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A Look at the Wide Spectrum of Wireless Power Transmission

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Abstract

Wireless Power Transmission (WPT) was first postulated by Glaser (1968) in connection with his Solar Power Satellite project. However, no significant follow-on steps on this project have been implemented until now, due to the extremely long return times required to recover the large investments that are necessary in this enterprise. Perhaps it is better to invest in projects with more limited scopes, in order to improve the level of scientific and technological competence, and as a stepping stone for more ambitious implementations. This paper examines these intermediate applications that are based on techniques for wireless energy refuelling of high-altitude platforms and airships, a subject area which is of great interest to Homeland Security (HS) and to telecommunication services, among others. The objective of this paper is to highlight the role of the scientific community within this new research area, arguing that the advancement of WPT needs the creation of a "new" science and not just an extension of the existing science that is tailored to information rather than to power transmission. This paper provides a few examples to lend credence as well as support to this assertion.

Index terms – Airships, atmospheric satellites, electromagnetic momentum, electromagnetic wind, high-altitude platforms, microwaves, rectenna, UAV, wireless power transfer, WPT.

1. Preliminary considerations

Wireless Power Transfer (WPT) using electromagnetic energy is by no means a new idea [1]. A number of experiments, including several in recent times [2-3], have demonstrated the feasibility of the concept. The original idea of energy transmission from space down to the Earth, as proposed by Peter Glaser [4] in connection with a project entitled *Solar Power Satellite*, is comprised of two steps. The first of these steps is to collect DC electric energy by using solar cells mounted on a platform in space and convert the DC power to microwave energy, which is then transmitted as a wave beam that points down to Earth. The microwave field energy is then collected by an antenna

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array located at the receiver site, and is converted back to DC energy by loading each element of the array with a rectifying circuit. For obvious reasons such a receiving antenna configuration is commonly referred to as a *rectenna* (rectifying antenna) in literature. As mentioned above, Glaser proposed the solar power, collected by solar cells positioned in space on a satellite in a geostationary orbit.

It is well recognized that the first conceived application of WPT was based on the possibility of collecting renewable energy, which is essentially pollution free. The need for energy from renewal sources such as the sun is understandable, given the dizzying pace of the growth of Earth's population. It is widely speculated that the available energy sources, be they natural such as carbon, petroleum and gas, or renewable ones, e.g., hydropower, terrestrial solar energy, wind, geothermal, etc., would be sufficient to sustain the predicted trend of population increase only for the next 30-40 years at most. The solar energy collected in space could provide a viable solution to this critical problem of energy shortfalls as a supplemental alternative to nuclear energy, which is facing profound opposition from the general public following the Fukushima disaster.

This *Space Solar Energy* concept has been explored theoretically, primarily in the US and in Japan [5-6], suggesting the use of Solar Power Satellites in geo-stationary orbits, as originally envisioned by Glaser. However, the subsequent steps which entail practical realization of real-world systems based on the theoretical analyses require a thorough and convincing assessment of a number of technological, as well as economic issues that are summarised as follows:

(i) Construction, localization, and long-term (decades) operation of huge complex space-based systems in prescribed orbits that may not be geo-stationary.

(ii) Collection of vast amounts of solar energy at the DC level, and its subsequent transmission - within the constraints of stringent safety and efficiency requirements, as a beam of microwave energy directed towards a ground station, to be received and reconverted at DC level by the rectenna.

In addition to addressing the above two issues, it would be essential to comply with severe cost requirements and environmental safety rules. It is worthwhile to point out that these two requirements are somewhat contradictory to each other. For instance, we need to enforce the condition that microwave field intensities must not exceed a density of 200 W/m^2 at ionosphere levels to avoid induction of therein instabilities in the ionosphere, which can seriously affect radio propagation. Additionally, the intensity must not exceed the level of 1 W/m^2 in the accessible area around the rectenna in order to comply with the mandated "safe" exposure level[4] in open areas, namely 20 *volt/m*, or equivalently 0.1 mW/cm^2 [7]. These requirements impose an upper bound on the total transmitted power that can be carried by the microwave beam, which in turn, places a constraint on its design. This is just one example out of a large number of other issues that must be addressed in the process of designing WPT systems of this type.

More recent analyses [8-9] claim that all of the above mentioned problems can be solved, albeit at the expense of large investments. Furthermore, it would be necessary to carry out a significant number of preliminary experiments at the prototype level. The estimated time for implementing such a plan before proceeding with the final decision is on the order of 30 or more years [10], according to some of the more conservative estimates. In other words, harvesting industrial-level solar power from space can only be achieved at the expense of a substantial level of financial investments over a long haul. This conclusion in turn raises the question: What are the circumstances under which the solar power harvesting becomes viable?

The first that comes to mind is direct funding from the governments of developed countries. However, this possibility does not seem to be realistic since the excessive length of the estimated time necessary for the development is not consistent with the duration over which democratically elected people typically remain in power, and are able to place solar energy development as a top priority in their agendas, and given the difficult economic times that we face today all across the world.

