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Managing Satellite Debris in Low-Earth Orbit: Incentivizing Ex Ante Satellite Quality and Ex Post Take-Back Programs

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Abstract
Increased economic activity in low-Earth orbit (LEO) in the past century created debris fields that impede current and future economic activities. We propose an economic model that combines elements of patent law with space law to enable comparisons of policy instruments. In particular, we propose policies that leverage the intellectual property rights system and that facilitate additional joint research and development to incentivize ex ante increases in satellite quality. Our model also considers the impact of individual and collective ex post LEO debris take-back programs, analogous to those designed for terrestrial contexts. Our results suggest policy refinements for the outer space context that may be of interest beyond managing satellite debris in LEO.

Keywords Economics of outer space · Orbital debris · Outer space pollution · Space law

JEL Classification Q58 · K32 · H23

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1 Introduction and Literature Review

Increased economic activity in low-Earth orbit (LEO) in the past century created debris fields that impede current and future economic activities. This is a relatively new type of pollution control problem that exhibits some classic public bad characteristics such as weak property rights and barriers to formation of regulatory coalitions (namely, international environmental agreements), but also some exotic characteristics—namely, a form of pollution (artificial satellites) that propagates via collisional cascading and that mixes with natural debris in a location that is expensive to reach with current abatement technologies. To our knowledge, there is a relatively thin literature in economics on the general topic of outer space satellite deployment and management—Sandler and Schulze (1981), Macauley (1998), and Weinzierl (2018) are three key references that call attention to this general topic—and only three additional papers, by Adilov et al. (2015), Macauley (2015), and Adilov et al. (2018) are concerned with the specific topic of satellite debris generation and management. Adilov et al. (2015) propose an innovative two-period model that features firms selling satellite services to consumers located along a Salop circle and independently choosing satellite launch rates. The authors find that perfect competition between firms results in a level of satellite launches that surpasses the social optimum and investment in debris mitigation that is below the social optimum. The authors derive an optimal two-part Pigouvian tax for this competitive context: the tax is applied per launch, but also has a component that is a function of a debris creation parameter that firms choose (i.e. firms can choose satellites that cost more but that create less debris if collisions occur). Adilov et al. conclude by noting that the tax revenue could be used to finance debris removal programs (for instance, the tax approach can create a double-dividend); however, they also note that while the Pigouvian tax is optimal in this competitive context, there are significant institutional barriers to overcome in order to carry out the policy in a cost-effective manner. Namely, there is not an intergovernmental institutional arrangement in place (such as an international environmental agreement) to administer and enforce the tax. As in Adilov et al. (2015), Macauley (2015) also prescribes a system of launch taxes to control low-Earth orbit debris; however, she matches the launch taxes with refunds to companies that successfully corral their satellites at end-of-life, analogous to the deposit/refund approach used to manage aluminum beverage cans and automobile batteries and tires. Her approach also includes rebates to satellite producers for incorporating certain ex ante debris mitigation technologies that yield spillover benefits, and she concludes by showing how her model could be used to generate empirical estimates of the taxes and rebates/subsidies, based upon collision probability and harm data. Most recently, Adilov et al. (2018) provide a dynamic economic model of debris accumulation in low-Earth orbit and show that economic forces will curtail activities in that region before it is so congested as to physically crowd-out further activities in the region.

In light of the above literature, the purpose of our paper is to explore two families of alternative policy approaches that rely either upon *existing* institutional frameworks for implementation/enforcement or upon Coasian arguments wherein policy might merely clarify property rights or coordinate firms' gains from trade on collective or outsourced take-back of debris or joint R&D focused upon reducing (ex ante) expected debris per satellite launched. First, we propose a more general model than is featured in Adilov et al. (2015) and Macauley (2015), so that we are able to compare a wider array of policy options. Second, we generalize the potential impact that a firm's ex ante choice of satellite quality and ex post choice of on-board control of satellites can have on the privately and socially optimal outcomes. In particular, whereas Adilov et al. have a firm's choice of quality affecting only the rate of debris generation and firm profit only increasing as satellite quality falls, we explore further the context suggested by Macauley (2015) in which firms capture private gains from designing satellites that are less prone to collision—and that when collisions occur, generate less debris per collision—but do not necessarily take spillover benefits from ex ante design into account. Third, we are inspired by Fleckinger and Glachant (2010) to consider incentive design for take-back programs that are either individually or collectively managed in this context. As a result, our approach emphasizes the identification of opportunities within existing institutional/regulatory structures to incentivize firms to build, launch, and operate more robust satellites, on the assumption that—as Adilov et al. (2015) and others describe—there does not exist a federal or intergovernmental institution that can impose typical regulatory instruments such as Pigouvian launch taxes or subsidies for implementation of certain technologies.

Before proceeding to our model and analysis, let us consider the historical context for the low-Earth orbit (LEO) pollution problem. At the start of the space age, LEO operations were undefined and unrestricted, as the United States and the U.S.S.R. were the only competitive space actors. Ten years after the Sputnik launch, the 1967 Outer Space Treaty failed to establish a clear and enforceable definition for orbital debris [see Tallis (2015)]. Shortly after this international agreement, the Space Liability Convention was held to further clarify the terms of the Outer Space Treaty, but it did not clarify the definition of space debris or establish a system to enforce any LEO pollution standard.[1] In the meantime, satellite launches to low-Earth orbit by a wide range of agents have increased dramatically over the past few decades.[2] With a higher level of launches, the ambient level of debris within operating orbits has increased. This initially was of little concern to the international community, which operated according to the "Big Sky Theory", i.e., that the sky is such a big place that the probability of a satellite collision is so small as to be of no concern. Kessler and Cour-Palais (1978) were pioneers in recognizing that further endeavors in space (particularly in low-Earth orbit) would become increasingly hazardous due to the careless production of satellites in that era and the chain reactions of collisions between active and defunct satellites. They found that from 1966 to 1978, the amount of trackable objects in orbit increased at an average of 13% per year. From this data, they produced probabilistic timetables of future collisions, noting the devastating severity even the smallest impact could have on a functioning satellite and the order of magnitude at which resulting debris is produced. The increasing rate of generation of new debris from collisions between satellites is referred to as collisional cascading.

