Funded by esa		Project: BPT No. 4000135893/ 21/ NL/ GLC/ ov Document: Executive Summary Version: Final Date: 13/ 01/ 2023
A Consumable-less Propulsion System Based on a Bare-Photovoltaic Tether		

Executive Summary

Prepared by Universidad Carlos III de Madrid, TU Dresden, University of Padova and SENER Aeroespacial for ESA Contract No. 4000135893/ 21/ NL/ GLC/ ov

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1 Background and Goal of the Project

Space ElectroDynamic Tethers (EDTs), i.e. long conductors in orbit that interact with the planet's magnetosphere to generate a Lorentz force without using propellant, experienced an important progress during the last few decades. Old EDT systems, like the ones flown in the Tethered Satellite System-1 (TSS-1) and TSS-1R missions by NASA and ASI in 1992 and 1996, involved very long (20 km) insulated wires equipped with a big sphere for electron collections and active electron emitters. A radical change happened in 1993 [1], when the bare tether concept was introduced and the need for a big sphere was eliminated because the tether itself captures the electron passively. More recently, it has been proposed to eliminate the electron emitter by coating a tether segment with a low-work-function material and emit the electrons passively through the thermionic [2] and the photoelectric [3] effects. Parallelly, it was shown that the use of tape instead of wires provides better performance and safer operation [4]. These innovations have transformed EDT technology that are nowadays much more simple, compact and involve much shorter tether length (in the order of the kilometer). Two examples of recent missions with EDTs are the Tether Electrodynamic Propulsion CubeSat Experiment (TEPCE) by the Naval Research Laboratory and the Miniature Tether Electrodynamics Experiment (MiTEE) from the University of Michigan, both involving cubesats. In Europe, the E.T.PACK Initiative [5,6] is preparing a 12U deorbit device to be demonstrated in orbit in 2025. This renewed interest on EDTs is based on their reversible character to exchange orbital and electrical energy and produce drag and thrust, their maneuverability capability, scalability, and their good performance in a broad range of orbital parameters. EDTs are a promising technology for a broad range of space applications like deorbiting, in-orbit servicing, drag compensation scenarios, and missions to planets with magnetospheres.

To boost the performances of EDTs and prepare an even more compact system it was recently proposed to combine thin-fill solar cell and EDT technologies in a single concept named the bare photovoltaic tether (BPT) [7]. Harvesting power from the tether itself has two potential benefits. In the first place, the power can be used to increase the electric current, thus reaching a higher Lorentz force and performances. In the second place, it opens the possibility of using expellant-less electron emitters, like Electron Field Emitters, while reaching high currents. Both benefits can be achieved while keeping the simplicity and passive character of EDTs because the solar cells are fully integrated with the tether and the only impact is a slight increase of its thickness.

The goal of this project is to demonstrate the feasibility of the BPT and assess its potential impact on EDT technology. To achieve it, the following objectives are proposed: (i) Identify the most promising pv technology and make an electrical and mechanical design of the bare-pv tether, (ii) Demonstrate the feasibility of the BPT by performing a detailed electrical and mechanical characterization, and (iii) Incorporate a bare-pv model into a mission analysis software and study its performances.

2 Project Results

2.1 Bare-Photovoltaic Tether Design

2.1.1 Requirements

Mission, functional, performance, interface, design, and operational requirements for the BPT were prepared based on the state-of-the-art of thin-film solar cells, as well as in view of the future exploitation as part of a EDT system. EDT system will be used not only for deorbiting but also for station keeping and orbit mobility.

2.1.2 Solar Cells Trade-off

The trade-off analysis of thin film solar cells included a broad range of criteria that included the origin of the provider, the substrate, the efficiency, the thickness, the bend radius, and the cost, among others. Copper-Indium-Gallium-Selenide (CIGS) cells were chosen as the most promising for this project, and the Austrian company Sunplugged as the preferred provider. They offer PCEs (9%) and bend radii (4 cm), are capable of manufacturing on both polyimide, aluminum, and stainless-steel foils and have significantly lower prototyping costs. All the samples of the project were ordered to Sunplugged.

