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17 **Supplementary Information for**

18 **Orbital-use fees could more than quadruple the value of the space industrye**

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Supporting Information Text

Extended description of methods and discussion of results

We generate the path of an optimal orbital-use fee (OUF) in three steps. First, we calibrate functions describing the physics and economics of orbit use to match observed data on satellite and debris stock levels and aggregate satellite industry costs and returns prior to 2015. Then, using the calibrated values, we generate open access and optimal launch paths from 2006 to 2040. Finally, by comparing the open access path of collision risk to the optimal path of collision risk, we calculate the path of the optimal OUF which induces open access satellite owners to internalize the externality they impose on other orbit users.

It is important to emphasize that our goal in this article is not to precisely estimate the value of an OUF. Rather, our goal is to provide order-of-magnitude estimates of the optimal OUF and the NPV gains from implementing it, and to show the qualitative features of both the OUF path and NPV gains. As we discuss below, our conclusion that a globally-harmonized OUF is necessary to improve the value of the satellite industry is robust to the limitations in our estimation methodology.

We measure the value of the satellite industry as the net present value (NPV) of cash flows generated by the satellite fleet. NPV accounts for the time value of money — the fact that cash flows received sooner are preferable to cash flows received later — by discounting future cash flows according to the interest that could have been earned on those cash flows had they been received in the present and immediately reinvested in capital markets. In this article, we use the infinite-horizon NPV of the satellite fleet. To calculate this value, we assume that satellite costs and revenues evolve according to the projection in ?) until 2050, after which they stabilize at 2050 levels and are constant for the infinite future.* The resulting NPVs reflect the sum of short- and long-run costs and returns from the satellite fleet. To express these in terms of equivalent constant cash flows received each year, we convert the NPV into an annuitized present value in the main text.† For example, given a discount rate of 5%, a net present value of \$1 trillion in 2020 is equivalent to an annuitized present value of \$47 billion received in perpetuity in each year from 2020 onwards.‡

We obtain physical functions relating launches, satellites, and debris stocks to collisions, new fragments, and satellite and debris growth from the engineering literature, and economic functions relating the decision to launch to collision risk, costs, and returns from the economics literature. To calibrate the physical functions, we estimate the unknown parameters from satellite stocks, debris stocks, and launches observed over 1957–2017. We constrain the parameters to comply with theoretical restrictions imposed by the engineering model. To calibrate the economic functions, we estimate the unknown parameters from satellite stocks, debris stocks, launches, aggregate satellite industry costs, and aggregate satellite industry returns over 2005–2015. To allow the estimation process to adjust for unobserved launch market frictions, we do not constrain these parameter estimates.

A. Data.

A.1. Satellite and debris counts, 1957–2015. We use data on satellites in orbit from the Union of Concerned Scientists' (UCS) lists of active satellites to construct the satellite stock and launch rate series (?). The UCS data provide details on payloads in low-Earth orbit (LEO) and their projected lifetimes. The data are described in Extended Data Table 1.

We construct the numbers of active satellites in each year by calculating the number of objects launched a particular year, adding the number of satellites previously calculated in orbit, and then subtracting the number of satellites listed as having decayed in that year.§

Letting ℓ_t be the number of collisions observed in year t and Z_t be the number of payloads listed as decayed in t , we construct the launch rate in t , X_t , from the law of motion for the satellite stock series as

$$\begin{aligned} S_{t+1} &= S_t - Z_t - \ell_t + X_t \\ \implies X_t &= S_{t+1} - S_t + Z_t + \ell_t, \end{aligned} \tag{1}$$

where S_t is the number of active payloads in t and Z_t is the number of payloads listed as decayed in t .

The debris and collision risk series we use were provided by the European Space Agency. We use debris data from the DISCOS database (?) and collision probability data used in (?) (the variable p_c in that paper). We use only objects with a semi-major axis of 2000km or less in

*The projection in ?) only goes till 2040 — we extend it to 2050 by calculating the compound annual growth rate of the costs and revenues, and assuming that they continue to grow at those rates from 2040 until 2050.

†The annuitized present value (PV) of an NPV level is the constant number of dollars received each year such that the discounted sum of annuitized PVs is equal to the target NPV level. Formally, defining the NPV of a stream of uneven cashflows x_t as $NPV = \sum_{t=1}^{\infty} \beta^{t-1} x_t = \sum_{t=1}^{\infty} \beta^{t-1} A = A(1 - \beta)^{-1}$ for some constants $A > 0$ and $\beta \in (0, 1)$, the annuitized PV is $A = NPV(1 - \beta)$. These conversions facilitate comparisons between uneven streams of cash flows, as they can be expressed in a common unit at a single point in time (NPV terms) or in a common unit at every point in time (annuitized PV terms).

