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REVIEW ARTICLE

Could the space probe Philae© be energized remotely?

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Space probes suffer from a fundamental problem, which is the limited energy available for their operation. Energy supply is essential for continuous operation and ultimately the most important sub-system for its sustainable functioning. Considering, for instance, the last space probe put on Comet 67P/Churyumov–Gerasimenko, called "Philae", which was sent by Rosetta (http://www.esa.int/Our_Activities/Space_Science/Rosetta), to operate and to monitor comet activity, its operation was jeopardized due to the fact that it landed on a shadowed zone (no direct sunlight). Since its operational energy was only based on solar harvesters, the energy for its operation was limited by solar energy availability. In this paper a study on a viable alternative based on wireless power transmission is presented and discussed at the system level. It is proved that, using current technology, it is possible to create alternatives or supplement to existing power sources such as solar panels to power up these important space probes and to secure their operation.

Keywords: Energy harvesting, Space probes, Near-field, Far-field

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I. INTRODUCTION

On September 29, 2016 Rosetta spacecraft died as programed by the European Space Agency (ESA). A successful space mission ended but a shadow remains on the overall picture of this amazing adventure. The space probe "Philae" launched from the Rosetta spacecraft on November 12, 2014 landed on the comet in the shadowed zone by a nearby cliff. Philae was unable to collect solar power and charge properly its batteries. Consequently, its scientific mission was drastically amputated once its batteries discharged. Due to this DC power problem Philae performed only a few days of scientific experiments during the 2 years of Rosetta mission. This issue highlighted one of the key sub-systems in space exploration and monitoring: energy availability and energy generation. Energy is mostly generated using solar panels, and sometimes fossil and/or atomic generators. However, they have always specific problems: fossil is limited, atomic collides with legal and societal constraints and both requires high lift-off costs at the launching phase.

In many situations solar harvesting is the best option, but there is imposition that this source of energy be available (by solar availability we assume that sun is within the line of sight and that the spacecraft or probe has a direct solar illumination), this is not always the case. In the recent Rosetta mission the Philae probe landed on a comet surface and the landing site did not allow for a continuous solar exposition, as shown in Fig. 1, thus limiting the available energy and subsequently the operation of the probe.

One alternative solution to overcome such situations is to use another energy path, leading to the potential solution of far-field wireless power transmission (WPT). This is the case of probes that are powered up by RF/microwave beams from a main spacecraft, which may be in direct line-of-sight (LoS) with sun light. The solution may use a microwave source of energy with energy beams tuned in order to maximize the energy availability in the probe as is explored in [1] for the dark side of the moon probes.

II. WIRELESS POWER TRANSMISSION CONCEPT AND ITS MAIN BUILDING BLOCKS

WPT has three main alternatives: inductive/capacitive coupling, resonant inductive/capacitive coupling, and far-field electromagnetic transmission. The coupling solutions are quite interesting for small distances, around tens of meters are reported in the literature, one of those examples already tested in space by NASA is the concept of RINGS (Resonant Inductive Near-field Generation System)[1] that was used to

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[1] http://www.nasa.gov/content/rings-resonant-inductive-near-field-generation-system/#.VPgtkPmsUeo.

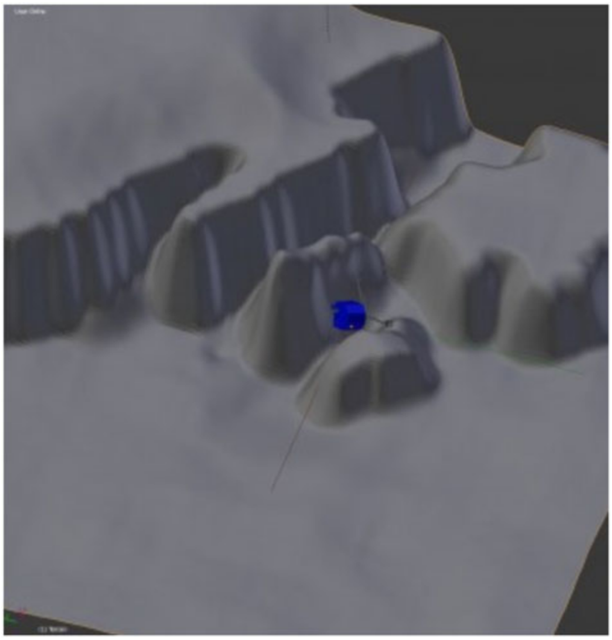

Fig. 1. The likely orientation of Philae probe, shown in a visualization of a topographic model of the comet's surface. Credits: ESA/Rosetta/Philae/CNES/FD, from http://www.esa.int/Our_Activities/Space_Science/Rosetta.

