Geosci. Instrum. Method. Data Syst. Discuss., 2, C253–C268, 2012
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Geoscientific Instrumentation Methods and Data Systems
Discussions

Interactive comment on "Electric solar wind sail mass budget model" *by* P. Janhunen et al.

P. Janhunen et al.

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Received and published: 6 November 2012

REPLY TO REFEREE 2

We thank the referee for his thorough reading of the manuscript and for the numerous valuable comments that helped to improve it.

Note: Corrections due to Referee 1 comments appear in red and corrections due to Referee 2 comments (i.e. the present ones) appear in blue. The revised manuscript is in a "supplement file" attached to this reply.

COMMENT 1: In the abstract, it refers to the "number of tethers" while the need for tethers is not obvious for the reader unfamiliar with the concept.

ANSWER 1: We added the following sentence to the abstract: "The E-sail consists of thin centrifugally stretched tethers that are kept charged by an onboard electron gun and, as such, experience Coulomb drag with the high-speed solar wind plasma stream." We also added the following sentence to the Introduction: "The charged tethers experience Coulomb drag with the high-speed solar wind plasma stream and thus generate a propulsive thrust which is transmitted to the spacecraft mechanically by a slight bending of the tethers perpendicular to their spin plane (Figure \ref{fig_schematic3D}).", and we added a supporting schematic Figure 1.

COMMENT 2: The potential applied is always assumed throughout the paper to be 20 kV; it is not clear as to why this is not considered as a variable parameter in this study. This is regarded as one short-coming of the paper... The lack of using the High-Voltage value as a variable parameter is however a short-coming that should be corrected in the revised manuscript. The parametric variation of the HV value, may allow addressing the technology related to the High Voltage technology and identify critical aspects related to this feature of the E-sail.

ANSWER 2: We have now added a subsection with two new figures where the effect of varying the voltage is investigated.

COMMENT 3: Lots of parameters are defined throughout the paper and referred to by a symbol. I have spotted some that are either not defined or not defined the first time they are used.

ANSWER 3: The other referee also noted some of these errors. Corrections due to his comments appear in red.

COMMENT 4: An overall mass margin of 20% is assumed, which may be a rather low value for a new system that is based on a new concept. I would suggest to use a higher value.

ANSWER 4: Our aim is to get a more or less conservative /estimate/ for the true mass of the system, rather than an upper bound which with some high certainty would not be exceeded. Based on our provided numbers, a reader is anyway free to add his/her

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own margins if desired. If we would be designing a real mission, we would of course apply the margin policy used with the specific organization who builds it.

COMMENT 5: Line 6: The term "scientific payload" may be misleading. Throughout the paper it should be understood as the mass of everything else but the E-sail system itself. With reference to an electric propulsion mission (Dawn, BepiColombo) it would then mean that all but the electric propulsion subsystem constitutes the scientific payload, which is not what the term scientific payload is meant to be. I would suggest to use another term instead of "scientific payload".

ANSWER 5: We now call it just "payload" throughout and have added the following explanatory paragraph: "Note that the term “payload” in this paper refers to the payload instruments and the telemetry system, but it does not include the power system, structure or thermal control subsystems. The rationale for lumping the telemetry system with the payload is that the payload drives telemetry requirements, not the E-sail. On the other hand, the power system is kept separate because typically the payload uses only little power during the cruise phase and thus it makes sense to share the power system hardware between the E-sail and the payload."

COMMENT 6: Line 25: It should be made clearer that a High Voltage power supply is required to polarise the tether at high voltage. The electron gun is only a support device to help expel the electron current collected by the tethers: hence to help maintain the spacecraft bus near zero volt; the phrasing "... are kept in a high positive potential by an on-board electron gun..." is misleading. It should be rephrased.

ANSWER 6: We added: "... onboard electron gun PUMPING OUT NEGATIVE CHARGE FROM THE SYSTEM".

COMMENT 7: Line 29: I suggest to use the word "reference" instead of "baseline"

ANSWER 7: We now write: "Our reference full-scale E-sail propulsion system..."

