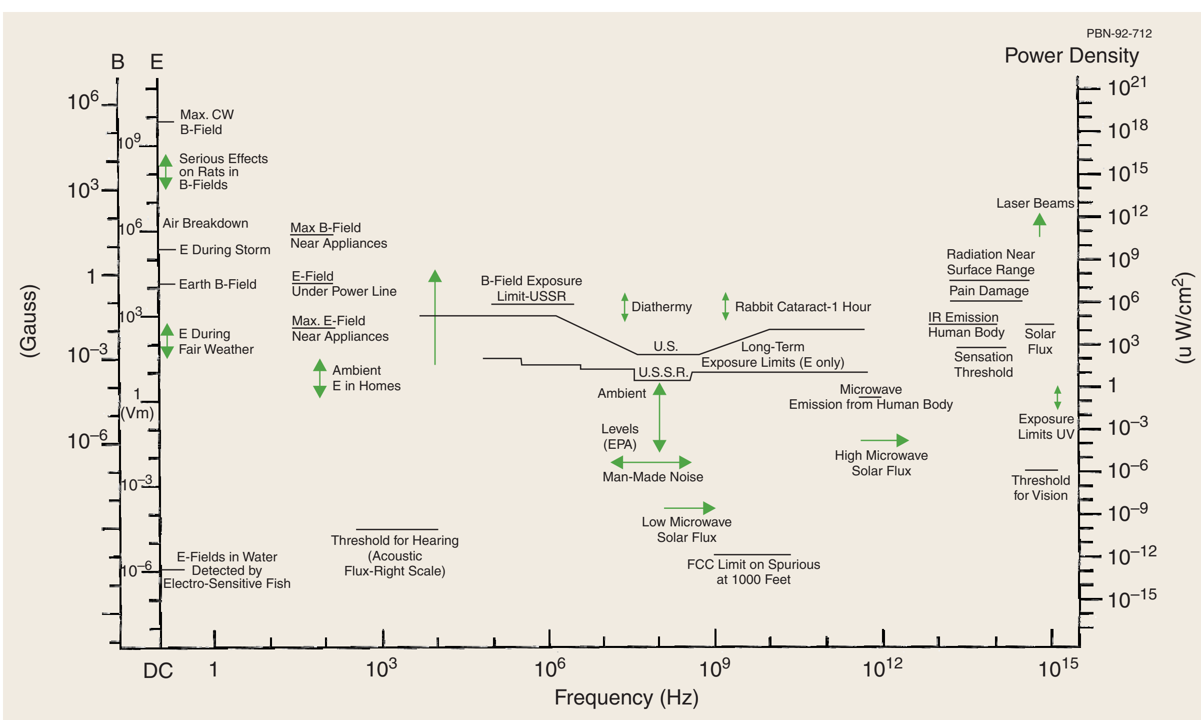


**Figure 3.** *A chart of benchmarks of environmental fields from natural and man-made sources at different parts of the electromagnetic spectrum from dc to light.*

high frequencies, i.e., solar radiation, as well as ordinary black-body infrared (IR) radiation. The naturally low level of radiation in the microwave range is indeed the reason for its popularity for communication, especially to space. We now also find the microwave range optimum for MPT as a key part of the SPS.

The judgment of safety for public exposure from proposed SPS systems is strongly supported by reference to safety standards throughout the world. Critics, however, bring up the question of "athermal" effects. It is a fact that such effects—more accurately described as low-level chronic-exposure effects—have never been proved to exist in a meaningful form. Many papers suggesting such effects were marred by various artifacts, which explains why all responsible bodies have discounted such literature. It may be pointed out that most of such speculations have linked allegations of "athermal" effect to the presence of certain types of modulation or pulse characteristics that are absent in proposed SPS systems. One might add that real effects, like the auditory effect associated with transient heating, result from low duty cycle pulses or very complex modulations, both of which are absent in the SPS systems under consideration. Despite continuing speculation, the only confirmed mechanism for bioeffects at microwave frequencies is heating. (One can note that basic EM theory shows that absorbed EM energy is thermalized in biological tissue in a period of picoseconds to nanoseconds.) All international safety standards recognize this, and we also note that all practical applications [10] of microwave power are based on heating. Safe exposure limits are based on average measures of power or field (squared) parameters through time averaging.