power up Synchronized Position Hold, Engage, Reorient Experimental Satellites (SPHERES) (http://www.nasa.gov/content/rings-resonant-inductive-near-field-generation-system/#.VPgtkPmsUeo). These tests allow pico-satellites to be powered up around the international space station. Nevertheless if the objective is to go further in distance, the alternative is actually to use far-field WPT based on electromagnetic microwave beams.

Figure 2 shows the general concept of WPT far-field systems, where three main components can be seen:

1. *DC–RF generator*, which converts solar DC energy to RF microwave beams. In this case the breakthrough advancing state of the art is on the increase of the DC–RF energy efficiency [15].
2. *RF–RF air interface*, which transmits the RF energy from the source (Tx: transmitter) to the probe (Rx: receiver). In this case the breakthrough advancing state of the art is on the increase of the RF–RF energy efficiency, called beam efficiency.
3. *RF–DC converter* that converts the energy back from RF to DC to power up the probe. In this case the breakthrough advancing state of the art is on the increase of the RF–DC energy efficiency [15].

The main objective of our approach is actually to demonstrate that an electromagnetic beam can be used as a mean to transfer (via RF) wirelessly an amount of electric power from the satellite to the probe, maintaining a continuous energy level in the probe. For this to be achieved the whole chain has to be optimized from the efficiency point of view: (i) DC–RF conversion, $\eta_{DC\text{–}RF}$; (ii) transmitting antenna beam efficiency at the spacecraft as well as receiving antenna beam efficiency at the probe and their respective optimum location and polarization, $\eta_{RF\text{–}RF}$; and (iii) RF–DC power conversion efficiencies at the probe side, $\eta_{RF\text{–}DC}$ [14].

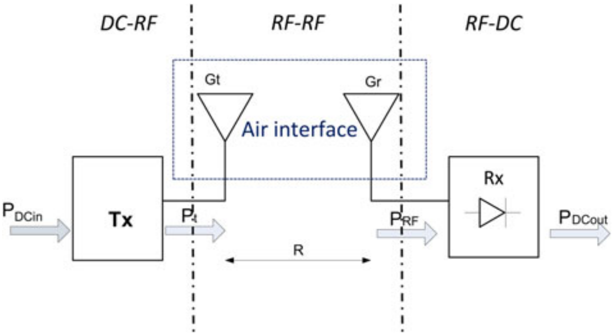

Fig. 2. Typical far-field WPT arrangement.

The overall efficiency is evaluated as, from Fig. 2:

$$\eta_{DC-DC} = \eta_{DC-RF}\eta_{RF-RF}\eta_{RF-DC} = \frac{P_{DC,in}}{P_{DC,out}}$$

This overall DC to DC efficiency can be optimized by exploring each of the sub-systems individually. Actually in the case of powering up the space probes the efficiency is not the main issue to be resolved, because the need to supply the power to the probe is much more important even if we lose power within the conversion process. Thus the first step for this approach is to guarantee that the system level calculations make sense and that the required technical solutions are feasible (size of the antennas, RF power capability of the amplifiers, etc.).

III. ROSETTA MISSION CASE STUDY

The Rosetta Mission case study was selected as the baseline for this paper, in order to demonstrate the interest and motivation of WPT in space environments. The situation in this approach assumes that we have an orbiter, the Rosetta spacecraft, and a probe/lander, the Philae, as shown in Fig. 3.

A real approach to this mission can be seen in Fig. 4, where the orbiter can get as close to the probe as 6 km.

With this mission in mind, the approach is to calculate the overall need to implement a WPT system. Thus we will assume the parameters given in Table 1.

At present, comet is at 2.25 AU to sun (with 1.25 AU minimum distance of its orbit). So we can consider at this moment Power density $= (300/2.25^2) = 60\ \text{W/m}^2$ for the solar panels.[2]

With this assumption it follows that the available power on board the Orbiter from solar panels is in the range of 3–4 kW.

Potential available power on the Lander (Philae) from solar panels is about 60 W if the solar panels were receiving direct sun light, which may not be the case.