More recently, Levin et al. (2013) estimate that each year there currently exists a 6% chance of catastrophic events in LEO. Indeed, a catastrophic event in LEO in 2009 demonstrated Kessler and Cour-Palais's prescience, wherein the defunct Russian satellite Kosmos-2251 collided with the commercially deployed telecommunications satellite Iridium 33. Resulting debris from this collision is estimated to have increased the probability that

[1] See Gabrynowicz (2010) and Landry (2013) for excellent overviews of space law, particularly in the U.S. context.

[2] As of 4/30/18, there were 1886 satellites in low-Earth orbit; see https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database#.W9SGk3tKh0w. As Anzaldua and Hanlon (2018) describe, while most current satellites are government-owned, commercial enterprises are planning to add upwards of 20,000 satellites into low and medium-Earth orbit in the near future. We are grateful to the anonymous reviewers for these excellent references.

an active satellite would be struck by debris greater than 10 cm by 24%. This was also the first hyper-velocity collision between orbiting intact satellites. As described by Wang (2010), prior to this event, much of the debris present in LEO was produced by missile tests, discarded rocket stages, and mechanical failures. As noted by Levin et al. (2012), active debris removal may be a viable solution given recent developments in electrodynamic debris removal systems, which have an estimated capability of removing 99% of LEO debris by mass created from collisions. Klima et al. (2016) focus upon this particular aspect of the debris generation and mitigation challenge, proposing a game-theoretic model of why it has been difficult thus far to increase ex post debris clean-up amongst the many contributors to the debris stock, and simulating the potentially dire consequences to all if a successful coordination mechanism cannot be found.

In what follows, we extend these lines of inquiry by considering the economic problem of debris generation and mitigation starting from the representative firm's point of view. A key difference between our model and the model in Adilov et al. (2015) is that our representative firm has a clear incentive to take precaution with the quality of its satellites (to make them less prone to breaking up into debris) and to expend some effort taking back debris. Our baseline model is presented in Sect. 2, wherein the representative competitive firm has some incentive—but not a socially efficient incentive—to produce and operate relatively robust satellites. In Sect. 3, we elaborate upon the baseline model in the ways described earlier, locating elements of current intellectual property law and space law within the economic model and suggesting where policy-makers might discover Pareto-improvements. We focus in particular upon how the current intellectual property rights system in the US and in other countries might be used as an unconventional but effective means to improve the robustness of satellites, and upon how country-specific or NGO-specific policy could be used to reduce transaction costs between firms that could collaborate on or contract for ex post LEO debris take-back initiatives. Our paper concludes in Sect. 4 with a summary of the take-away points and some directions for future research.

2 The Baseline Model

We consider the decisions of a representative satellite-producing firm operating in what we assume for now is a reasonably competitive global market for satellite services in low-Earth orbit. The representative firm seeks to maximize profit from its line of satellites in any particular period by judiciously choosing two inputs: ex ante care, A, and ex post or take-back care, T. As described by Macauley (2015, p. 162), ex ante care, A, could comprise shielding and other elements of "smart" technology such as built-in orbital maneuvering ability and collision threat detection and avoidance capability. Ex post or take-back care, T, concerns the firm's post-launch effort to track, secure, return for re-use and/or to dispose of its spent satellites and any debris they create if they should collide with other objects in low-Earth orbit. Hence, take-back could involve returning the materials to Earth; steering the materials into the atmosphere for burn-up; or successfully parking the materials in a designated parking lot orbit. While it is possible to build a dynamic model in which decisions made in an initial period are brought to fruition in subsequent periods, we abstract from that complication by examining the decision the firm makes in any particular steady-state period that is long enough to capture the expected cradle-to-grave lifecycle of a satellite. We also abstract from modeling non-perfect competition that might characterize the market.[3] We will comment upon these forces along the way, but not modeling them in our basic framework will enable us to introduce other complexities that would become unwieldy if we try to maintain intertemporal dynamics and imperfect competition as well. The baseline model of LEO debris control we have in mind is inspired by the models of Barrett and Segerson (1997) and Dyar and Wagner (2003). In each of those models, there is a representative competitive agent that chooses two inputs in order to achieve privately optimal environmental quality outcomes that are then compared with socially optimal outcomes. The focus of both papers is upon the range of policy approaches that can be taken to motivate agents to take Pareto-improving actions in the presence of uncertainty about one or more aspects of the decision-making environment. The main idea is that a first-best approach in each context may be politically infeasible (just as Adilov et al. (2015) conclude with respect to Pigouvian taxation in their context of LEO debris control), so that attention must turn to creating alternative incentives that motivate private parties to take decisions that achieve second-best efficient outcomes.

The baseline set-up of the representative, risk-neutral firm's expected profit inspired by the Barrett and Segerson (1997) and Dyar and Wagner (2003) models is thus:

$$\Pi(A,T) = pS(A,T) - w_A A - w_T T \tag{1}$$

where the firm produces a line of satellites at competitive price p with quantity normalized to one with a likelihood S that the satellite survives over its working life and is retired in the long-run without incident. In other words, we assume S is a continuous and differentiable function that takes real values between zero and one and that increases at a decreasing rate in both inputs A and T that are invested in satellite production (that is, prior to launch and operation) and on-board servicing (that is, after launch and during and after its operational life). Hence, input A represents ex ante design and installation of hardware such as shielding that affects the satellite's ability to avoid collisions in low-earth orbit and, if it does collide, to remain intact and functioning. In contrast, input T represents the amount of ex post "take-back" effort exerted by the satellite company (with or without partners) to manage the satellite with on-board servicing after the satellite is launched and operational in low-earth orbit and then to manage the satellite through its post-operational phase.