2.1.3 Electrical Design of the Photovoltaic Tether Segment

Several drawbacks were identified for the electrical design proposed in Ref [BPT]. For this reason, the project proposed two alternative architectures and made a trade-off analysis to select the most appropriate for the project. In the selected configuration, which is shown in **Fig 2.1.3a** and it was introduced in this project, the pv cells and the bare tether are separated by a layer of insulation (see top panel **Fig. 2.1.3a**). The pv cells are organized into cell/submodules that are connected in parallel. Therefore, the voltage at every cell/submodule is the same, whereas the current delivered by each cell is added up. Therefore, this configuration results in a constant voltage over the length and a current gain per length of the PTS. To connect the submodules in parallel, it was necessary to include two additional electrical paths. Such a design results in an additional loss of active photovoltaic area. However, it allows connecting the solar cells in parallel and has the two poles of the PTS at the S/C, where the power can be used to enhance the performance of the tether or other subsystem. The electric pathing must be dimensioned to both comply with the tether thickness of tens of microns and to withstand the thermal environment and the electric current.

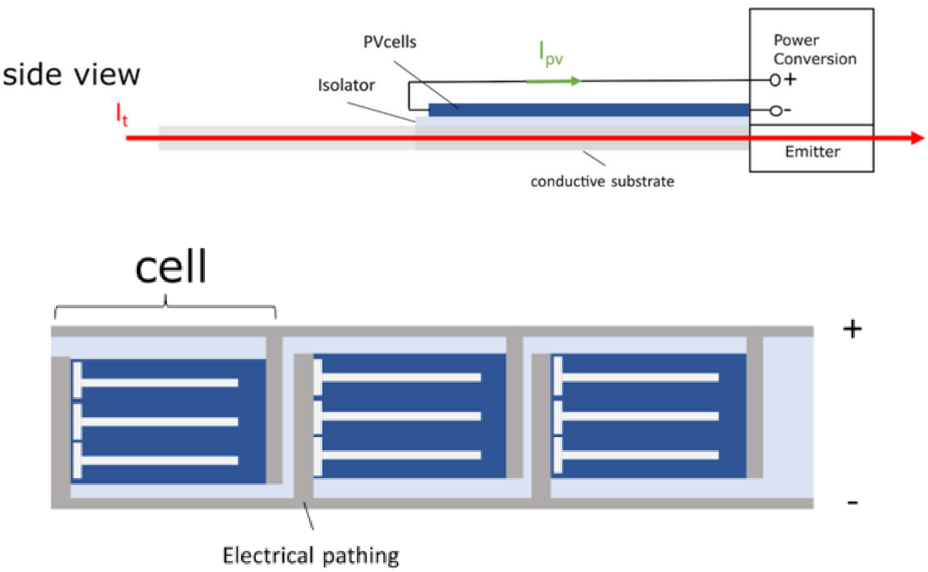

Figure 2.1.3a. Design of the photovoltaic tether segment (PTS).

2.1.4 Mechanical Design of the Bare-Photovoltaic Tether

The analysis set a requirement for the mechanical resistance of the BPT tape to be better than 10 N. This requirement stems primarily from the tensile force used to wrap the tape onto a spool or alternatively into a set of coils that have a stable geometry and can withstand the launch. The tensile loads provided by the torque motor to extract the tape from the deployer are substantially lower than the spooling values. Moreover, the tensile load on the tape during deorbiting and associated with the tether dynamics driven by the environmental forces are much lower (i.e., less than 1 N) as shown by simulations.

The project also analyzed the compatibility of the BPT with the deployer that has been developed in the framework of the E.T.PACK project. For such a deployer, the BPT is pressed and pushed out by two driving pulleys. Consequently, a test was performed to measure the PTS performance before and after the deployment experiment with the goal of verifying that the deployment does not damage the photovoltaic cells. It was found that the deployment through the drive pulleys does not dramatically impair the PTS performance: in the worst case scenario that was analyzed, a maximum loss of power post-deployment of 27% when compared to the pre-deployment performance.