‡We discuss the interpretation of the discount rate as the opportunity cost of funds invested below.

§This procedure is likely to produce an upward-biased estimate of the returns-generating satellite stock in any given year, since satellites which are no longer operational will not be removed from the estimated stock until they have deorbited. Thus, the satellite stock in this procedure includes some objects which are, economically speaking, "socially-useless debris". We use this procedure despite the attribution issue for two reasons. First, we do not have data on when specific satellites were declared nonoperational by their owners. Such a determination can be particularly tricky when a mission has ended, but the satellite still has fuel and could be repurposed for another mission. Second, to the extent that our estimates of the satellite stock are biased upward (toward positive infinity), our physical and economic parameters estimates will be biased downwards. The downward bias in economic parameters will deflate both the open access and socially optimal launch rates, while the downward bias in physical parameters will inflate both the open access and socially optimal launch rates, with the net effect being difficult to determine. However, the downward bias in our estimated collision risk coefficients and the upward bias in our estimated satellite stock will bias our estimated OUF downward, so that it is a lower bound.

all our data series. We prefer to use the DISCOS fragment data rather than the Space-Track fragment data (?) as DISCOS considers fragments from the time they were created or detected, whereas the Space-Track data tracks fragments from the time their parent body was launched. The DISCOS attribution method is closer to how economic agents in our model receive information and make decisions. Given the difficulties in determining operational status, the collision probability estimates account for the probability of collisions with all intact bodies. This produces an upward-biased estimate of the probability of collisions with only operational satellites. This upward bias likely deflates the number of open access and optimal launches we project. However, since the open access and optimal launch rates are chosen to equate collision risk with measures of economic returns (described in equations 6 and 9), the resulting estimated OUF paths will not be biased upward by the same degree as the collision probability estimates.

A.2. Aggregate satellite industry returns and costs, 2006–2040. We use data on satellite industry revenues from (?), and UCS data on satellites in LEO (semi-major axis less than 2000km) (?). The economic data provide a breakdown of revenues across satellite manufacture, launch, insurance, and products and services. The satellite industry revenues data cover 2006-2015, while the active satellites data cover 1958-2017. To generate launch rate and OUF projections out to 2040, we use revenue and cost projections from (?). These projections are shown in Figure 1a of the main text. The historical and projected data are described in Extended Data table 1.

We calculate the per-period returns on owning a satellite (π_t) as the revenues generated from commercial space products and services, and the per-period costs of launching a satellite (F_t) as the sum of revenues from commercial infrastructure and support industries, ground stations and equipment, commercial satellite manufacturing, and commercial satellite launching. The ratio π_t/F_t then gives a time series of the rate of return on a single satellite, as the number of satellites cancels out of the numerator and denominator.[¶] Since the numbers provided in (?) are for the satellite industry as a whole, the ratio still needs to be adjusted to represent satellites in LEO. We do not explicitly conduct this adjustment, but let the adjustment be calculated during the estimation of equation 7.[¶]

Note that the data we use for π_t and F_t are industry-level aggregates, rather than satellite-level figures. To convert the data from industry-level figures to per-satellite figures, we must apply a scaling factor which “disaggregates” the data. This unknown factor is common to both cost and revenue aggregates, and so cancels out of π_t/F_t such that the ratio correctly represents the rate of return per satellite. Since we use π_t/F_t to compute the open access and optimal policy and value functions, the unknown scaling factor does not affect our solutions (launch rates). However, it does affect our calculated time paths of NPV under BAU and optimal management as well as the OUF, since those values do not involve ratios which would cancel out the unknown scaling factor. Since the unknown scaling factor is on the order of the reciprocal of the number of satellites in orbit (or projected to be in orbit) in each period, we proxy for it in our projected time paths by dividing by the BAU satellite stock path. This choice of proxy does not affect our qualitative results or the order of magnitude of the OUF or NPV under BAU and optimal management — using alternate proxies such as the optimal management path of satellites or the observed number of satellites in 2015 produces similar results, although our proxy results in more conservative projections than those alternative choices.

B. Models.

B.1. Orbital mechanics with limited lifespans, missile tests, and certainty. Our physical model uses physical accounting relationships in the aggregate stocks of satellites and debris for the laws of motion, and draws on (?) for the functional forms of the new fragment creation and collision probability functions $G(S,D)$ and $L(S,D)$. The time scale is set as one calendar year to match our data. S_t denotes the number of active satellites in an orbital shell in period t , D_t the number of debris objects in the shell in t , X_t the number of satellites launched in t , $L(S_t, D_t)$ the probability that an active satellite in the shell will be destroyed in a collision in t , μ is the fraction of satellites which do not deorbit in t , and m is the average amount of debris generated by launching satellites (such as rocket bodies). δ is the average proportion of debris objects which deorbit in t , and $G(S_t, D_t)$ is the number of new debris fragments generated due to all collisions between satellites and debris.^{**} A_t is the number of anti-satellite missile tests conducted in t , and γ is the average number of fragments created by one test. We assume that satellites which deorbit do so without creating any additional debris.