Taking the first-order conditions and assuming the second-order conditions are met for optima, we obtain the standard prescription as to how each satellite input should be selected for private optimality:

$$\frac{\partial \Pi}{\partial A} = p\frac{\partial S}{\partial A} - w_A = 0 \; or \; choose \; A^* \; where \; p\frac{\partial S}{\partial A} = w_A, \tag{2}$$

$$\frac{\partial \Pi}{\partial T} = p\frac{\partial S}{\partial T} - w_T = 0 \; or \; choose \; T^* \; where \; p\frac{\partial S}{\partial T} = w_T \tag{3}$$

In each case, the inputs are selected such that the (private) marginal revenue product equals the (private) marginal resource cost. The economics suggested by Eqs. (1)–(3) has a dual formulation whereby the firm chooses (in a Lagrange multiplier framework) inputs that maximize the likelihood of the satellite's success subject to a budget constraint, viz:

$$L(A,T) = S(A,T) + \lambda\left[M - w_A A - w_T T\right] \tag{4}$$

[3] Assuming a steady-state and assuming competitive markets to begin the exploration is a common strategy for building intuition; see, for example, Fullerton and Wu (1998), Walls and Palmer (2001), and Holland et al. (2009).

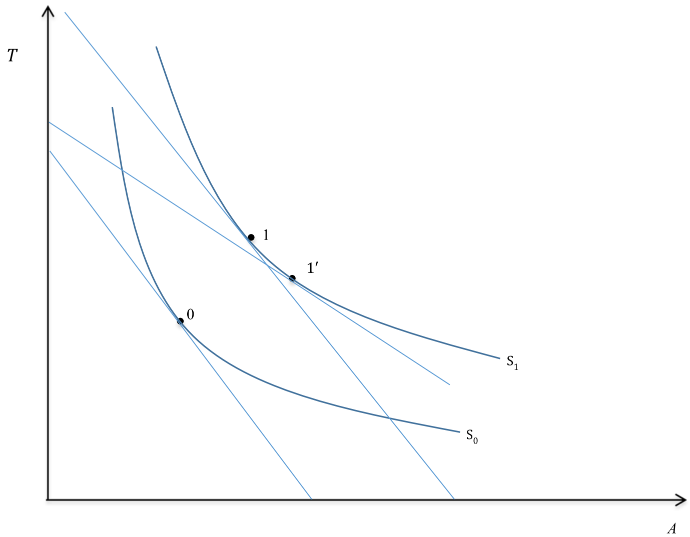

Fig. 1 Private and social optimality comparison

The first-order conditions for the dual problem posed by (4) are:

$$\frac{\partial L}{\partial A} = \frac{\partial S}{\partial A} - \lambda w_A = 0 \tag{5}$$

$$\frac{\partial L}{\partial T} = \frac{\partial S}{\partial T} - \lambda w_T = 0 \tag{6}$$

$$\frac{\partial L}{\partial \lambda} = M - w_A A - w_T T = 0 \tag{7}$$

Here, as in Dyar and Wagner (2003, p. 509), the firm produces as much likelihood as possible given exogenous budget M, exogenous input prices, and its current technology S. Equations (5) and (6) can be combined to yield the standard result that inputs should be selected such that their marginal rate of technical substitution equals the input price ratio:

$$\frac{\frac{\partial S}{\partial A}}{\frac{\partial S}{\partial T}} = \frac{w_A}{w_T} \tag{8}$$

It is instructive to graph this situation, and two representative isoquants are represented in Fig. 1. Output in this private, no-externality constrained optimization context is maximized at Point 0 in Fig. 1. One important observation to make at this stage is that private satellite producers have, across a wide range of reasonable technology functions and input prices, incentives in the absence of laws, regulations, or policies to take positive rates of ex ante care A and ex post take-back T to enhance (indeed, maximize) the survivability S of their satellites. The economic challenge is that private parties do not necessarily take into account the impact of their actions on other parties and therefore are underinvesting in A or T (and therefore S) from a social point of view. To the extent that the representative firm builds more shielding and the like into its own satellites and undertakes effort to control its satellites once launched, benefits accrue to others in the form of reduced debris in low-earth orbit and reduced economic damages. This discrepancy between private and social optimality in input selection can be made explicit in our baseline model by adding an external benefits function, $B(A, T)$, to the model, where B is assumed to be continuous and differentiable in each input A and T, with positive first derivatives and negative second derivatives.[4] We add the external benefits to the model by way of the representative firm's budget constraint, in that if the representative firm were able to capture the monetized value of the external benefits in some manner, the impact would basically be to reduce the effective input prices the firm faces for each input. For instance, if one more unit of A costs the satellite producer \$10,000 to implement, but implementing that unit creates external benefit of \$2000 that the firm is able to capture in the marketplace, then the satellite producer is actually paying \$8000 for that unit of A. The social version of the representative firm's private problem in (4) then becomes:

$$\mathrm{L}(A,T) = S(A,T) + \lambda\left[M + B(A,T) - w_A A - w_T T\right]. \tag{9}$$