Instead, if we turn to institutions whose mission is to sponsor projects of interest to the social community, a typical time frame for successful completion of the mission and accomplishment of expected economical returns which should make the project viable is on the order of 3-5 years. Again, we see no reasonable hope that industrial organizations belonging to the energy sector would integrate such a plan in their existing budget, or would increase the same to fund the plan outright. To emerge from this impasse in which we find ourselves, we may need to rethink our strategies as follows.

We may instead explore some less demanding applications in which WPT might be of interest. Fortunately, this appears to be a promising avenue to pursue, as evidenced by the fact that several authors and scientific institutions have recently examined problems asking for *wireless technology for terrestrial applications*, *point to point energy supply*, and *power beaming to high altitude platforms* [11,12]. A complete view of the rising prospects is reported in the book: "High-

[4] Exposure limits are usually different in different countries. We are listing one of the most restrictive.

Power Microwaves" by Benford et al. [13] *(namely Sec. 3.4"Power beaming", Sec.3.5"Space propulsion", and related references)*. Most significant applications fall within the Homeland Security (HS) scenario, and they require that the sensors in inaccessible areas be energized, sensors swarming over permanent *Unmanned Aerial Vehicles* (UAV) be located, high-altitude long-endurance platforms for wireless transmission be refueled, and other new applications be explored to see if duration and required investment levels are consistent with business expectations. Thus, the new WPT science can be developed along these lines, and the associated technological problems be successfully addressed to the extent that they enjoy a significant improvement in terms of reliability both at the political and media levels.

We detail these concepts in the Sections that follow, which begin with a brief and much abbreviated history of experimental accomplishments in the WPT arena.

2. The key experimental tests in the Wireless Power Transmission arena

The first successful experiment [2] of point-to-point WPT over the earth was conducted by Brown and Dickinson (JPL and Raytheon) at Goldstone (Venus-Site, see Figure 1) in the year 1975. A magnetron was used to generate a microwave signal at the frequency of 2.45 *GHz*, and a single disk ($D = 26$ *m*) antenna was employed to radiate the power P_T at a level of 450 *kW*. At the receiver site, which was located approximately 1.6 *km* from the transmitter, a DC power level $P_R = 34$ *kW* was measured at the load of the receiving rectenna, whose dimensions are 3.4×7.2 m^2.

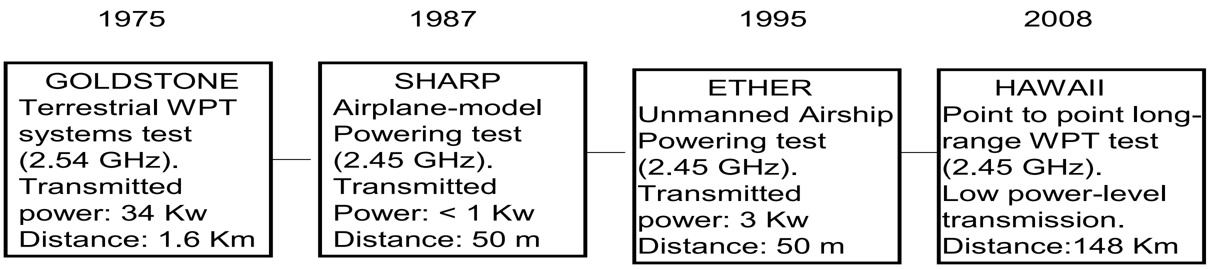

Figure 1. Basic history of key experimental accomplishments in WPT scenario: a synthetic graphical presentation.

Next, we turn to R.M. Dickinson of JPL, who in 1999 performed an analysis [14] sponsored by NASA, in which he carried out a comparative study of transmissions of electric power via wireless and cable from a cost point of view, using $\$/(MW \times km)$ as the key parameter. The study concluded that the cable transmission has advantages over WPT, given the state of technology to-day. However, there may be particular applications in which WPT may be economically viable; for instance, when beaming microwave power for energy refuelling of stratospheric platforms, such as airships for long term earth observation, and telecommunication relay stations. These applications were suggested by Dickinson to be pursued in the near-term time frame; however, they have been considered earlier, as we point out below.

During early 1984, the *Communication Research Centre* (CRC) of Canada proposed the project SHARP (*Stationary High Altitude Relay Platform*) [15]. Their aim was to place a small pilotless airplane around a stationary point at an altitude of 22 *km*. Their plan for energy refueling was to generate a microwave beam at a frequency of 2.45 *GHz*, which was to be transmitted from the ground and to be received on board by a rectenna. A small-scale prototype experiment (see Fig. 1) was successfully performed in 1987 with a mini-UAV orbiting at an altitude of a few tens of meters. But the project was discontinued because the sponsoring Public Agency did not recognize the economic payoff if the full-scale solution was pursued.

A follow-up experiment was planned 10 years later, jointly by CLR (*Communication Research Laboratory*) of Tokyo, Kobe University, Nissan and other minor Japanese organizations. They implemented the first realization of the project ETHER (*Energy Transmission toward High-altitude long endurance airship ExpeRiment*), described the project, and published the details in 1996 [16]. The small airship HALROP-16 (*High Altitude Long Range Observation Platform*), which was 16 *m* in length and whose diameter was 6.6 *m*. It was equipped with 2 electric motors, whose overall power was 5 *kW*. These electric motors were fueled by the DC energy supplied by a $2.7 \times 3.4\, m^2$ rectenna mounted on the external surface of the airship and illuminated by a microwave beam from the Earth. The first successful experiment was conducted at Kobe in 1995 (see Fig. 1), with the airship positioned at an altitude of 50 *m*. A two-port parabolic antenna, 3*m* in diameter, radiated a 10 *kW* microwave beam at a frequency of 2.45 *GHz*, illuminating the rectenna mounted on the airship.