## Interference Considerations

While the bioeffect exposure issue may be more perception rather than reality, interference problems compose the real environmental issue, which requires thorough and creative engineering techniques for successful mitigation. The many factors include nonlinearity of microwave oscillators and amplifiers, harmonic and spurious signals, scattering, and nonlinearity in the environment. The global and complicated scope of these problems can be deduced from Figure 1, as well as the chart in Figure 4 that classifies all the different types of RFI phenomena—including those that occur at high power. One of these is the creation of interfering signals at new frequencies through the mixing of the SPS signal and other ambient signals at different frequencies, through nonlinear effects, such as the "rusty-bolt" effect. Because microwave energy is pervasive through scattering from passing planes, as well as the rectenna, the potentially vast scope presented in Figure 4 might be, in fact, applicable—at least to the higher-power SPS systems. As depicted in Figure 4, potentially interfering signals may be intended, unintended, in band, or even out of band. This helps us to recognize that high-power sources of microwave energy present a full spectrum that needs to be controlled, and not just the main signal. Thus, at a minimum, low-cost filtering of harmonics will be mandatory—with an important radio-astronomy band at the second harmonic of the 2.45 GHz band.

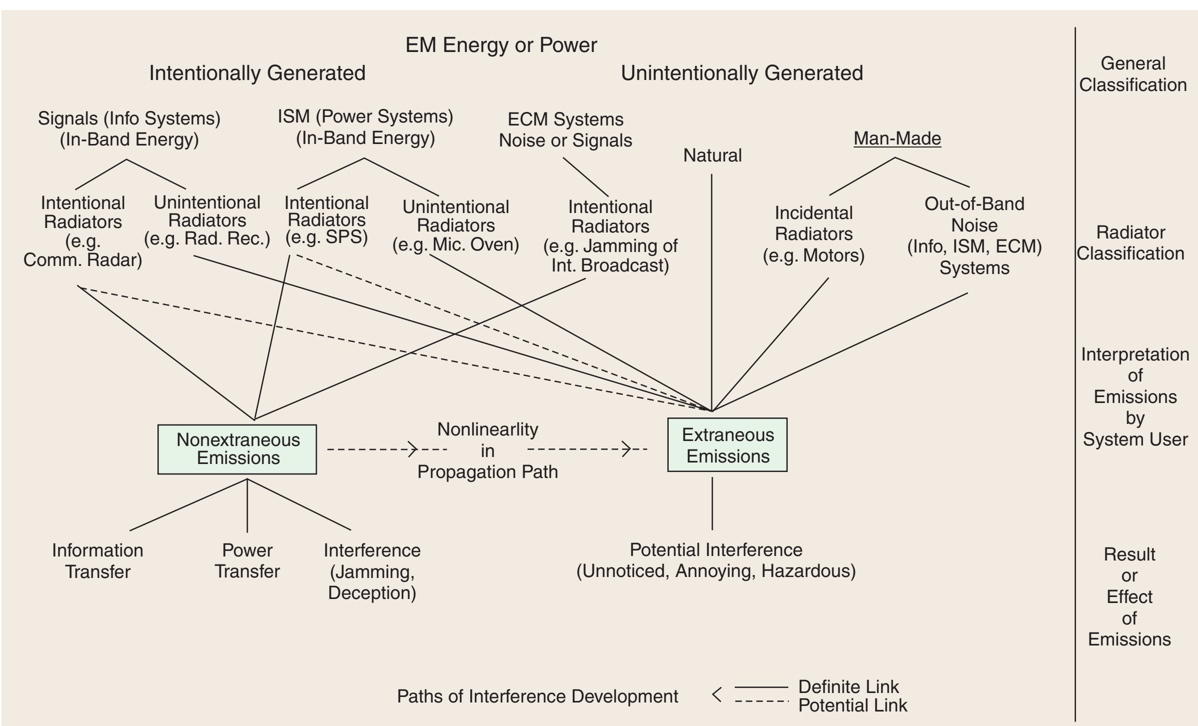


**Figure 4.** *Classification of various RFI phenomena, including the interaction of ISM systems, like the SPS, and communication and other electronic equipment.*