Range of power consumption for typical Lander from it's on board instruments is 10–100 W, we will consider 20 W for our calculations. The Sun visibility from the Lander is at this moment <10% time, close to zero in most of the situations.

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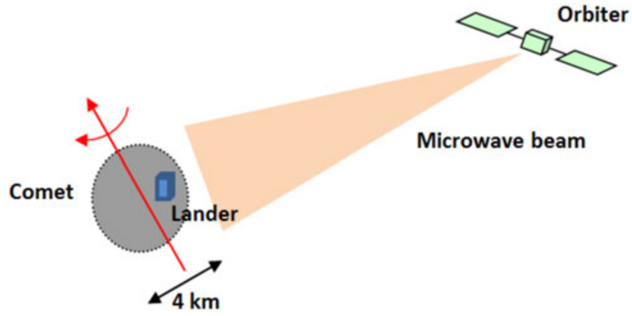
[2] $300\ \text{W/m}^2$ is standard power density at 1 AU distance to sun (about 150 million kilometers).



Note: Orbiter and Lander size not to scale

Fig. 3. Rosetta mission case study.

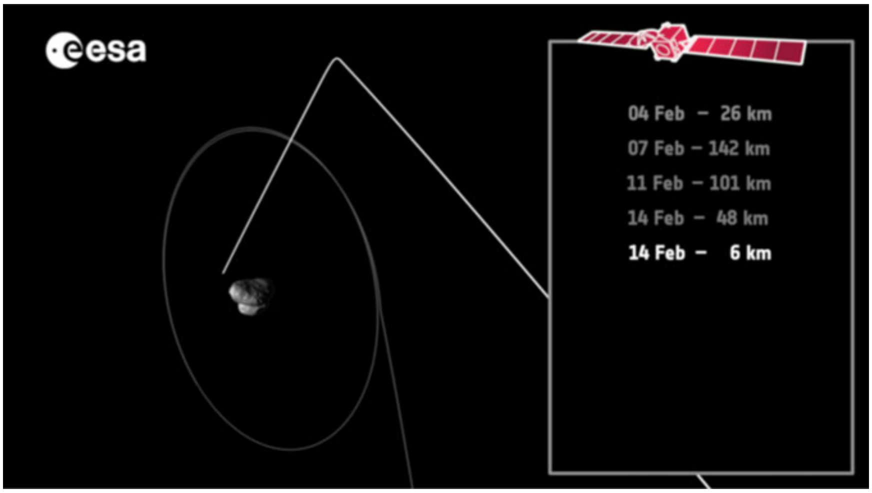


Fig. 4. Rosetta mission orbits from http://www.esa.int/Our_Activities/Space_Science/Rosetta.

In order to get an estimate of the visibility time between orbiter and lander, at first the orbiter is assumed to be in a fixed position. This choice can be justified since the comet rotation time is much longer than the spacecraft orbit time about the comet. Furthermore, the comet shape is irregular shape and far from being spherical one.

As a result the percentage of time with LoS condition can be estimated roughly 2 h over 10 h (20% of time).

Thus, a tentative reference requirement for WPT in this scenario could be:

Distance (altitude):	6 km
DC power need on the lander:	20 W

We assume that the Lander is equipped with batteries to be re-charged by sun or WPT. Using the Friis formula at this stage for free space and the beam efficiency calculated above, we can actually estimate the overall mission power needs. For these calculations we assume the following potential frequencies of operation: 2, 5, 10, and 18 GHz. The calculations are made for 80% of aperture efficiency,[3] and the distance between the lander and the orbiter is 6 km. The frequencies were selected to show the pros and cons of each band. Higher frequencies allow better beam efficiency, but the DC–RF and RF–DC efficiencies are lower due to technological constraints.

The assumptions are then:

- For each frequency, the beaming efficiency is optimized to be higher than 1%, i.e. the relation between the RF transmitted antenna aperture and the RF receiving antenna aperture can be given by: $A_T A_R = 0.01\lambda^2(6000)^2$ to guarantee a minimum of 20 W in the probe [1].
- The far-field condition FF $\sim 4A/\lambda$ [2] is calculated with respect to the transmitting aperture area (A) and the wavelength (λ), since the rectenna elements could have individual detectors, and RF-wise they are not in an array (only the DC adds).[4]

The calculations implemented in Table 2, can be summarized as:

$$P_{RF_{TX}} = P_{DC_{TX}}\eta_{DC-RF} \tag{1}$$

$$G_{TXAnt} = 4\pi\frac{AntennaSize^2_{TX}}{\lambda^2}\eta_{APTX}$$ (2)[5]

$$L_{freespace} = \left(\frac{\lambda}{4\pi d}\right)^2 \tag{3}$$

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[3] The aperture efficiency can be calculated as the ratio between the antenna aperture and its physical size.