A study on the joint between the two tether parts (bare segment and PTS) was also carried out by making a trade-off analysis between a double size transfer tape, glue, and soldering/brazing. It was concluded that the preferable solution is a double-sided transfer tape for its simplicity and versatility. Glue option will be also valid in case more structural resistance is required. Nonetheless, such a joint can be avoided if the insulation layer and the pv-cells shown in **Fig. 2.2a** are directly prepared on the top of the same tape of aluminum of the bare tether.

2.2 Photovoltaic Tether Manufacturing

For the selected configuration, samples of PTS with different patterns for the arrangement of the pv cells and using different material were manufactured. In total, 35 submodules were manufactured on a stainless-steel substrate, which all have a length of 25 cm and a width of 2.5 cm. Additionally, 60 submodules were manufactured on the aluminum tether with the same dimensions. Twelve of them were connected together to form a 3 m PTS sample. In addition, six PTS samples of 1.5 m length were manufactured, using 36 submodules. An example of a 1.5 m PTS sample is shown in **Fig. 2.2a**.

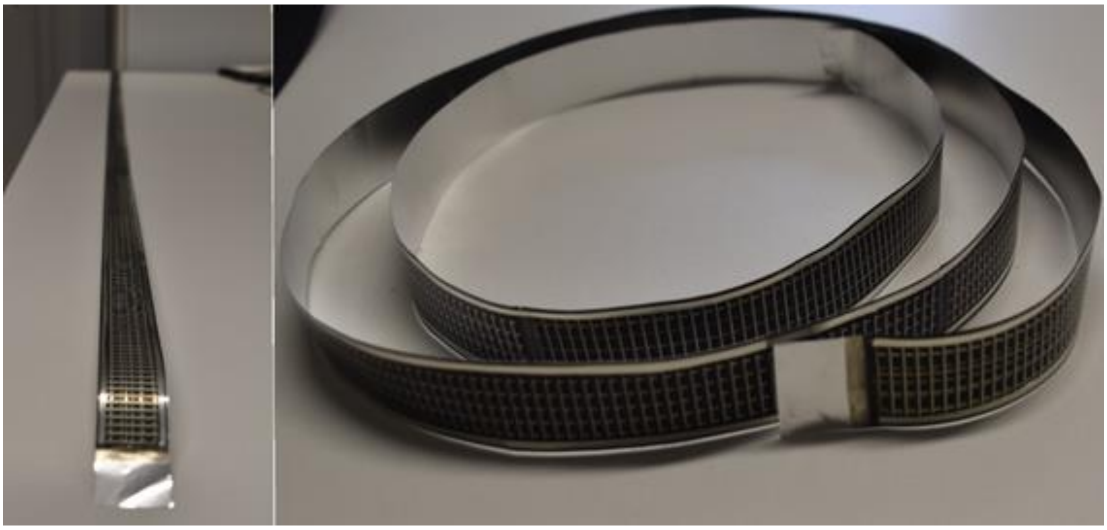

Figure 2.2a. PTS sample with a length of 1.5 m. It has 6 submodules and each of them consists of four parallel strings of 80 solar cells in series.

For the investigation of the PTS robustness to atomic oxygen, 48 special samples of different materials with 40 mm x 40 mm geometry were manufactured on stainless-steel. Their material combinations involve silver and copper for the grid, solgel and CAG37 for the encapsulation, and Aluminum-doped Zinc-Oxide and Indium-Tin-Oxide for the transparent conductive oxide.