At this point, the interested scientific community began to accept the idea -- as testified by Dickinson in 1999 [14] -- that a *microwave propelled airship,* suitable for a wide number of interesting applications, could indeed be realized. As a matter of fact, stratospheric *High Altitude Platform System* (HAPS) had already been under consideration for many years, and was of considerable interest to the military [17], as well as to civilian organisations in several countries, for long-endurance missions, pertaining to the areas of *Intelligence Surveillance Reconnaissance* (ISR) and telecommunication. This would require an enabling technology which could maintain, over a sustained period, a platform in an almost geostationary position *hovering* at an altitude of around 20 *km*, where atmospheric perturbations are essentially absent.

Experiments with point-to-point WPT over the earth are still ongoing, although mainly for the purpose of exploring the atmospheric absorption of the transmitted microwave beam. More recently, a research group led by J. C. Mankins (Managed Energy Technologies LLC) has projected and carried out, in collaboration with N. Kaya (Kobe University) and other US scientists, the demonstration of the first long-range microwave energy transmission, which was sponsored by the Discovery Channel [18]. The test facility was equipped with a transmitting station (a solid-state powered phased array operating at 2.45 *GHz*), located on the island of Maui. The receiving apparatus was positioned at a distance of 148 *km* (Mauna Loa - Hawaii), which is about 100 times longer than the distance covered by the first JPL-Raytheon WPT experiment conducted in 1975 by Brown and Dickinson at Goldstone [2]. The transmitted power level was 1,000 times smaller than that of Goldstone, viz., on the order of 50 *watt*. Though the received power was not specified, it is estimated to be a fraction of watt. The beam has been monitored along its entire path by sensors carried onboard a helicopter, designed to check the atmospheric conditions and their impact on the transmission efficiency. The Hawaii test (see Figure 1) successfully performed on May 2008 represented a key step toward the path to WPT, opening the way to significant applications over a long range.

3. High-Altitude Long-Endurance Missions--refueling critical point

As pointed out in Section 2, a significant interest has been developing in recent years in the area of high-altitude and long-endurance missions. This appears to be a timely development, insofar as the existing technology and market opportunities are concerned. This point will be discussed in this section in some detail.

Several commercial organizations in the USA, Japan, and Europe, have recently been funded to develop prototypes of *High-Altitude Platform Systems*. They claim that they would be ready to offer to the market within the next few years, stratospheric airships devoted to security and telecommunication programs. They also claim that the performance of these new systems would not only be comparable, but may even be superior to those offered by the satellite systems, though at a significantly lower cost. We list, in particular, the projects by Lockheed-Martin and SWRI (South

West Research Institute)/RAVEN Industries–Aerostar. However, high-altitude and long-endurance tests of these projects have yet to be carried out.

All of these projects assume that the necessary power to operate them is provided by the solar flux, intercepted by the solar cells located on the outside surface of the vehicle. The collected energy is partly utilized in real time, and partly stored in large-accumulation batteries, which enable the airship and its instruments to fully operate during the night. However, it must be noted that experiments with these systems have not been sufficiently convincing to indicate that these anticipated goals have yet been met fully and satisfactorily.

As a matter of fact, high altitude tests have been performed both by using the prototypes HALE-D (Lockheed-Martin) and HISentinel80 (SWRI), and the tests have been claimed to be successful. However, as yet we have had no assurance of this, insofar as the continuity of operation for sufficiently long time intervals is concerned. This is because the tests did not continuously run for a full 24-hour cycle, since the tests in question were interrupted before the cycle was completed. Since no explanation has been provided for these interruptions, assurance of long-endurance operation of the systems cannot be taken for granted.

This leads us to conclude that alternative types of fueling sources, as well as harnessing them should be developed, even if the proposed airships could only be used for *Intelligence Surveillance Reconnaissance* (ISR) and/or telecommunication systems.

An attractive solution would be wireless energy harvesting, which has been tested, albeit at a smaller scale, in the SHARP [15] and ETHER [16] projects, which we mentioned in Section 2. However, no significant progress has been made during the last 10 years along these lines, due to the complexities and costs of realizing the radiating antenna and receiving rectenna, operating at a distance around 20 *km* from each other, at frequencies of either 2.45 *GHz* or 5.8 *GHz*. Under these constraints, the estimated diameters of the two apertures are found to be very large. When added to the fact that their realization could be complex, this is certain to lead to high costs. Although the use of higher frequencies would be more appropriate, lack of hardware on the shelf for the generation of the required level of power that can be procured at reasonable costs, renders these alternative choices unfeasible. At present, the technological scenario is much more favorable, and hardware components such as Klystron and Travelling-Wave Tubes (TWT), as well as related systems capable of delivering power levels of the order of *kWs* are available at frequencies around 35 *GHz*, which provides a reasonably good atmospheric window. As an example, an active phased array with an equivalent aperture of 20 *m* in diameter, operating at 35 *GHz* in the transmit mode, and a rectenna of the same dimension located on a high altitude platform at an elevation of 20 *km* (at the upper level of the *Rayleigh range*), would result in the collection of some tens of *kWs* of power, which would be sufficient for all operational needs of the platform, including the requirements of the instrumentation on board. All the elements validating convenience and opportunity of this type of approach have been reported by Gavan and Tapuchi [19], which asserts that *Microwave Powering* technologies are the right choice to assure unlimited autonomy of high altitude platforms, for *unmanned* missions devoted to security and support of telecommunications.