COMMENT 8: Line 32: How do you come to the value 960 W for the electron gun?

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ANSWER 8: From Equation (4). Since this is the Introduction, the reader of course cannot know where the value comes from. But we think that it's better to give some numerical value already here, rather than not to give any value. It should be implicitly clear to the reader, we hope, that the values given here follow from the formulas presented later.

COMMENT 9: Line 33: Provide a reference to previous work for this reference design, and explain in more detail the reasons behind the choice of this reference design. It should be verified that it does not bias the results of the parametric study.

ANSWER 9: We added a reference to Janhunen et al.(2010) at this point. At a later point (at the end of the first paragraph of Section 2), we added the following sentences: "The reason for including the auxiliary tethers is that they keep the tether rig dynamically stable without the need of active control (Janhunen et al., 2010). The motivation for including RUs is to host the auxiliary tether reels and small thruster whose purpose is to generate the initial angular momentum and possibly to control the spin rate later during flight if needed."

COMMENT 10: The reader may be confused with the use of the word "potential", it may be understood as an adjective while it is meant to the noun. The sentence should be rephrased.

ANSWER 10: We now write: "ELECTRIC POTENTIAL STRUCTURE overlapping between them ..."

COMMENT 11: The overlapping of the sheaths is also a function of the High Voltage applied to the tethers. It should be said that the sheaths always overlap near the root of the tether as the spacing is small, and the overlapping breaks at a certain distance from the root of the tether (this distance being a function of the HV applied, and the Solar Wind conditions). Some numbers (distance at which the overlaps breaks vs HV value) should be given to illustrate concretely this point.

ANSWER 11: This is a worthwhile comment. We added the following paragraph: "Our above assertion that overlapping between electric potential structures of different tethers can be neglected can be justified as follows. At 1 au the potential structure radius is $\sim$100 m under average solar wind conditions. In all E-sail models considered in this paper the distance between the tether tips is 2*pi*20 km/100 = 1257 m. Thus under normal conditions, overlapping affects about 200 m/1257 m=16 % of the tether length. The electric potential structures scale as proportional to the solar distance r because they are proportional to the plasma Debye length which goes as $\sim$ 1/\sqrt{n} where n is the plasma density, and n $\sim$ 1/r^2. Therefore, at 4 au overlapping can affect $\sim$64 % of the tether length. Near the main spacecraft where the tethers are quite close together, they form an effectively impenetrable obstacle to solar wind ions such that ions are reflected back. Modelling of how the thrust behaves inside the overlap region has not yet been done. We estimate roughly, however, that on average, within the overlapping region the thrust is 60 % of the free tether value. This would imply that at 1 au the thrust is reduced by $\sim$6 % by overlapping and at 4 au it is reduced by $\sim$25 %."

COMMENT 12: Line 36: Provide a reference to the fact that the thrust varies with 1/r

ANSWER 12: Added a reference to Janhunen (2009).

COMMENT 13: Line 47: Delete "expectedly"

ANSWER 13: Done

COMMENT 14: Line 49: Clarify that these numbers apply for the reference case. Provide a literature reference (the same as the one requested above) for the numbers provided.

ANSWER 14: Added Janhunen et al. (2010).

COMMENT 15: Line 55: The technique behind the constant power strategy should be explained. Does it have an effect on the sizing of one of the subsystems?

ANSWER 15: The story of why the E-sail thrust varies (or can be arranged to vary) much less than the solar wind dynamic pressure is rather long, and to explain it in full would require one to explain rather many other concepts too (such as current-limited versus voltage-limited operating regimes of the electron gun). Since the explanation is already given in the reference (Toivanen and Janhunen, 2009), we do not think that one should write it again in this paper. We actually think that what we wrote is a reasonably good one-sentence summary of it. We just added now: "... due to certain plasma physical effects SUCH AS DEBYE LENGTH SCALING...".

As to the question wether it has some effect on subsystem sizing, we think not. Using all available electric power for running the electron gun is, we think, a simple strategy to implement. The only thing is that one has to select the electron gun voltage so that the gun operation is (in the optimal case) neither current nor voltage limited. The optimal voltage depends only on the instantaneous solar wind plasma density: when the density is low, the current gathered by the tethers is also low, so one can use a higher voltage with the available power and vice versa.