Taking first-order conditions and rearranging, we obtain:

$$\frac{\frac{\partial S}{\partial A}}{\frac{\partial S}{\partial T}} = \frac{w_A - \frac{\partial B}{\partial A}}{w_T - \frac{\partial B}{\partial T}} \tag{10}$$

and

$$M + B(A,T) - w_A A - w_T T = 0. \tag{11}$$

The righthand side of (10) illustrates the essential gap between the private and social valuations of the respective satellite inputs, A and T. If private parties are able to monetize and capture the full (private and external) value of its input selections, they have full incentive to choose socially optimal inputs. Otherwise, underproduction or underinvestment occurs. The private party would choose inputs A and T according to (8) rather than according to Eq. (10), because in the absence of policy that enables monetization and capture of external benefits, the private party views the $\frac{\partial B}{\partial A}$ and $\frac{\partial B}{\partial T}$ terms on the righthand side of (10) to equal zero. Society's optimal rate of satellite integrity S is higher than the privately optimal rate, S_0, perhaps at bundle 1 on isoquant S_1 as illustrated in Fig. 1. To foreshadow our policy analysis in the next section, note that visually an outcome such as bundle 1 could be achieved if the marginal external benefits from A and T ($\frac{\partial B}{\partial A}$ and $\frac{\partial B}{\partial T}$, respectively) are roughly the same and if there is a framework in place by which the private firm can monetize and capture those benefits.

Other bundles along isoquant S_1 are of course feasible and equally desirable on social efficiency grounds. The basic physics of how policy can move us from the privately optimal isoquant S_0 to the socially optimal isoquant S_1 can be seen by writing the firms' potential budget constraint in (9) as:

[4] Note that we are imposing very little structure on the forms that the sustainability function S and the external benefits function B may take, including the form of the debris-generating process, so that our analysis may be as general as possible. Certainly the debris-generating process is highly interesting in and of itself; see Macauley (2015) and Adilov et al. (2018) for detailed analysis of the low-Earth orbit debris generation process.

$$T = \frac{M + B(A, T)}{w_T} - \frac{w_A}{w_T} A. \tag{12}$$

The firm's ability to monetize and capture external benefits B to any extent increases the funds the firm has available to produce S from M to $M+B(A,T)$. Adding B increases the y-axis intercept in (12), moving us to a tangency at a higher isoquant than isoquant S_0. How high of an isoquant the firm can reach depends upon the extent of monetization and capture of the external benefits from the firm's actions. At the same time, the optimality condition expressed by (10) tells us that the shift in (12) may be parallel or it may involve a change in the slope of the budget constraint. For example, if the firm is able to monetize and capture external benefits generated by its selection of input A to a greater extent than its selection of input T, then $\frac{\partial B}{\partial A} > \frac{\partial B}{\partial T}$ so that the righthand side of (10) falls and the new budget constraint will be tangent to an isoquant like S_1 at a point south and east of bundle 1, such as at a point like bundle $1'$, illustrated in Fig. 1.

A few final observations are useful before we leave the baseline model illustrated in Fig. 1 and analyze policies that we believe are feasible in the current institutional environment for closing (or at least shrinking) the gap between private and social optimality in this area. First, notice that it is certainly theoretically possible for a social planner to directly impose upon the representative firm the input mix represented by points 1 or $1'$ on the firm's isoquant S_1. However, there are two complications with that approach. First, we don't believe this is feasible in the current institutional environment. Second, it is certainly not incentive-compatible for the firm. If the social planner unilaterally moved the private firm to the socially optimal rates of input usage without compensation to the private firm, the firm's profit unequivocally falls. This can be seen via (5) and (6); the social planner would be driving the firm to input usage rates such that $\frac{\partial S}{\partial A} < w_A$ and $\frac{\partial S}{\partial T} < w_T$. Our focus in the next section of the analysis is rather upon the scenario in which imposing such an economic loss on the firm is not feasible (even though it may raise overall social welfare). Third, it is likewise theoretically possible to consider fairly standard socially efficient approaches to challenges like this one by, for instance, setting Pigouvian subsidies at differential rates per input type. However, as we noted earlier, Adilov et al. (2015) conclude their study by indicating concern that a Pigouvian approach is not institutionally feasible. For the same reason, Holland et al. (2009) explore the efficiency properties of low-carbon fuel standards, even though differential Pigouvian taxes per fuel-type would be socially efficient. US Congressional representatives have given up on (at least for now) addressing carbon emissions via Pigouvian taxes or cap-and-trade mechanisms in the face of political resistance and are now in search of feasible second-best instruments. In our analysis that follows in Sect. 3, we examine a few different ways by which Pareto-improvements could be achieved in the absence of the standard pollution control economic policy tools of Pigouvian taxes and cap-and-trade, and without taking command-and-control approaches that are not incentive-compatible to private firms.

3 Policy Analysis

3.1 Subsidies

With the baseline model in hand, we now consider ex ante and ex post strategies that might enable us to move from the firm's privately optimal bundle 0 in Fig. 1 to—or at least toward—a socially optimal point along isoquant S_1 such as point 1. As noted just above, this could of course be achieved in theory by directing to the representative firm a Pigouvian subsidy of size $\frac{\partial B}{\partial A}$ with respect to input A and a subsidy of size $\frac{\partial B}{\partial T}$ with respect to input T, as suggested by Macauley (2015). Such a policy would align the privately optimal (8) with the socially optimal (10); the firm would be efficiently compensated for the additional cost it incurs to produce higher quality satellites that in turn cause lower external damages to other agents in the environment, i.e., that generate external benefits. There are two challenges with this approach that motivate our ideas below, however. First, subsidies along these lines may not be politically feasible or there may not exist an institutional structure within which such subsidies could be dispensed. Second, the subsidies would need to be renewed in every time period going forward. That may be feasible, but what would be ideal is if the firm's choices could be altered in a single time period and not need to be revisited. The policy strategies set forth below are ones that we believe could be implemented within the current institutional framework in place and that would not need to be revisited in subsequent periods. Moreover, these strategies would at least in theory raise social welfare without reducing firm profit. Thus, the strategies are designed to be incentive-compatible for firms.