2.3 Electrical and Thermal Characterization

Tests were carried out to investigate the impact of vacuum, temperature and atomic oxygen on the I-V characteristic of PTS submodules [7]. The experimental results show no detrimental influence of a high-vacuum environment, but even slight improvement in efficiency was measured. The average power conversion efficiency (PCE) of the submodules of the current design under AM0 illumination was 5.2% at room temperature (20 °C). The PCE is highly changed at different temperatures. An average temperature coefficient of -0.508 %/K was determined, meaning that an increase in temperature from 20 °C to 120 °C leads to a decrease of the PCE by 50.8%, so that the PCE of the current PTS at 120 °C would be 2.6%. To overcome this problem, the use of coating to improve the thermo optical properties was investigated. Experiments showed that the uncoated sample reached a steady state temperature of 140 °C, while the coated samples reached temperatures of 106 °C (silicate-based Solgel) and 85 °C (CAG37) respectively. The coatings were also investigated as a protection against ATOX. Both coatings successfully protected the silver electron collecting grid of the PTS during the exposure to a microwave-plasma-based ATOX source.

2.4 Mechanical Characterization

The strength characteristics of the tape either for the Steel or Aluminum substrates are much higher than the required 10 N level specified by the requirement BPT-P-0020. The experimental results on the damping coefficient appear to be reliable as similar results are found with two completely different methods of testing. With the vibrometer the damping coefficient was estimated from the decay of an induced oscillation, while with the Bose ElectroForce© machine the coefficient was derived from computing the energy dissipated within the hysteresis cycle. The values of the damping coefficients for the PTS are low (i.e. damping coefficient in the range 2 – 4 Ns/m), reinforcing the need for adding damping into the tether system as the one used in E.T.PACK system or with active control by a reeling deployer. On the other hand, deployment tests through the drive pulleys do not dramatically impair the PTS performance: in the worst case scenario that was analyzed we evaluated a maximum loss of power post-deployment of 27% when compared to the pre-deployment performance.

2.5 Bare-Photovoltaic Tether Performances

Theoretical models to compute the current and voltage profiles for BPTs in the passive and the active modes were prepared. Code was developed to compute them efficiently and robustly. The power harvested by the pv cells appears in the model as a power supply placed between the tether and the electron emitter. These models were used to prepare optimum design scheme that allow to select the optimum size of the PTS for a given mission. The analysis made evident the benefit of using a pv-segment, especially when the BPT is combined with expellant-less electron emitters like electron field emitters. The performance, measured in terms of the normalized average current and for the same total tether length, increases considerably (about 30% and, in same extreme cases, almost a factor 4).

The mission analysis software BETsMA v2.0 [8] was extended to include the operation of BPTs in the passive and the active mode. The software was used to determine the performances of the BPT in three scenarios: (i) the IOD of the E.T.PACK-F project, (ii) key commercial scenarios identified in the market analysis of the BMOM project, and (iii) the deorbiting of the Orbit Transfer Vehicle of an European microlauncher. The simulations highlighted the strong benefits of adding a pv-segment because fully autonomous deorbit devices based on BPTs, with mass a small fraction of the total mass of the system, can deorbit within a few months even at high inclined orbits.

2.6 BPT Development Roadmap

The development plan of the BPT was aligned with the schedule of the E.T.PACK-F project, which includes an In Orbit Demonstration mission in 2025. It was proposed an independent development and qualification plan for the BPT that will run in parallel with the E.T.PACK-F activities. A BPT segment will be included in the E.T.PACK IOD mission only in case of successful Qualification Review (QR). A schedule with key milestone and decision points for the development of the BPT were prepared and some critical areas were identified. They include the mechanical resistance to deployment, the electrical interface, and failure propagation to the system.

A BPT preliminary design for the IOD was prepared. It was proposed to fly a 3m PTS that could potentially provide “fully lit” about 2.4 W at 100 ºC in vacuum. The width is the same considered in E.T.PACK-F (2.5 cm) and its overall thickness is 95.9 microns. The arrangement of the BPT submodules was design to connect the BPT directly to E.T.PACK commercial Electrical Power System. First compatibility test were performed.

3 Conclusions

The experimental and theoretical activities conducted in the project showed that the Bare-Photovoltaic Tether concept is feasible and its implementation in tethered system can boost the performance. The development roadmap identifies the E.T.PACK IOD as a good opportunity to test the concept in the space environment and increase its TRL.

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