[4] As said before, the final decision on the receiving antenna will be discussed afterward.

[5] Antenna size is the physical size of the antenna, TX, and RX, d is the distance between the orbiter and the lander, and .. is the aperture efficiency of RX and TX.

Table 1. Baseline metrics for the WPT link case study.

Metric	Value
Distance between Orbiter and Comet	5–50 km, let's consider 6 km
Rotation period of the comet	About 10 h
Orbiter solar panel surface	About 60 m^2
Lander solar panel surface	About 1 m^2

$$G_{RXAnt} = 4\pi \frac{AntennaSize_{RX}^2}{\lambda^2} \eta_{APRX} \tag{4}$$

$$P_{RF_{RX}} = P_{RF_{TX}} G_{TX_{Ant}} L_{freespace} G_{RX_{Ant}} \tag{5}$$

$$\eta_{BEAM} = \frac{P_{RF_{RX}}}{P_{RF_{TX}}} \tag{6}$$

$$P_{DC_{RX}} = P_{RF_{RX}} \eta_{RF-DC} \tag{7}$$

This can be simplified using some simplifications, for instance the transmitter and receiver antenna aperture can be given by

$$A_T = AntennaSize_{TX}^2 \eta_{APTX} \tag{8}$$

$$A_R = AntennaSize_{RX}^2 \eta_{APRX} \tag{9}$$

Thus

$$\eta_{beam} = \frac{A_T A_R}{\lambda^2 d^2} \tag{10}$$

And the overall efficiency will be:

$$\frac{P_{DC_{out}}}{P_{DC_{in}}} = \eta_{DC-RF} \eta_{beam} \eta_{RF-DC} \tag{11}$$

The results presented in Table 2, clearly prove the feasibility of the proposed scheme, the computed DC power exceeds the threshold of 20 W. Higher powers can be achieved if the distance is reduced, as is the case in a space probe or pico-satellite scenario. The achieved efficiencies considered in Table 2 are viable and can be obtained as in [1] and http://www.teslasociety.com/columbia_expo.htm. The low overall efficiency (DC to DC) is the price to pay for a technical solution which can save a lander mission when the solar power is unavailable or limited.

The overall systems can be described as shown in Fig. 5. On the transmitter side (Tx, Rosetta spacecraft) several phased locked RF oscillators are combined with a high efficiency GaN power amplifier (PA) in order to feed the corresponding element of the transmitting antenna. In this way fairly low power GaN devices can be used to power up the overall energy beam with a power in the order of several kilowatts. As an example, 4 kW of the RF power can be obtained by using an array of 500 GaN PAs. The amount of energy per element should be around 8 W, which is feasible at the current state of space hardness GaN solutions available on the market [1]. Since the objective is WPT and not data communications, the PA could be pushed into compression (using very high efficiency configurations as class E, F, etc.) to pursue its maximum power efficiency and thus contributing to the optimization of the overall efficiency on the whole chain. The antenna implementation on Tx side will benefit from the recent advances in antennas for space communications [2–13].

Multiple-beam antennas composed of a multiple feed per beam (MFB) focal array and a deployable reflector seem to be ideal candidates because of their beam shaping (the

Table 2. Potential figures for the case study feasibility.