4. Possible market opportunities

At this point, it is worthwhile to explore the possible market opportunities that would help the improvement of WPT, along the lines presented previously in Sections 2 and 3. The above opportunities are summarized in the following as relevant *business cases*.

4.1 The *Intelligence Surveillance Recognisance* business

As mentioned in Sections 2 and 3, the ISR market is already well developed, and is based on traditional technological solutions. For this application, a large number of sensors are disseminated in the areas to be secured together with connecting networks at several levels, up to the final decision centre where defense strategies and countermeasures are implemented to counter the assessed threats.

In many instances, for example, when surveillance of very large urban areas is required, a solution which is based exclusively on a ground-distributed sensor network is not convenient owing to its complexity and poor reliability. Lack of security may be viewed as an intrusion, whose goal is to corrupt the data sensed by the network.

Alternative solutions that have already been widely experimented with in the military sector, are based on the use of unmanned aerial platforms; for instance, *tethered* airships flowing at an elevation of approximately 3,000 *m*, where suitable sensors are located. The platform is bound to the ground by means of cables that are also used to assure both energy refuelling and the information exchange. But given the severe air-traffic constraints imposed by the control systems, and the tight security required for the binding system, this solution does not really fit in the urban scenario. In addition, the implementation of such systems in built-up areas is not an easy task.

It is rather evident that wireless refuelling, as discussed in Section 3, together with wireless communication networks, would be the ideal solution for the ISR service implementation via an unmanned airship, equipped for long-endurance missions at altitudes ranging from 3,000 to 5,000*m*.

Design, simulation, prototype experimentation, and finally industrial realization of this system, offer a very attractive *business case* for the market.

4.2 Alternative central node implementation for a broadband communication network

Satellites on geostationary orbits (GEO), or satellite constellations on lower orbits (LEO), are widely used to host central nodes of broadband communication systems, especially- though not exclusively- for large distances, e.g., transoceanic communications. Radio links are most commonly used to cover shorter distances. Wireless powered unmanned airships, indefinitely hovering at an almost geostationary position at about 20 *km* altitude, could offer a truly viable alternative [12-19]. The key issue is to carry out a comparison between satellite-based and *high-altitude platform*-based solutions in which we examine both economic as well as security aspects, taking into account all construction and operational costs. The microwave-refueled stratospheric platform network is likely to offer effective security advantages over satellites [20] and; hence, we may conclude that this offers yet another attractive *business case* for the market.

4.3 Atmospheric satellite applications

Recently, Google and Facebook have been exploring the possibility of providing access to the Internet over remote and rural areas in the world, by employing stratospheric/long-endurance platforms such as balloons and UAVs equipped with receiving/transmitting systems, which could be cheaper and more effective than the GEO or LEO satellites. In June 2013, Google started the Project-Loon [21], by launching hundreds of helium-filled, solar-powered balloons in space as receiving-transmitting unmanned platforms, at an altitude of about 20 *km* . These balloons are, in fact, circulating around the world, floating over the stratospheric winds at a fixed height. Their positions are coarsely controlled by remote stations, to form a ring-shaped pattern flying over the areas to be served by the Internet. As for Facebook, it also announced plans [22] to provide Internet to many poorly-connected areas in the world, such as those in Africa, via unmanned stratospheric platforms. Unlike the balloons of Google's Project-Loon, Facebook's platforms have been envisaged as winged, solar-panel powered aircrafts, such as the *Solara-60* (Titan-Aerospace) and the *Zephyr* (Ascenta) prototypes, whose locations and movements can be precisely controlled over pre-defined areas. Following the Facebook declarations, Google proudly responded by announcing its acquisition of the UAV Company Titan-Aerospace [23], and intends to employ UAVs extensively as *atmospheric satellites.*

Hundreds of high-altitude unmanned platforms, such as the Project-Loon balloons and/or solar-panel powered planes, will probably populate our sky in the near future. Many of these platforms are expected to hover around fixed positions for years, either to bring Internet connectivity to remote places or to attend other environmental monitoring tasks. However, the actual available platforms that have been selected for these long-endurance operations are prototypes (as Titan-Aerospace *Solara 60* and Ascenta *Zephyr*), equipped with solar panels and battery systems to collect and use the energy they need. In common with the nodes for broadband communication networks (see Sec. 4.2), an unmanned airship which relies upon wireless to continuously refuel microwave power, appears as an interesting alternative to conventional solutions, assuring continuous operation without landing. However, the wireless-powered airship choice needs to be thoroughly investigated from the point of view of reliability, economic performance and, of course, safety.