One possible strategy for controlling the gun voltage could be as follows. When the gun is in current-limited mode, its voltage is higher than the tether voltage so that the expelled electrons still have excess kinetic energy after having been shot by the gun into the surrounding plasma. In other words, in the current-limited regime, increasing the gun voltage does not increase the tether voltage. One can detect when the gun is in the current-limited regime by measuring the electric potential of the spacecraft with respect to the plasma (at some reference point whose voltage with respect to the tethers is known) by e.g. a small omnidirectional electron detector. The detector produces the electron energy spectrum from which one reads off the energy of the peaked electron flux corresponding to solar wind electrons accelerated by the spacecraft potential. Then, one way to control the gun in a nearly optimal way is to ensure that we are always slightly in the current-limited regime so that the tether voltage (as determined by the electron detector) is slightly smaller than the gun voltage. The only hardware one needs to do this is the simple electron detector and a proportional (or PD, or PID)

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controller.

COMMENT 16: Line 59: ".. The main tethers are spun..." should be rephrased. It's not the tethers which are spun, but the spacecraft bus that holds the tether deployment mechanisms.

ANSWER 16: We now write: "The SPACECRAFT WITH ITS ATTACHED main tethers are spun..."

COMMENT 17: Line 60: why is a factor of 5 so critical? Is there any latitude in this number?

ANSWER 17: It's a rough number, as indicated by the "$\sim$" sign. In dynamical simulations of the tether rig one sees that stable behavior results if the centrifugal force is at least about five times larger than the solar wind force.

COMMENT 18: Line 62: Clarify the unit "cN".

ANSWER 18: It is centinewton, now written in parentheses.

COMMENT 19: Line 64: Replace "along" by another word

ANSWER 19: Replaced by "over"

COMMENT 20: Is there not also a potential risk associated with an impact on the spacecraft bus itself as it would induce a plasma cloud around the spacecraft that may be a disturbing environment for the HV involved. It is recommended to address this point.

ANSWER 20: When a plasma cloud is produced by a micrometeoroid colliding with a tether wire, the resulting electrons are partly pulled back to the wire and partly remain trapped until being removed after few minutes by orbit chaotisation and collisions (Janhunen, 2009). Positive ions are repelled by the tether and thus they move out. Our baseline approach is to have the main spacecraft body in floating (nearly ambient) potential. Then, plasma produced by a micrometeoroid hit on the main spacecraft

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behaves similarly to solar wind plasma: electrons are mostly not trapped by the wire potentials but move through in hyperbolic orbits, and ions are repelled as before. Collision with the tethers is much more likely than collision with the main spacecraft, because the tethers typically have a larger combined surface area.

The total charge in the tethers of a full-scale E-sail is of the order of one coulomb. Thus a trapped electron population circling around the tethers can appreciably reduce the thrust by shielding the positive charge of the tethers only if it contains of the order of 1e18..1e19 electrons. When a single tether wire is cut by a micrometeoroid hit, typically about 50 micrometer cubed volume of aluminium is vapourised. This amount of aluminium contains only of the order of 1e12..1e13 electrons if ionised. Thus, in normal micrometeoroid hits the number of electrons produced is too small to affect the thrust. Even if the impactor is larger, the result does not change much, for example if a 1 mm grain hits a 50 micron wire, the material vapourised (1 mm long 50 um diameter wire segment) still has only 5e13 aluminium atoms.

High voltage parts may arc if intermediate density gas (whose mean free path is larger than in ambient atmosphere but smaller than the device size) is present, because then the strong local electric field may cause an electron impact ionisation cascade. Therefore, outgassing issues must be taken seriously by E-sails and other HV containing space equipment. However, gas from a micrometeoroid impact (if occurring on the spacecraft hull) becomes non-collisional rather soon after the molecules leave the impact point. The risk that intermediate density gas might get inside the spacecraft seems small and possible to eliminate by proper design.