While some microwave devices, such as solid-state sources and klystrons, show low noise, they do not exhibit high efficiency. Crossed-field devices exhibit very high efficiency but, perhaps as a concomitant, exhibit high noise and spurious signal generation [11]. In Figure 5, we show typical noise spectra from the most common low-cost and efficient crossed-field device—the cooker magnetron. We see that low noise exists at high anode current with very high random or discrete (spurious oscillations) noise at lower currents. More engineering work is needed to perfect noise and spurious signal suppression in these devices. This poses a key problem for the SPS. High efficiency is a leading priority for the SPS. So far, only crossed-field devices show high efficiency, and the potential penalty is noise. It remains to be seen if other devices, such as solid state, can compete.

The most serious issue is the impending RFI crisis between wireless systems; various LAN systems, including Bluetooth; and the ISM equipment at 2.45 GHz. Controversy exists over the effectiveness of spread spectrum and digital techniques as mitigation while real RFI incidents continue to occur. If SPS systems were to operate in ISM bands like, 2.45 GHz, would this conflict intensify? On the other hand, if the SPS is moved to 5.8 GHz, the next higher ISM frequency, could crossed-field devices be developed to match the efficiency of the 2.45-GHz device, and is the increased potential attenuation in rainy weather acceptable? There is some technical dialogue between the various involved parties on the RFI issue in the 2.45 GHz band. Still, as Dickinson [12] has shown, the frequency allocation issue is key for the success of the SPS. In the past it has been assumed that the preferred spectrum for SPS is monochromatic, but recent discussions [2] open up the possibility that preferred signal characteristics may involve some modulation and, hence, usage of more of the ISM band.

## Future SPS Applications and Philosophical Issues

In the popular press, the potential danger of an SPS turned into a weapon has often been raised, but at lower microwave frequencies, this is ruled out by physical limits on focusing. Beneficial weather modification, such as preventing damaging freezes in orange groves, does seem feasible. More dramatic applications, like the proposal to suppress tornadoes [13], would require more highly focused beams and, hence, higher frequency than that suitable for SPS.

Well before the SPS or the more futuristic applications of microwave beams from space become reality, public perception of "microwaves" will have to be changed from that of mysterious, unseen "radiation" to a recognized extension and amplification of the solar spectrum that already exists—per the oversimplified concept of mere downshifting of the spectrum—neglecting matters of coherence, etc.

The perception of risk from microwaves has always been aided by elements of electrophobia and underlying poor-quality science. In recent times, this has been exacerbated by the pernicious philosophy of the "precautionary principle" [14] embellished by much sophistry in the form of "post-normal science." I believe that such thinking amounts to the abandonment of science