5. Birth of a new science

There is no doubt that the success of the microwave power beaming, as well as its expansion toward a wide number of applications needs a large investment as a prerequisite, both for theoretical research as well as for experimental confirmations. Moreover, efficient WPT systems require the most advanced design techniques in order to set up both the directional and self-steering transmitting antenna array as well as the receiving rectenna, required by the applications [24-26] that we have in mind. At this point, some key comments are in order.

An in-depth investigation of the topic of WPT needs a thorough understanding of the physics of the problem. It also requires reviewing the choice of various parameters and developing convenient models. These tasks are largely a responsibility of the scientists and, more specifically, those belonging to the academic world. However, it appears that only very recently [27-29] this community has become aware of these new aspects of the electromagnetics discipline. In addition, almost all of the contributions on WPT that are presented in various workshops [28-29] typically only address the issue of power transmission in the inductive zone, and not in the radiation zone. In other words, only the well-trodden and traditional approach of inductive coupling via a transformer system has been modernized and extended, in terms of frequencies, appropriate technologies and power levels. However, the present approach is based on circuit, and not electromagnetic-field theory. It has not yet been recognized that a full-scale WPT scenario needs the development of a new science, not just an extension of an existing one, which is solely devoted to the wireless transmission of information. Some examples to support the last statement are now presented. It should be understood that these are by no means full solutions to the relevant scientific problems associated with WPT, but only suggestions for the right path to follow when carrying out further studies to search for solutions, and technical implementations of these solutions for various applications.

5.1 The Rectenna

As already introduced in Section 1, the rectenna is the receiving antenna of the WPT channel. In its simplest and typical configuration, it is an array whose elements are terminated by a rectifying circuitry, so that the output of each element is a DC current. These currents are then combined to flow through a convenient load, as for instance, the batteries on board an unmanned aerial vehicle to provide wireless power to the receiver site.

In conventional receiving arrays, the output currents of its elements are summed up *coherently* (in the phasor domain) in order to maximize the received power and equivalently the *effective area* of the antenna. This phase control is implemented by using an appropriate choice of the element spacing, as well as appropriate circuitry at the terminals of the elements. But, in the case of the rectenna, we need not concern ourselves with the phase, since we are dealing with DC currents. As a result, the effective area of the array is just the sum of the individual effective areas of each element (or smaller sub-arrays which constitute the full array). The effective area is independent of the element spacing, provided that their effective areas of the elements do not overlap each other. Consequently, the above-mentioned spacing may be viewed as an additional design parameter which could be used to our advantage. In particular, it is permissible for us to shift the position of the array element along the direction of the incoming signal. Accordingly, very large rectennas collecting energy from *Solar Power Satellites* can be located in uninhabited mountainous regions, and not in populated areas where the terrain is relatively flat, thus avoiding the exposure of the population to the intense incoming radiation.

Furthermore, from the technical side, the efficiency of the rectenna can be improved [30] by using the system shown in Figure 2. It is well known that the currents induced in the receiving antennas deliver power to their load, while they backscatter an equal amount of power when we match the elements. Unfortunately, this backscattered power cannot be captured because it propagates along the direction opposite to that of the incident field and, hence, the backscattered field in this configuration interferes with the incident radiation.

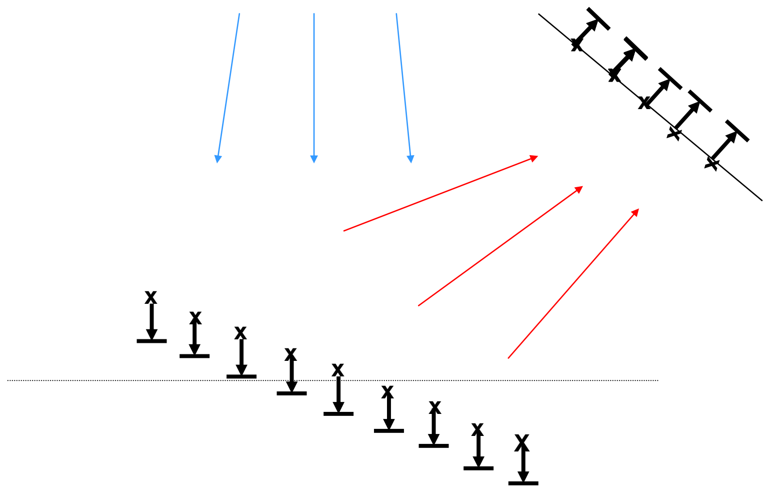

Figure 2. Visual sketch of the rectenna. Each element of the array is indicated by a cross and is loaded with a rectifying circuit. The array elements, originally located over the horizontal line, have been vertically translated and aligned along an inclined line, so that a linear phase difference is induced along the array. Accordingly, the backscattered field can be conveniently directed, and the re-radiated power can be collected.