COMMENT 21: Line 71: Is it reasonable to assume full thrust for 10 years of flight at 1 N? At what distance from the sun would the thrust remain at 1 N?

ANSWER 21: The thrust scales as 1/r so it remains at 1 N only at 1 au. We added: "about 1 au".

COMMENT 22: Line 72: Remote the "s" in "MNs".

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ANSWER 22: MNs is correct: meganewtonsecond.

COMMENT 23: Line 77: For a full comparison, would it not be appropriate to address what is limiting the efficiency of an electric thruster? Am I correct in assuming that, if the ejection velocity of the ions could be increased (by increasing their acceleration voltage) the efficiency of the electric thruster would be increased, hence less propellant would be required. Would it be relevant to consider, for comparison, the performance of an electric thruster that works with the same HV as the one used for the E-sail (25 kV)?

ANSWER 23: If one could build an electric thruster with very high specific impulse (the relationship between the voltage and the specific impulse depends on the type of ions), indeed one can thereby lower the propellant consumption. But the showstopper is that then the power consumption becomes very high per produced thrust. For example, if the specific impulse would be as high as 300 km/s so that one could eventually reach hundreds of kilometers per second total delta-v as the E-sail, the power needed to produce 1 N of thrust would be 0.5*F*v=150 kW, and in practice more since electric thrusters do not have 100% efficiency. This is huge power compared to the below 1 kW level consumed by the E-sail. Having such high power levels in space is not only a problem of where to obtain the energy, but also especially how to get rid of the inevitably large waste heat. Of course, it can be done in principle by using nuclear energy sources, but even then with orders of magnitude heavier propulsion systems than the E-sail apparatus.

We think that it is safe to conclude that if the E-sail works anywhere close to its predicted performance, no ion engine can compete with it in raw performance (total impulse per mass, for given thrust), and the reasons for this are more of fundamental than technical nature.

COMMENT 24: Line 86-87: Explain what is meant by "near-term technology data"

ANSWER 24: We meant that the masses are not "science fiction" but are mostly based on existing systems. Anyway, we removed the expression because it is not essential.

COMMENT 25: Line 91: Replace "constituted by" by "consisting of"

ANSWER 25: Done

COMMENT 26: Line 92: add a "a" in "having a length"

ANSWER 26: We don't agree, grammatically. But we now write: "each one with length L".

COMMENT 27: The parameter m_str and eta_str do not seem to be defined

ANSWER 27: We removed m_str because it is not used anywhere (it is included implicitly by eta_str). Eta_str is now defined as per Referee 1 corrections (red text in the revision).

COMMENT 28: The fact that new parameters used in equation (2) are only defined in the next subsection makes it difficult for the reader to understand the equation (2)

ANSWER 28: Fixed as per Referee 1 comments (red text in the revision).

COMMENT 29: 3rd line in section 2.1: What is the reference for "gamma_eg = 1.0 kg/kW". Is this applicable to the required parameters for the electron gun in this application?

ANSWER 29: We added a reference to Zavyalov et al. (2006). It is an internal unpublished report.

COMMENT 30: Line 113: Here it is mentioned that a "... simple strategy of varying the tether voltage..", while later, line 143, it is written that each tether can have its own high voltage source..". If each tether has its own voltage source, does it require that all voltages are synchronised or can each high voltage source be adjusted independently from the others? It is not clear how the P_eg is controlled if there is a power source for each tether.

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ANSWER 30: To turn the spin plane, one must modulate the tether voltages so that, for example, the voltage is a bit smaller always on the left side of the sail where the directions are defined with respect to some inertial coordinate frame. This means that the modulation must be synchronised with the rotation. There are many ways to achieve the modulation technically. For example one can use a single central HV source and have a tunable resistor (potentiometer) between each tether and the main spacecraft (or the HV bus inside the main spacecraft). Alternatively, each tether could have its own HV source. Intermediate cases are also possible: the tether might be clustered so that each cluster has its own HV source and inside cluster, modulation is done by resistors.