3.2 Strengthening Intellectual Property Rights

The analyses in Krystofik et al. (2015) and in Schreck and Wagner (2017) suggest one possible debris mitigation strategy in this context, vis-à-vis promotion of intellectual property licensing in relatively green technologies. In the present context of encouraging production of higher-quality satellites, society might consider granting stronger intellectual property rights than granted thus far in order to incentivize the dissemination of input technologies that lead to higher-quality satellites being constructed ex ante and/or that lead spent satellites to be retrieved or managed more reliably. If the intellectual property rights that firms currently hold for high-quality satellites are not as strong as they could be, profit maximizing firms will implement input A and/or input T at a lower rate than is socially optimal and the robustness S of the satellites will be lower than what is socially optimal. This inefficient outcome can obtain for at least three reasons: Either because there is inefficient "red tape" involved with innovating firms fully capitalizing on technologies A embedded in higher-quality satellites (either internally or via licensing to other satellite producers), or because of what Landes and Posner (2003, pp. 297–300) describe as incomplete appropriability by the patent holder that basically results from inefficiently weak establishment or social enforcement of intellectual property rights, or because not all of the claims innovators list in their original patent applications are approved by the patent office.[5] Relaxing one or more of these three constraints would incentivize innovators to substitute away from low-quality satellites and their on-board management toward high-quality satellites and their on-board management.

One or more of these three factors can be taken into account in our baseline model by generalizing the social planner's model with the multiplication of the $B(A,T)$, $\frac{\partial B}{\partial A}$, and $\frac{\partial B}{\partial T}$ terms in Eqs. (9–11) by a parameter $0 \leq \sigma \leq 1$. This new parameter σ represents the share

[5] See Lerner (1994), Churnet (2013), and Marco et al. (2016) for detailed discussion of this point that claims in original patent applications are routinely pared back in revise-and-resubmit negotiations with patent examiners regarding the appropriate scope or breadth of the patent coverage.

of external benefits from input choices that innovators are able to capture and monetize. That is, we want our model (through σ) to account for the fact that innovators are typically not able to capture and monetize the full social benefits of their innovations, and to show the social consequences of this failure to capture. We will then have $\sigma B(A,T)$, $\sigma\frac{\partial B}{\partial A}$, and $\sigma\frac{\partial B}{\partial T}$ in the baseline system, as follows:

$$\mathrm{L}(A,T) = S(A,T) + \lambda\left[M + \sigma B(A,T) - w_A A - w_T T\right], \tag{13}$$

$$\frac{\partial L}{\partial A} = \frac{\partial S}{\partial A} + \lambda\left[\sigma\frac{\partial B}{\partial A} - w_A\right] = 0, \tag{14}$$

$$\frac{\partial L}{\partial T} = \frac{\partial S}{\partial T} + \lambda\left[\sigma\frac{\partial B}{\partial T} - w_T\right] = 0, \tag{15}$$

$$\frac{\partial L}{\partial \lambda} = \left[M + \sigma B - w_A A - w_T T\right] = 0. \tag{16}$$

There are several points to note about this generalization. First, observe that comparing the firm's baseline system of Eqs. (4)–(8) with this generalization of the social optimization in Eqs. (13)–(16), the firm's system of equations obtains when $\sigma = 0$—that is, under the assumption that the firm has no way to monetize and capture any of the external benefits its input choices generate. Second, comparing the original social optimization system in Eqs. (9)–(11) with the generalized system represented by Eqs. (13)–(16), we see that (9)–(11) immediately obtain when $\sigma = 1$. When $\sigma = 1$, it effectively disappears from the social optimization and the socially optimal plan involves private firms being able to fully monetize and capture all of the external benefits generated by its input choices—for instance, by strengthening the intellectual property rights in the outer space domain. Third, the preceding observation obtains in a world in which it is costless for the social planner to basically toggle between $\sigma = 0$ and $\sigma = 1$. In reality this is not costless. σ is rather a function of costly effort, e, on the part of society's institutions. In the simplest case, effort e can be exerted at a constant per-unit cost to society of w_e such that total social expenditure on e is given by $w_e e$. For $\sigma(e)$, we assume that this function is continuous and differentiable, with $\sigma' > 0$ and $\sigma'' < 0$ at least over part of its range as e becomes very high. In other words, we assume that $\sigma(e)$ is either strictly concave over its entire range or that it is a logistic function that approaches 1 as e becomes very high. The intuition for placing this kind of structure on $\sigma(e)$ is that there is quite likely diminishing returns to society's institutional effort to see that private innovators capture and monetize the full social benefits of their innovations. Taking account of this cost of effort e and generalizing σ so that we have $\sigma(e)$, the social planner's system in Eqs. (13)–(16) becomes:

$$\mathrm{L}(A,T,e) = S(A,T) + \lambda\left[M + \sigma(e)B(A,T) - w_A A - w_T T - w_e e\right], \tag{17}$$

$$\frac{\partial L}{\partial A} = \frac{\partial S}{\partial A} + \lambda\left[\sigma\frac{\partial B}{\partial A} - w_A\right] = 0, \tag{18}$$

$$\frac{\partial L}{\partial T} = \frac{\partial S}{\partial T} + \lambda\left[\sigma\frac{\partial B}{\partial T} - w_T\right] = 0, \tag{19}$$

$$\frac{\partial L}{\partial e} = \lambda\left[\frac{\partial \sigma}{\partial e}B - w_e\right] = 0, \tag{20}$$

$$\frac{\partial L}{\partial \lambda} = \left[M + \sigma(e)B - w_A A - w_T T - w_e e\right] = 0. \tag{21}$$

