Technical Comments

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Reply by the Authors to A. D. Guerman and G. Smirnov

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BEFORE addressing the comments by Guerman and Smirnov [1], it is useful to briefly describe the aim of our paper [2] and the main assumptions made therein.

Because of their more efficient configuration, compound solar sails offer, in principle, significant performance improvements with respect to conventional flat sails. However, many uncertainties remain regarding the true superiority of the compound sails, because their characteristics are usually established assuming ideal reflection conditions. For these reasons, it is important to look for increasingly refined models that better approximate the real behavior of compound sails and to establish their performance limits.

The concept of compound solar sail, or solar photon thrustor (SPT), was drawn to the attention of the scientific community by Robert Forward in his famous paper [3] of 16 years ago. In that paper, he established the performance of what is usually referred to as the ideal SPT [2], the adjective *ideal* being related to the fact that all of the SPT components (collector, reflector, and director) are perfectly reflecting mirrors. In [3], the performance of the ideal SPT is found in a purely analytical form, neglecting physical phenomena such as aberration and shadowing. Also, as it is clear from the paper context, multiple reflections between SPT components are implicitly not allowed. This well-established model has been taken as a reference by various authors [4–8].

The aim of our paper [2] is to take a step further, by developing a more realistic SPT model in which, under the same assumptions made by Forward [3] (with the only exception of ideal reflection), the optical properties of its components are taken into account. In analogy with the common practice for solar sails [4], the new mathematical model is referred to as a nonideal or optical force model [2]. Based on this nonideal model, the resultant force acting on the sailcraft is calculated, and a link between the force coefficients and the optical sail film properties is established. Not only are the results expressed in an analytical form, but the ideal SPT model is easily recovered when the force coefficients are set equal to those of a perfectly reflecting surface. In this sense, the optical force model extends the ideal SPT model.

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Let us turn our attention to the comments by Guerman and Smirnov [1]. It appears that they [1] did not detect the relationship between Forward's [3] model and our [2] model. This lack is at the heart of much of the incorrect statements made in [1].

Consider, for example, the discussion on the ideal reflectors. In Fig. 3 of [1], the authors compare the ideal SPT model (curve 6) with their simulations and comment upon the discrepancy between curve 6 and their results. In doing so, they attribute curve 6 to us. This is incorrect, because, as previously pointed out, curve 6 is actually attributable to the original work by Forward [3] and is identical to that obtained by McInnes (see [4], p. 94) and by Flint [6]. The same result appears in [2] too, but there the ideal case is viewed as a particular case of our more refined optical model.

One interpretation offered by Guerman and Smirnov to explain the preceding discrepancy is that "the first effect missed in [1] is related to the substitution of the parabolic mirrors, usually considered for a DR SPT, by the spherical ones" [1]. Unfortunately, Guerman and Smirnov do not support the use of parabolic mirrors with any reference. On the other hand, when discussing the different SPT components, Forward states, "A spherical surface takes the nearly parallel light rays from the sun and concentrates them down at a focal point that is at one-half the distance to the center of curvature of the collector lens" [3]. It is following Forward that we have developed our model under the assumption of a spherical collector, as explicitly maintained in [2].

Having clarified the rationale behind our assumptions, the question remains of the remarkable differences between the results of Guerman and Smirnov [1] and those corresponding to an ideal model. This is a complex issue; because Guerman and Smirnov do not provide any information on their simulation model, their results can hardly be reproduced and their correctness cannot be checked. At high values of the sail cone angle, their results are clearly counterintuitive. In fact, from Fig. 3 in [1], the force due to the solar radiation pressure attains its maximum when $\alpha = 90$ deg (i.e., when the director surface is parallel to the incoming sunlight). This behavior fully contrasts with all available models [3,4] and, as such, should be supported by some evidence. Unfortunately, Guerman and Smirnov do not provide any convincing physical explanation for their results (the aberration effect is hardly a justification).

We will not address the comments on the nonideal SPT model, because our remarks would be similar to those already provided.

To summarize, the force model proposed in [2] is obtained in analytic form under the same main assumptions made by Forward [3]. The nonideal force model [2] provides the optimal control law for minimum-time interplanetary trajectories. The simulation results in [2] are completely consistent with the developed model and, as such, they are exact.

In conclusion, although the SPT model proposed in [2] represents an improvement with respect to the ideal model by Forward, the comments by Guerman and Smirnov [1] are not corroborated by clear and reproducible simulations. Also, their results for high values of the sail cone angle [1] are in sharp contrast with the physical explanation available in the literature [3,4].

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