The electron gun voltage must be set equal to the potential of the tether which has the highest voltage (or somewhat larger, so that the gun operates slightly in the current-limited regime if that is easier to control). The first sentence "..simple strategy.." concerns the overall control of the electron gun which is more an algorithmic than hardware topic, while the latter sentence refers to the hardware question how many HV sources and/or potentiometers are used to achieve the necessary differential tether potential modulation.

It would also be possible to equip each tether, or cluster of tethers, not only with its own HV source but also its own electron gun. One might even have them in the Remote Units rather than the main spacecraft. Overall the number of possible HV engineering designs is rather large.

COMMENT 31: Line 147: I was not able to find information on the Ultravolt voltage source model 35A24-P30. A proper reference should be given. What is the output voltage? If it is below the value needed for the envisaged application, can the same technology be used for the required HV value? The availability of the HV technology for the envisaged application should be further discussed, as it is a critical item. It would be useful to make reference to already flown HV subsystem and discuss applicability of the used technology to the E-sail.

ANSWER 31: The relevant Ultravolt page is http://www.ultravolt.com/products/373 ("30A-40A Series"), and one should load the data sheet http://www.ultravolt.com/uv_docs/30A-40A.pdf. The type "35A24-P30" means 35 kV output voltage, 24 V input voltage and 30 W output power. Power levels 4 W, 15 W and 30 W, input voltages 12 and 24 V and maximum output voltages 30 kV, 35 kV and 40 kV are available in any combination. The datasheet also gives the masses of the various models (on the second page), the 35A24-P30 weighs 0.426 kg.

We added a reference to Ultravolt's www page.

We also added the sentence: "Regarding space qualified high voltage systems, electrons guns with up to 40 kV energy have been successfully operated on sounding rockets for scientific purposes (Nemzek and Winckler, 1991)."

COMMENT 32: Line 155-160: is the parameter rho_Al defined?

ANSWER 32: It was defined in the first sentence of section 2.2, "Main tethers".

COMMENT 33: Line 160-165: Provide a reference for the description of the two test missions mentioned: ESTCube-1 and Aalto-1

ANSWER 33: Three new references added.

COMMENT 34: Section on Remote Units. I am missing a description of this unit. What is the power supply for it? How are they controlled?

ANSWER 34: We added reference to Wagner et al.(2012). The Remote Unit is self-powered by small solar panels and it is commanded remotely by radio from the main spacecraft. The reference added contains a detailed design of the Remote Unit. The Remote Unit mass estimates are also based on that design.

COMMENT 35: In several places, remove the "s" from "Ns"

ANSWER 35: Ns (newtonsecond) is the correct unit of impulse and momentum.

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COMMENT 36: Formula (8): is Rho_Ka defined somewhere? Section 2.6

ANSWER 36: Kapton mass density rho_Ka is defined at start of section 2.4, "Auxiliary tether"

COMMENT 37: The performance of the camera (operating under day light conditions) are not assessed

ANSWER 37: For example, a 1 W light-emitting diode at 20 km distance, radiating in 1 srad solid angle (30 degree half-angle) is already equivalent to magnitude 2.2 star, i.e. a rather bright star. Since the diode emits at only one wavelength, background stars can be efficiently removed from the image by filtering. Considering these numbers, imaging the beacons should not be a difficult task.

COMMENT 38: Line 199: What are the pointing requirements for the optical beacon; where is the receiver? under which conditions are the pointing requirements met?

ANSWER 38: According to our dynamical simulations, the Remote Unit is rather well kept in its nominal attitude by the three tethers attached to it (one main tether and two auxiliary tethers). Thus, the same side of the Remote Unit always faces the main spacecraft. Nevertheless in answer 37 above we assumed conservatively that the beacon's radiation pattern has a half angle of 30 degrees. The receivers (cameras) are on the main spacecraft.

COMMENT 39: Line 202: an allocated mass of m_gc=1 kg seems to be a low number for a guidance computer; what level of radiation shielding is assumed?

ANSWER 39: Given that an entire satellite (CubeSat) can nowadays be implemented with 1 kg mass and less, and because the computing power requirements are low in this case, we think that 1 kg is actually a conservative estimate for the needed computer mass. The required radiation shielding level correspond to the solar wind, i.e. less severe than for typical MEO or Molniya satellites which are partly in the radiation belts.