Equation (20) tells us that society should choose e where $w_e = \frac{\partial \sigma}{\partial e} B(A, T)$. Equations (18) and (19) tell us that inputs A and T should be selected such that the input MRTS equals the input price ratio that now features $w_A - \sigma(e)\frac{\partial B}{\partial A}$ in the numerator instead of $w_A - \frac{\partial B}{\partial A}$, as well as $w_T - \sigma(e)\frac{\partial B}{\partial T}$ in the denominator instead of $w_T - \frac{\partial B}{\partial T}$. In words, from a social point of view, choosing more effort e raises the degree to which private firms are able to capture the external benefits from their innovations, represented in the model by $\sigma(e)$. This in turn raises the firm's incentive to implement more A or more T, which increases S. As $\sigma(e)$ grows closer to 1, the firm's potential budget constraint pivots left to right, away from a tangency at point 0 toward a tangency at a point like bundle $1'$ in Fig. 1. If raising e were costless, society would choose the maximum e necessary to yield $\sigma(e) = 1$; in words, the firm would then have the unquestioned ability and social support through strongly enforceable intellectual property rights to monetize and capture 100% of the external benefits flowing from its innovations. But since implementing e is not costless, $\sigma(e) \leq 1$ and 100% appropriability may not be socially optimal, as Landes and Posner (2003) describe more generally. (Indeed, our $\sigma(e)$ is motivated in part by the parameter $0 \leq z \leq 1$ that Landes and Posner (2003, Chapter 3) utilize in their baseline model of optimal copyright strength.) Moreover, it is important to observe that strengthening the intellectual property rights alone will almost surely not be sufficient to bring σ to a value of one; complementary policy instruments may be necessary as well.[6] Also, (18) and (19) tell us that the socially optimal program has private firms imperfectly appropriating the external benefits from their innovations in a manner that effectively lowers the prices the firm pays for the inputs A and T that it cleverly utilizes for both private and social good. While the appropriation may be less than 100%, more appropriation is warranted than in the baseline model in which appropriation is zero.

We hasten to add that strengthening a firm's intellectual property rights along these lines could create deadweight loss from newly acquired market power that in a vacuum would be of concern. However, as Landes and Posner (2003) as well as Segal and Whinston (2007, pp. 1723–1724) suggest, the idea here is that enacting policies that protect the incumbent in innovative industries can lead to higher rates of innovation and greater net welfare when all is said and done. The increase in social welfare resulting from higher-quality satellites can in principle be offset by (or be greater than) the decrease in social welfare stemming from the deadweight loss that results from strong patent rights, ceteris paribus. But the purpose of our study is to suggest the *possibility* that the net gain from such policies could be positive.

3.3 Clarifying Intellectual Property Rights

Now, in place of or in addition to *strengthening* known intellectual property rights to effect ex ante increases in satellite quality or ex post investments in the take-back of spent satellites, policy-makers might devise strategies for *clarifying* the ambiguous intellectual property rights that entrepreneurs may already have in outer space. Clarifying uncertain rights has the same impact within our modeling framework above as

[6] We are grateful to an anonymous reviewer for this insight.

strengthening known rights. Uncertainty over property rights has been shown in a wide variety of contexts to slow innovation, and as Coase (1960) argues, property right clarification is a key step for improving market efficiency. Indeed, multiple legal scholars have voiced concerns recently about uncertain property rights in the outer space context. Herron (2016, pp. 558–559) summarizes international treaties regarding activities in outer space and concludes “Little has changed in the international space treaty regime for many years, creating some uncertainty with respect to the legality of certain non-government activities.” He cautions that there is particular uncertainty in the area of private, commercially-oriented activities, since the international treaties were devised in an era when nuclear arms control was the focus. Schaefer (2017, pp. 117, 134–136) describes how on-orbit activities such as satellite servicing and space hotels currently fall into a regulatory gap between the FAA and FCC, and how the fact that on-orbit activities appear to be unregulated creates a cloud of regulatory uncertainty that impedes commercial progress in this domain. In other words, while the legally unstructured on-orbit environment would seem to encourage firms to carry out practically unbounded R&D and deployment of resulting technologies, Schaeffer cautions that firms are concerned in this ‘permissionless’ environment that costly intellectual and physical property investments made today will be found unacceptable to—and reversed by—regulators at a future date. Ro et al. (2011) provide an excellent overview of salient issues at the nexus of space law and patent law. They note that none of the international space treaties address how patents awarded by terrestrial nation-states will extend to activities in outer space, which creates uncertainty for innovators. The Outer Space Treaty does require launched objects to be registered to a country, however, and in 1990 the US codified in 35 U.S.C. §105 [with the Patents in Outer Space Act, Pub. L. No. 101–580; 104 Stat. 2863 (1990)] that inventions, patents and their enforcement in outer space on objects under US jurisdiction (that is, on US-registered spacecraft) would have the same standing as would be the case terrestrially. But Ro et al. describe in their Section III.D the uncertainties that still exist regarding the extraterritorial reach of US patent law—namely, that it is not obvious that a US private, commercial entity that arranges for its space object to be launched in another country (under a ‘flag of convenience’) can be sued for patent infringement under US patent law. The authors argue at the top of their Section IV that such ambiguities reduce incentives to undertake R&D in outer space-related endeavors. Kleiman (2011) and Perlman (2012) also provide insightful discussion of these points regarding the ambiguities in current US intellectual property law as it relates to activities in outer space.