However, the above limitation does not exist for the rectenna, since we can modify the spacing between its elements, and focus both the fundamental and the harmonics of the reradiated field generated by the rectification process along a suitable direction, such that another rectenna can collect the backscattered power, as shown in Figure 2. In a more sophisticated arrangement, a metal mirror can be used instead, so that the field is reflected back toward the rectenna. This reflected radiation is rectified again, and the process is automatically repeated [27]. However, an improved design is necessary to ensure that all the induced currents sum up coherently in each array element.

The suggested WPT technologies presented above have not yet been implemented to the best of our knowledge. As we have already mentioned, they are just concepts that need to be examined and developed. However, this requires us to carefully examine the issue of power transfer, and not that of information transmission, from a totally novel point of view.

5.2 Mechanical forces of electromagnetic fields

It is well known [31-32] that mechanical forces are associated with electromagnetic fields, and to present possible use of these forces in the context of WPT, it is convenient to briefly recap their derivation along a simple and heuristic fashion.

Consider a plane wave propagating in a homogeneous isotropic lossless medium with speed *c,* the velocity of light. In the phasor domain, the *power density*, which is the modulus $\boldsymbol{S}\ W/m^2$ of the Poynting vector associated with this field, propagates with the same speed *c*. If we divide *S* by c^2, we obtain an *equivalent mass* by following the Einstein equivalence principle. This *equivalent mass, when* multiplied by *c*, provides the *Electromagnetic Momentum M:*

$$M = \frac{S}{c}\left[\frac{W/m^2}{m/sec} = \frac{joule}{m^3} = \frac{Newton \times m}{m^3} = \frac{Newton}{m^2}\right] \tag{1}$$

Assume now that the wave is normally incident upon a half-space comprising of two media of dissimilar electromagnetic parameters. The Momentum, given in (1), undergoes a change ΔM owing to the reflection process, and there exists a *radiation pressure density* $P = \Delta M\ Newton/m^2$ at the interface between the two media. Two simple examples [32] are considered here. If the Poynting vector impinges upon a perfectly-absorbing half space, $\Delta M = S/c$, since the Poynting vector vanishes after crossing the absorbing surface, and the pressure density is S/c at the surface. Similarly, for the case of a totally reflecting metal mirror, the applied pressure density equals $2S/c$, because the Poynting vector changes sign during the process of reflection, and the variation of the Momentum is doubled. From a physical viewpoint, propagation of the electromagnetic field may be modeled as an *electromagnetic wind*, which does not depend individually either on the electric or the magnetic field, but only on the power associated with these fields.

Consider now the case when the propagation takes place in a lossless medium, wherein small particles are diffused. As before, the electromagnetic Momentum undergoes a change along its propagation path due to reflection, scattering, absorption, etc., caused by the wave interactions with the diffused material. These particles are subjected to a radiation pressure, with the results discussed as follows.

One might conjecture that this electromagnetic wind may open a clear funnel (see Fig.3) in a *vapour-charged* environment (clouds, fog, mist, haze, and pollutants) [27], and thus create a clean atmospheric channel in which the wireless power can propagate freely. Such a possibility is certainly worth exploring because it would allow the use of much higher frequencies for WPT which are currently excluded because of high attenuation, when propagating in an atmosphere filled with vapour and charged with water droplets.

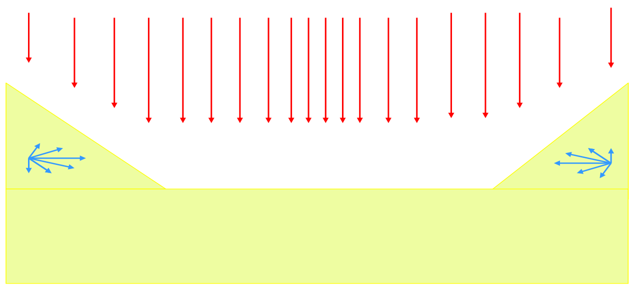

Figure 3. A visual sketch of a possible processing development for opening a clear funnel within a vapour charged atmosphere, due to the radiation pressure exerted by the incoming high power radiation. The electromagnetic wind must compete with the atmospheric turbulence, and the diffusion forces created by the induced non-uniform density of the environment.

For instance, the frequency $f = 94$ *GHz* is located in an atmospheric window, so that it propagates freely when this window is clear. But high losses are introduced in the presence of steam or water droplets, and the frequency of 94 *GHz* can no longer be used. This frequency could still be chosen if a clear funnel could be generated, enabling the use of a much smaller radiating antenna as well as a receiving rectenna, and resulting in significant improvements for WPT applications. Obviously, exhaustive theoretical analysis and validating experiments are needed to ascertain this possibility, but we believe that this would be a worthwhile investment in time and effort.

At this point, it is worthwhile to go over some preliminary considerations upon which the above reasoning is based. Let us assume that the vapor is homogeneously distributed in the atmosphere, and that the winds and turbulence are absent, so that an equilibrium state is present. As already stated, wave propagation is affected by a change of its electromagnetic momentum. Let γ m^{-1} be the attenuation coefficient per unit length along the direction of propagation. The distributed *pushing force density* of the wave is given by $\gamma S/c$ *Newton/m*^{3} (see Eq. (1)) and the Newton's equation reads as follows:

$$\gamma S/c = \rho a, \tag{2}$$

where ρ *kg/m*^{3} is the vapor density, and a *m/sec*^{2} the impressed acceleration on the unit volume of the vapor, along the direction of wave propagation. The impressed acceleration, which provides us important information about the relevance of the wave *pushing force,* is given by

$$a = \xi \frac{S}{c}, \qquad \xi = \frac{\gamma}{\rho}, \tag{3}$$

where ξ *m*^{2}*/kg* is a key parameter of the problem, the other being the radiation pressure.