Signal information				
Frequency (GHz)	2	5	10	18
Wavelength, λ (m)	0.15	0.06	0.03	0.017
DC–RF conversion				
DC power in transmitter P_{DCTX} (W)	3700	3700	3700	3700
DC–RF efficiency, $\eta_{DC\text{-}RF}$ (%)	80	75	65	60
RF transmitted power, P_{RFTX} (W)	2960	2775	2405	2220
Beam efficiency				
TX antenna size (m)	18	13	10	7
Aperture efficiency on TX side, η_{APTX} (%)	80	80	80	80
TX antenna gain, G_{TXAnt} (dB)	51.6	56.7	60.5	62.5
Distance, d (m)	6000	6000	6000	6000
Far field, FF (m)	4320	5633	6667	5880
Free space attenuation, $L_{freespace}$	3.96×10^{-12}	6.33×10^{-13}	1.58×10^{-13}	4.89×10^{-14}
RX antenna gain, G_{RXAnt} (dB)	47.3	51.4	52.5	55.1
Rx antenna Size (m)	11	7	4	3
RF–RF efficiency, η_{BEAM} (%)	3.10	4.09	3.16	2.82
RF–DC conversion				
Received RF power, P_{RFRX} (W)	91.69	113.48	76.01	62.66
RF–DC efficiency , $\eta_{RF\text{-}DC}$ (%)	80	78	76	74
DC power, P_{DCRX} (W)	73.35	88.51	57.77	46.37
Overall DC–DC efficiency				
DC–DC efficiency, $\eta_{DC\text{-}DC}$ (%)	1.98	2.39	1.56	1.25

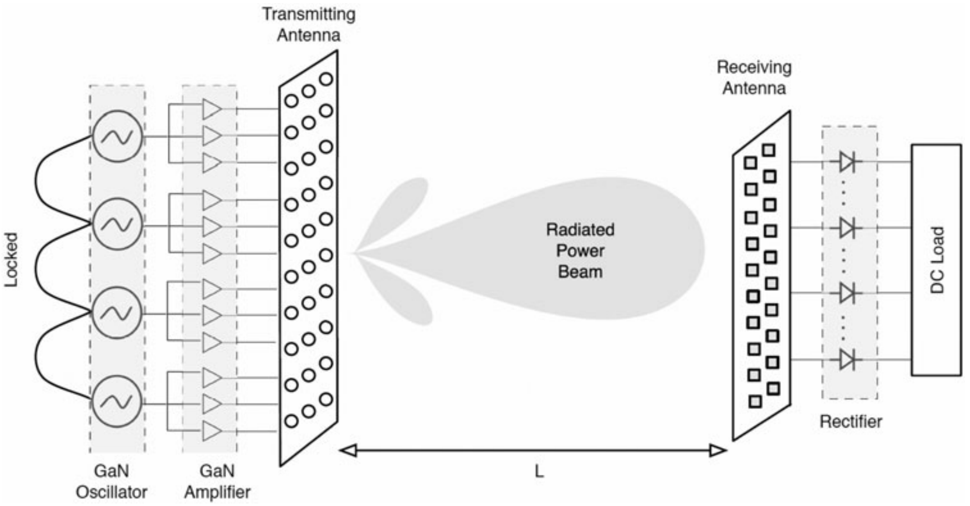

Fig. 5. WPT demonstrating proposed solution.

spacecraft needs to shape the microwave beam in order to track the position of the space probe) and power handling capabilities. The MFB focal arrays, having excellent power handling capabilities, are traditionally manufactured by using a mechanical/milling technological process and their performances have been proved for satellite broadcasting data links.

A recent interesting solution has been presented in [4] consisting of a very large planar holographic metasurface reflectarray at 5.8 GHz to form a focused spot in the Fresnel-zone (for the present case 6.5 m) for microwave wireless power transfer experiment. A 40% of the transmitted power was estimated to incident onto the receiver at the focus point.

The emerging 3D printing techniques can offer new perspective for manufacturing such antennas.

Regarding the receiver, RF–DC converter, the approach to be followed is to use high efficiency RF–DC converters using approaches based on class E or F rectifiers, followed by DC to DC sub-system to guarantee constant impedance at the output of our RF–DC converter.

IV. DISCUSSION

In this paper we show that the powering up by means of remote far-field WPT of space probes/landers could be a viable solution for the last Rosetta mission, and could actually be a "must" solution for next space missions with the purpose to significantly improve their probability of success. By using theoretical computation and based on the today state-of-art solutions for PAs, antennas, and RF–DC converters a realistic FF WPT approach was proposed. A DC power exceeding 20 W can be transferred over a distance of 6 km offering a reliable alternative solution to power up space probes when the solar power is unavailable or limited. We note also that all the building blocks of the proposed FF WPT solution are based on mature technologies that were already used in space missions or are selected for the next (decade) space missions.

The data reported in Table 2 actually demonstrate that the proposed solution can be achieved with current state of the art technologies for PAs, antennas, and RF–DC converters; it is mainly a matter of developing the next missions with this WPT capability in mind in order to avoid DC power issues as recently Philae experienced.

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