To summarize on this point, strengthening or clarifying intellectual property rights as they appear in the high-quality satellite production market might be leveraged as an unconventional but effective lever for raising the quality of satellites and reducing expected debris/harm in Pareto-improving ways. Our best practical suggestion for making policy progress along these lines is for individual countries with significant satellite industries to add a specific office within the patent division of federal governments that would manage patent applications that have primary domain in outer space. Within such a framework, inventors could code their applications for primary and possibly secondary domains, with patent examiners assigned according to their relative domain expertise. This would be analogous to economists assigning primary and secondary JEL codes to their manuscripts, and editors assigning manuscripts to reviewers according to reviewers’ expertise in those JEL codes. The patent review process rules could be different in different domains, as is already the case. For instance, in the United States, patent application disclosure rules differ according to whether inventors are applying for US patent protection only, or if the inventors are simultaneously filing applications for patent protection in multiple countries that are signatories to the Patent Cooperation Treaty of 1970.[7]

3.4 Promoting Satellite Debris Take-Back Initiatives

We turn now to consider the merits of individual country governments or NGOs promoting take-back initiatives that satellite producers/operators might naturally find attractive, analogous to the promotion of terrestrial take-back programs for materials like packaging and electronics. Such a policy approach translates into firms seeing that their profits will be unchanged or grow if they were to individually or cooperatively undertake more take-back. The Coasian role for policy is to help break down (fixed) transactions costs to that cooperation. One possible transactions cost to break down is that firms may misperceive that the per-unit cost w_T is greater than it actually is. This could be the case when take-back technologies are not well-known or well-understood.[8] In this case, the *true* per-unit cost is $w'_T < w_T$ and substituting the true, lower cost into the model at (4) results in an expansion in the firm's (and subsequently society's) budget constraint, permitting the firm and society to reach a higher level of satellite sustainability S than was initially considered possible. In Fig. 1, the revelation that $w'_T < w_T$ would twist the original budget constraint from a tangency with isoquant S_0 clockwise to a tangency at a higher isoquant, perhaps S_1. From that point, one could derive society's compensating variation—which is to say, the upper bound on how much society should spend on Coase-inspired programs that clarify or disseminate the true cost of take-back technologies. The upper bound is given by the distance between the "true" and "perceived" budget constraints as we shift the "true" budget constraint in the southwest direction in Fig. 1 to its first tangency with isoquant S_0. (Note that since the slopes of the true and perceived budget constraints differ, back-shifting the true budget constraint will place us at a different point than Point 0.)

If take-back technology costs are generally well-perceived, a second policy option is to facilitate collaboration amongst firms that are interested in take-back efforts. Fleckinger and Glachant (2010) is a key reference on the topic of evaluating individual versus collective take-back program designs in terrestrial settings. However, we note that Fleckinger and Glachant (2010, p. 62) do not take economies of scale in cooperative take-back programs into account; instead, they focus only upon the welfare-reducing effect that market power creates when firms are allowed to collaborate on take-back. However, being able to collaborate on take-back should generate significant economies of scale in the outer space context, and the ability to share the tremendous fixed cost of initiating any take-back programs should be expected to be the main driver for any agreement. Referring once more to the representative firm's problem in (4), the impact of such a policy that facilitates cooperative take-back efforts enables the representative firm to execute take-back effort at a per-unit cost of $w'_T < w_T$. Since the take-back effort is reducing debris in low-Earth orbit, it is raising the sustainability S of the firm's satellites and those of other firms in orbit. The analysis described above with regard to misperceived prices carries through analogously here in this case of achieving collaborative take-back effort between like-minded firms. Now,

[7] See Johnson and Popp (2003, p. 98) for excellent discussion of this dynamic that is set forth in the American Inventors Protection Act of 1999.

[8] For instance, in the related context of green building, Issa et al. (2010) found that the cost premium for utilizing relatively green materials in the construction of new buildings is typically overestimated.

it may be that firms are concerned to collaborate—notwithstanding expected cost reductions—if their collaboration could be misperceived by antitrust regulators as conspiracy. A Coasian, Pareto-improving strategy for overcoming this possibility is suggested to us by Ruble and Versaevel (2014). They suggest that public policy in the presence of expected social gains from collaborative R&D within industries could involve granting participating firms safe harbor from such antitrust inquiries. Our intuition is that an arrangement along these lines could be formalized in our model and implemented in the marketplace; however, this would involve considerably more industrial organization and/or game theory modeling and we look forward to exploring this possibility in future research.

Finally, observe that Anzaldua and Hanlon's (2018) argument that satellite producers/owners might benefit from contracting with third-party space salvors to manage spent satellites and their debris—analogous to salvors who are compensated for retrieving wrecked ship cargo and/or containing the spread of debris under international maritime salvage laws—finds expression within our model as well. Policies that enable the outsourcing of ex post launch satellite management to third-party space salvors enables satellite companies to obtain this type of ex post care at a per-unit cost of $w_T' < w_T$ within the firm's profit maximization problem expressed in (4). As per Fig. 1, the impact is that outsourcing some or all of the firm's ex post care to space salvors twists the satellite firm's isocost function outward to higher optimal rate of sustainability S of the firm's operations (i.e. to a bundle like 1′) with spillover benefits to other firms operating in low-Earth orbit. As Anzaldua and Hanlon (2018) note, clarifying the legal and practical aspects of permitting space salvor activity is a complex task. However, as we described earlier in this section when discussing the Coasian merits of clarifying intellectual property rights in the outer space context, social efforts to generally clarify property rights (in this case, of space salvors) while costly can constitute Pareto-improving strategies for raising both the private and social sustainability of valuable activities in the outer space domain. In contrast with Anzaldua and Hanlon's (2018) concern regarding how to raise funds for space salvor operations (with no international body that is currently capable of raising such funds), our proposal is that space salvors are just as likely to be commercial firms, just like the satellite launching firms, and hired on an outsourced basis by said launching firms rather than funded by an international entity.