It is evident that no final conclusion can be drawn at this stage of the analysis because of possible atmosphere turbulence, and the diffusion forces induced by the non-uniform density of the environment (see Figure 3), which we have not accounted for as of yet. In spite of this, some rough estimates of the two parameters which play a significant role in this preliminary model are of interest.

It has been already noted that an increase of the operating frequency is beneficial to WPT, because it not only enables us to use smaller radiating antennas and narrower radiating beams, but also to reduce the dimensions of the receiving rectenna. For instance, by moving from 3 *GHz* to 90 *GHz* and at the same time reducing the dimension of the transmitting antenna by a factor of 10, the (three-dimensional) width of the radiated beam would decrease by about the same factor, as would the dimensions of the receiving rectenna. It is evident that such size reduction would be beneficial for possible applications and involved costs.

The factor ξ is more difficult to analyze. It is evident that the increase of the vapor density ρ generates a similar increase of the attenuation coefficient γ, for obvious physical reasons. Consequently, we expected that the rate of change ξ would not be significant within the change in the vapor density. A detailed analysis of this parameter is certainly necessary, on the basis of theoretical and experimental results; however, the latter are not presently available in the frequency range of interest.

By using tentative numbers and assuming:
S = 300 kW/m^2, $\rho = 10^{-2}\ [Kg/m^3]$ (diffusion of 10 cm^3, i.e. 10 g of evaporated water in 1 m^3volume of clean atmosphere), $\gamma = 0.1\ [m^{-1}]$(full attenuation of the wave within the range of 10m; i.e., 3,000 wavelengths at f = 90 GHz), we obtain $\xi = 10[m^2/Kg]$, and $a = 10^{-2}\ \lfloor m/sec^2 \rfloor$. This is not an unreasonable value since it implies that a distance of 18 m would be covered in 1 minute, and 45m in 5 minutes. The conclusion is that a thorough analysis of the problem is desirable, both by using its model as well as its analytical representation. In addition, other future applications of WPT are likely to appear, and new parameters would have to be considered. Consequently, a comprehensive analysis of the problem at hand would be desirable.

It is interesting to recall that some experiments were conducted, modeled, and analyzed [33-35] in the Soviet Union, during the Cold War, for cleaning a channel through a vaporized atmosphere by using a high-intensity laser radiation. In this case, the objective was to generate a clean atmospheric channel for radio communication; however, the applied mechanism was not based on radiation pressure; but rather, on the absorption of the power radiated by the laser and its induced thermal effects.

These facts suggest that there may be a window of opportunity to use much higher frequencies for WPT application. Of course, these new ideas are likely to be explored only if we look at this new area with fresh eyes, and not with an already polarized attitude.

The final conclusion is that a new science must be created, not just an incomplete and limited extension of the available one. Hopefully, the scientific community would view this as a new opportunity and would devote its energies to meeting this new challenge.

6. Concluding remarks

In this paper, a brief history of WPT has been presented, and open problems have been highlighted. We began with the subject of satellite solar power, which remains high on the list of topics of interest in the context of WPT. We have noted that new industrial opportunities continue to be explored, essentially in the area of refuelling of unmanned aerial platforms, for continuous and more convenient Earth observation, security implementation, and long-range communication. Obviously, additional applications may also arise, opening up new areas to be explored, and requiring new approaches and solutions. However, the authors feel that the requisite scientific background is still lacking, at least from the correct perspective. For this reason, two examples of relevant problems in the WPT arena have been highlighted and discussed, not with the objective of providing solutions, but rather from the desire to illustrate the "correct" approach in the theoretical analysis aiming to clarify the physical background, to develop models, to introduce new parameters, and to identify appropriate mathematical procedures that should be followed. It is safe to say that the spectrum of WPT is truly wide, as has been stated in the title of the paper: developing a new science is not an option, but rather a necessity. Use of this science for suggesting and implementing new valuable applications obviously requires broad interaction between the academic and application communities, which could perhaps join forces in specific sessions at appropriate conferences, where special sessions on WPT are convened. An important role could be assigned to special issues of professional journals, and to FERMAT (www.e-fermat.org), whose mission is to facilitate connections and to encourage spirited discussions of contemporary topics among members of the scientific community.