COMMENT 40: Line 219: A power consumption of 0.1 W/kg seems to be very low.

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ANSWER 40: It is low, but please note that it's the idle power consumption. When the instruments are active, we assume a ten times higher value (1 W/kg). For many instruments, the idle power could be even zero (power turned off completely).

COMMENT 41: Line 230: Please clarify the value 1 W/kg. Does it mean that a 1000 kg power subsystem is required to provide electrical power to the electron gun(s)? It seems to be the right assumption when I refer to table 1.

ANSWER 41: This figure is for power consumption in the (scientific) instruments, not power production. It means that a 1000 kg payload would consume 1 kW of power when the instruments are in use.

COMMENT 42: Line 234: the parameter gamma_sa does not seem to be defined

ANSWER 42: It is defined in section 2.6: "We assume a specific mass value of gamma_sa = 10 kg/kW for the power subsystem as a whole,.."

COMMENT 43: Line 241: the parameter eta_sa does not seem to be defined

ANSWER 43: We added: "power produced by the panels at end of life is assumed to be eta_sa times less than at beginning of life".

COMMENT 44: Line 242: clarify "... the power system produced..."

ANSWER 44: we don't seem to find this exact phrase any more, probably it has been changed already

COMMENT 45: Line 250: Please clarify how pointing to the sun is maintained

ANSWER 45: Before deploying the tether rig, attitude is controlled in usual ways, typically momentum wheels and thrusters. During and after tether deployment the large angular momentum of the tether rig stabilised the attitude, which can, however, be changed by applying rotation-synchronised voltage modulation to the tethers when the E-sail is on, as explained earlier (Answer 30). When orbiting the sun with E-sail active, the attitude must be slowly corrected by this method because otherwise the spin axis

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tends to stay in a fixed position with respect to distant stars.

COMMENT 46: In the two-line text beteen formula (10) and (11), in the review version the meaning of the greek letter "Delta" above the sign "=" is not understood. This symbol is used in other places.

ANSWER 46: It means define, or by definition. We now replaced it with an equal sign with three horizontal lines.

COMMENT 47: Line 276-277: The reader should be referred to Table 1 earlier in the manuscript, when undefined symbols are used.

ANSWER 47: After corrections due to both referees, there shouldn't be undefined symbols any more in the manuscript

COMMENT 48: Line 285: remove the "s" of "accelerations"; the meaning of a 3 value vector is not obvious (although it can be deduced as meaning three different values by reading table 2,3,4)

ANSWER 48: Changed as requested

COMMENT 49: Line 365: Same remark as for line 285 for the 4-value vector

ANSWER 49: Changed as well

COMMENT 50: It is understood that such an E-sail may be used to get close to a NEA; does the conept allow to arrive at zero-velocity at the asteroid or does the mass budget include the mass required to slow to low velocity at the asteroid?

ANSWER 50: In principle it allows very slow approach of the asteroid. In principle a limit may be set by the small photonic thrust exerted on the tethers: because the small remnant photonic thrust cannot be zeroed by the E-sail, it must be zeroed by traditional thrusters during the proximity operations. Such cold gas thrusters are probably part of the ACS anyway.

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COMMENT 51: As noted above, the value of the high voltage is a variable parameter. The reason for the choice in this parametric study should be explained.

ANSWER 51: Hopefully fixed now by the addition of new subsection and new figures, as explained in Answer 2

COMMENT 52: Line 405: The wording "... but is wanting in ..." is not understood

ANSWER 52: It was indeed obscure. We now write: "..., but LACKS propulsive capabilities".

COMMENT 53: Line 411 and in several other places in the text it should be clarified that "scientific payload" is meant as the payload carried by the E-sail, not only the scientific payload as is commonly understood in a science mission

ANSWER 53: See Answer 5 above.

Please also note the supplement to this comment:
http://www.geosci-instrum-method-data-syst-discuss.net/2/C253/2012/gid-2-C253-2012-supplement.pdf

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