3.5 Specific Recommendations: The United States as a Case Study

Working toward our conclusion, we consider now refinements suggested by our model to debris mitigation (satellite robustness) policies that are already in place within one major marketplace, the United States. While there are multiple other regions in the world where satellite activities are either well-established or rapidly developing, we draw upon the United States case for illustration of our general points. As noted by Schaefer (2017, p. 134), the US FCC and NOAA require debris mitigation plans from commercial entities that apply for spectrum usage and remote-sensing licenses, respectively. US FCC (2004, Section III.B.16) states that "…plans must include a statement that the space station operator has assessed and limited the amount of debris released in a planned manner during normal operations, and has assessed and limited the probability of the space station becoming a source of debris by collisions with small debris or meteoroids that could cause loss of control and prevent post-mission disposal." The motivation for the debris mitigation plan requirement is described in US FCC (2004, Section III.C.28), indicating that "Although we anticipate that the majority of satellite operators have an economic incentive to design their spacecraft as robustly as possible in order to protect revenue-producing operations, this may not always be true. Although our preference is to leave spacecraft design decisions to space station operators, this preference does not foreclose the Commission from considering design issues insofar as they may impact the public interest." In other words, while firms have some incentive to take care, it is not obvious that they will take socially optimal care. The above parameters of US FCC (2004) are now codified in 47 C.F.R. §§ 5.63(e), 25.114(d), and 97.207(g).

All of the above subsections of 47 C.F.R. are consistent with, and find expression within, the economic model we set forth in this paper, wherein the private optimization differs from the social (or public interest) optimization by the external benefit generated by the firm's private choices of satellite input quality. The FCC's debris management plan requirement is designed to at least partially close the gap between (4) and (17), and hence the gap between points 0 and 1 or $1'$ in Fig. 1. The plan does so basically through a command-and-control approach, ostensibly requiring firms (in the language of our model) to raise utilization of inputs A and T to their socially optimal rates. However, as is the case for command-and-control regulations more generally, the regulatory assumption is that either it is costless to the firm to implement the requirement in the current period or that the cost is trivial, and that it also does not affect the firm's intertemporal decision-making in terms of investing in R&D and staking out intellectual property right claims over resulting innovations. It is for this reason that we advocated earlier in this analysis for an incentivizing approach to raising the degree of satellite sustainability firms choose to implement. Enabling innovating firms to monetize and capture the external benefits from its investments and enabling firms to realize economies of scale cost savings via collaborative take-back positively motivates firms to act like social planners. One additional concern that we have is that our review of a sample of debris mitigation plans required by the FCC and publicly available at https://www.fcc.gov/approved-space-station-list suggests that more detailed disclosures of the estimated probabilities of collision and the firms' marginal costs of reducing those probabilities down to minimums that firms are required by statute to achieve will be necessary before we are able to ascertain the overall impact of the FCC's rules regarding debris mitigation plans.[9] We therefore respectfully recommend that the FCC revise its guidelines to collect such data going forward. Future research would then be able to more accurately estimate the benefit function $B(A,T)$ that is central to the calibration of the policies we suggest herein.

3.6 Directions for Future Research

Finally, we note that while we comment above on the independent use of ex ante and ex post approaches to controlling the harm from satellite debris, several studies in the law and economics literature consider the merits of joint use of ex ante regulation and ex post liability in several contexts. We also note that joint use is in fact exhibited in US federal laws in the outer space domain and in federal agency (such as FCC) guidelines for implementing those laws. We have not explicitly considered the impacts of joint use of Pigouvian incentives to build more robust satellites and application of various forms of legal liability, including punitive damages, in our model, but this is a valuable

[9] At the FCC link, select "The List", and the debris mitigation plans are noted in Column K. Last accessed 10/30/18.

direction for future research. The outer space domain of focus in this paper features firms taking both observable and unobservable ex ante precaution, and said firms also face uncertain conviction for harm done by their technologies, given the ambiguities we surveyed in US federal and international space laws (particularly where those laws interface with intellectual property law). Hence, a framework like Bhole and Wagner's (2008) might be usefully synthesized with our model in Sect. 3 to further analyze policy possibilities under these circumstances. One further approach that we have not considered in our analysis is the promotion of an international environmental agreement on satellite debris management. We are not sanguine about such an agreement taking shape, for the barriers impeding such an agreement are similar to those that prevent the implementation of preferred policy instruments such as pollution taxes or tradeable permits. Kellenberg and Levinson (2014) describe how ineffectual international environmental agreements have been thus far—hence our interest in promoting effectiveness of relatively decentralized, Coasian strategies in this paper. Our intuition is that a good first step along this line of inquiry would start with a modeling approach similar to that in Bui (1998), who analyzed acid rain abatement negotiations between the US and Canada.

4 Conclusions and Directions for Future Research

There are two motivations for this paper: Adilov et al.'s (2015) correct observation that there does not presently exist an institution with the global authority to impose corrective, Pigouvian taxes, or individual or collective take-back initiatives upon producers of debris in LEO and Weinzierl's (2018) recent encouragement for economists to bring more study to bear on the outer space domain. Informed by these two papers, our focus is upon ways of encouraging Pareto-improvements via Coasian bargaining or via revelation of information or self-interested strategies that firms may have overlooked heretofore. To explore the promise of such approaches, we set forth a basic model of a representative firm's choices of satellite inputs that yield both private and external benefits. Since external harm falls as the satellite quality increases, we (and others) find that privately optimal choices will deviate from socially optimal results. Our take-home conclusion is that two unconventional strategies that reflect important elements of both intellectual property law and space law may generate Pareto-improvements in this emerging marketplace in low-Earth orbit. First, decentralized policy-makers may be able to strengthen or clarify the intellectual property rights involved in developing and producing high-quality satellites such that innovating firm profit rises or remains unchanged while higher-quality satellites result and social welfare increases from the reduction in satellite debris. Second, there may be misperceptions of green technology prices, or there may be unexploited opportunities for decentralized agents—individual country governments and NGOs that are concerned about external costs from satellite debris—to facilitate the emergence of collaborative or outsourced take-back initiatives in LEO that are analogous to terrestrial take-back programs. A key area for future research is to carefully consider the joint use of these approaches in this context, deriving the conditions under which the joint application of ex ante and ex post strategies can outperform using one or the other independently. Lessons learned would inform a wide range of policy debates regarding the optimal legal and economic structure in the outer space domain.

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