REFERENCES

1. N. Tesla, *Experiments with Alternating Currents of High Potential and High Frequency*, New York, McGraw Hill, 1905.
2. W. Brown, "The History of Power Transmission by Radio Waves", IEEE Trans Microwave Theory Tech, MTT–32, 1230-1242, 1984.
3. A. Celeste, et al., "The Grand-Bassin Case Study: Technical Aspects", Proc SPS '97, Montréal, Aug. 1997, 255-258.
4. P. E. Glaser, "Power from the Sun; Its Future", Science, 162, 857-886, 1968.
5. The U.S. National Security Space Office, "Space-Based Solar Power as an Opportunity for Strategic Security", Phase-0 Architecture Feasibility Study, Interim Assessment, 10 Oct. 2007.
6. Masahiro Mori et al., "Summary of Studies on Space Solar Power Systems of Japan Aerospace Exploration Agency (JAXA), Acta Astronautica, 59, 132-138, 2006.
7. URSI, "White Paper on Solar Power Satellites" – Inter-Commission Working Group SPS, Ghent, Belgium, 2006.
8. C. Cougnet, E. Sein, A. Celeste, L. Summerer, "Solar Power Satellites for Space Applications", 55° International Astronautical Congress IAC-04-R-3-06, Vancouver, Canada, 2004.
9. J.C. Mankins, "IAA Study of Space Solar Power", (8.2–Preliminary International Roadmap for Solar Energy from Space, p. 152), International Academy of Astronautics, 2011.

10. W. Fan, H. Martin, J. Wu, B. Mok, "Space Based Solar Power" – Industry and Technology Assessment, 6/2/2011.
11. Naval Research Laboratory (NRL), SBS Study Group, "Space Based Solar Power: Defence Applications and Opportunities for NRL Contributions", Final Report, Washington, DC, 23 Nov. 2008.
12. J. Gavan, S. Tapuchi, D. Grace, "Concepts and Main Applications of High-Altitude-Platform Radio Relays", The Radio Science Bulletin 330, Sept. 2009.
13. J. Benford, J. A. Swegle, E. Schamiloglu, "High Power Microwaves" *Second Edition,* Taylor & Francis - 2007
14. R.M. Dickinson, "Ground Base Wireless and Wired Power Transmission Cost Comparison", JPL, 1999.
15. J. Schlesak, A. Alden, "SHARP Rectenna and Low Altitude Flight Tests" Proc. IEEE, Global Telecommunications Conference, New Orleans, Dec. 1985.
16. Y. Fujino, M. Fujita, N. Kaya, et al., "A Dual Polarization Microwave Power Transmission System for Microwave Propelled Airship Experiment", ISAP '96 Proceedings, Chiba, Japan
17. The U.S. Army Space and Missile Defense Command / Army Forces Defense Command, M. Lee, "The High Altitude Efforts at the U.S. Army Space and Missile Defense Technology Center".
18. J. Foust, "A step forward for space solar power", The Space Review, Sept. 15, 2008.
19. J. Gavan, S. Tapuchi, "Microwave Wireless-Power Transmission to High-Altitude-Platform Systems", The Radio Science Bulletin 334, Sept. 2010.
20. M. Popovic, I. Basicevic, "On Security Advantages of HAPs Over Satellites", The Radio Science Bulletin 334, Sept. 2010.
21. www.google.com/loon/ *Balloon Powered Internet for everyone*
22. www.ainonline.com/aviation-news/2014-03-28/facebook-reveals-its-plan-solar-powered-uavs
23. www.techcrunch.com/2014/04/14/google-acquires-titan-aerospace-the-drone-company-pursued-by-facebook/
24. T.W.R. East, "A Self-Steering Array for the SHARP Microwave-Powered Aircraft", IEEE Trans. Antennas Propagat., 40, Dec. 1992.
25. K. Hashimoto, K. Tsutsumi, H. Matsumoto, N. Shinohara, "Space Solar Power System Beam Control with Spread-Spectrum Pilot Signals" The Radio Science Bulletin 331, Dec. 2004.

26. R.B. Vaganov, I.P. Korshunov, E.N. Korshunova, A.D. Shatrov, “On a Technique for Supplying Power to Global Radio Relays for High-Altitude Platforms by Means of Microwave Beams”, The Radio Science Bulletin 338, Sept. 2011.
27. G. Franceschetti, “The New Scientific Scenario of Wireless Power Transmission”, 2010 IEEE APS and URSI Symposium, Toronto, Canada.
28. 2011 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications, May, Kyoto, Japan.
29. 2012 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications, May 10-11, Kyoto, Japan
30. G. Franceschetti, A. Massa, P. Rocca, “Efficient Antenna Systems for Efficient Microwave Power Collection”, IMWS – IWPT, May 2012, Kyoto, Japan.
31. G. Franceschetti, C. H. Papas, "Mechanical forces and torques associated with electromagnetic waves",, Applied Physics, 23, 153-161, 1980.
32. G. Franceschetti, *Electromagnetics. Theory, Techniques and Engineering Paradigms*, Plenum Press, New York, 1997.
33. K.D. Egorov, V:P. Kandidov, S.S. Chseshokov, “Numerical analysis of the propagation of intensity laser radiation in the atmosphere”, Russian Physics Journal, 26, 151-173, 1983.
34. S.M. Chitanvis, S.A.W. Gerstl, “Aerosol clearing model for high energy laser beam propagating through vaporizing media”, J. Applied Physics, 62, 3091-3097, 1987.
35. S.M. Chitanvis, “Optical quality of a channel cleared in a water cloud by a high energy CO_2 laser: turbulence mixing and recondensation”, J. Applied Physics, 66, 4041-4049, 1989.