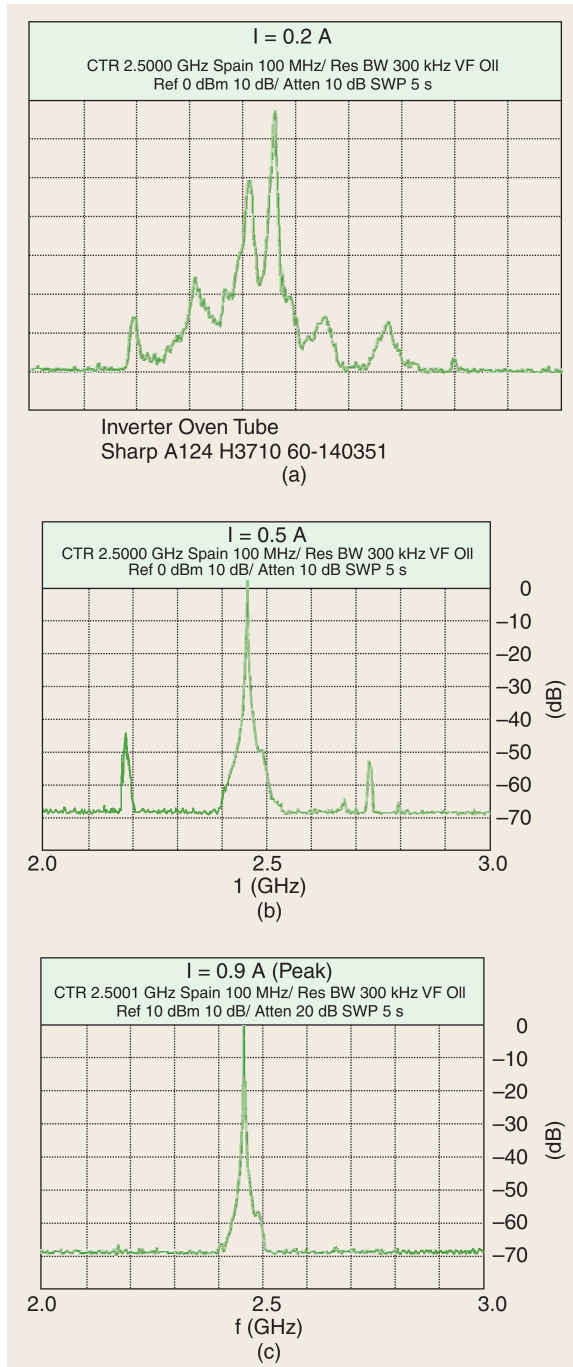


**Figure 5.** *Noise spectra between 2-3 GHz for the typical cooker magnetron, used in over 400 million microwave ovens in the world at three values of anode current: (a) I = 0.2 A, (b) I = 0.5 A, (c) I = 0.9 A.*

and should not be encouraged. Instead, the best antidote to such philosophy and the fears they precipitate is the strengthening of broad-consensus safety standards developed under due process, such as by the International Committee on Electromagnetic Safety (ICES) [15], sponsored by the IEEE. The IEEE is the world's largest technical professional society, with over 350,000 members (over 33% are outside of the United States). At present, ICES members outside of the United States comprise about 20% of ICES. Trends both in the IEEE and ICES indicate about 50% non-U.S. participation by 2010. ICES operates in a transparent manner, with full documentation, consensus balloting, and input invited from all stakeholders, including that of industry. ICES cooperates with other national and international groups like the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the International Electrotechnical Commission (IEC), which are more restricted in membership, process, and stakeholder input.

It is increasingly clear that the development of SPS systems with MPT, along with the resolution of environmental issues, will be a global endeavor. It is also clear that the increasingly global economy means that sources of key components for advanced technology, with low-cost manufacturing, are outside the United States [16] and, indeed, often in the underdeveloped parts of the world. For example, almost all the mass manufacture of cooker magnetrons is now carried out in Korea, Thailand, and China. On the other hand, electrophobia has spread from the United States around the world, and today the most intense fears of EM energy are found outside the United States, particularly in Europe, China, and part of the bloc of former communist countries in Eastern Europe. Thus, the activities of ICES and the IEEE become very relevant in achieving the goal of rational, international safe exposure standards, as well as international consensus on regulation of RFI, such as through the Comité Internationale Spéciale der Perturbations Radioélectriques (CISPR/IEC).

The realization of the SPS concept holds great promise for solving energy crises and improving the lot of mankind. Serious discussions and education are required before most of mankind accepts this type of technology with global dimensions. Fears are based mostly on ingrained perceptions built up over the years as irrational attacks have been made on each successive wave of EM technology—from the microwave oven and radar to today's wireless phone. In the history of man, great strides in human welfare have occurred after the acceptance of air-conditioning, the automobile, modern appliances, and airplanes. Man has progressed not by demanding absolute proof of safety before developing technology but by learning as work progresses [17], along with reasonable precautions based on science. Furthermore, fears of changing the environment should be dispelled if we realize, as Huber teaches [18], that efficient use of land and resources is possible only by applying the best hard technology (big, not small). Finally, we look forward to universal acceptance of the premise that EM energy is a key tool to improve the quality of life for mankind. It is not a "pollutant" but, more aptly, a man-made extension of the naturally generated electromagnetic spectrum that provides heat and light for our sustenance. From this viewpoint, the SPS is merely a down frequency converter from the visible spectrum to microwaves.

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