The number of active satellites in orbit is modeled as the number of launches in the previous period plus the number of satellites which survived the previous period (also shown in equation 1). The amount of debris in orbit is the amount from the previous period which did not decay, plus the number of new fragments created in collisions, plus the amount of debris in the shell created by new launches.^{††} Formally,

$$S_{t+1} = S_t(1 - L(S_t, D_t))\mu + X_t \quad [2]$$

$$D_{t+1} = D_t(1 - \delta) + G(S_t, D_t) + \gamma A_t + mX_t. \quad [3]$$

For simplicity, we assume all non-operational satellites are immediately deorbited, making our OUF estimates conservative. (?) use an analogy to kinetic gas theory to parameterize the probability of a collision as a negative exponential function, with the density of colliding

[¶]This is true whether the satellites were launched individually on separate rockets or in groups on the same rockets.

[¶]Another way to perform this adjustment is by calculating the yearly share of satellites in LEO and multiplying the ratio π_t/F_t by the share in LEO. This approach is difficult to generalize to future years since it requires projections of satellites in other orbits. It is also not clear that the returns of satellites in LEO are truly proportional to the LEO share of the total number of active satellites in all orbits; it seems more likely that LEO satellites earn less revenue per satellite than geostationary satellites.

^{**}For most of our sample, the number of observed collisions is zero. We use the probability of collisions in our models rather than the observed number for two reasons. First, it proxies for unobserved collisions, including non-catastrophic ones. Second, a model with stochastic collisions complicates the process of solving for the optimal time path by adding another state variable to the dynamic programming algorithm. As the number of objects in a single period increases, the fraction of satellites destroyed in collisions in that period converges to the probability of destruction, so this assumption provides a “mean field”-type approximation.

^{††}Empirically, we only consider the population of trackable fragments, i.e. those with size greater than 5-10 cm in LEO.

objects one of the arguments of the exponential function. We therefore parameterize $L(S_t, D_t)$ as

$$L(S_t, D_t) = 1 - \exp(-\alpha_{SS}S_t - \alpha_{SD}D_t), \quad [4]$$

where α_{SS} and α_{SD} include the difference in velocities between the objects colliding, the total cross-sectional area of the collision, and scaling parameters which relate the number of objects to their density in the volume. We use these probability functional forms to parameterize $G(S_t, D_t)$ as

$$G(S_t, D_t) = \beta_{SS}(1 - \exp(-\alpha_{SS}S_t))S_t + \beta_{SD}(1 - \exp(-\alpha_{SD}D_t))S_t, \quad [5]$$

where the β_{jk} parameters are interpreted as “effective” numbers of fragments from collisions between objects of type j and k .^{‡‡} We refer to the α_{jk} and β_{jk} as “structural physics parameters”, as they represent physical entities which are exogenous to our model.

We ignore the possibility of collisions between debris objects for two reasons. First, the data we have do not allow us to identify the effective number of fragments from such collisions, or the probability of such collisions, using our calibration approach. Second, our focus here is not on the probability of Kessler Syndrome, but on launch patterns and their response to the extant stock of orbiting satellites and debris. Our estimates of the optimal OUF path and the benefits of implementing it are likely understated due to this omission. Incorporating the possibility of Kessler Syndrome is an important piece of optimal orbit use analysis and policy design, and will likely require higher-fidelity physical modeling than the “aggregate calibration” approach we take here. This is an important area for future research.

Equations 3, 4, and 5 can be viewed as reduced-form statistical models which recreate the results of higher-fidelity physics models of debris growth and the collision probability. While higher-fidelity physics models may use similar functional forms, the key difference between our approach and the approach in such models is how we calibrate the models: rather than derive the appropriate parameter values from physical first principles given the data, we estimate the values of those parameters which maximize the fit between the data and model-predicted collision probabilities, satellite evolution, and debris stocks. Though our approach is computationally convenient, it likely sacrifices some predictive power.

B.2. Open access orbit use with time-varying aggregate returns and costs. The economic model of open access here is based on the model of open access in (?) to determine the satellite launch rate under open access, X_t , as a function of the collision probability, $L(S_{t+1}, D_{t+1})$, and the excess return on a satellite, $r_s - r$.^{§§} In the simplest case, where all of the economic parameters are constant over time, the open access launch rate equates the collision probability with the excess return:

$$L(S_{t+1}, D_{t+1}) = \underbrace{r_s - r}_{\text{excess return on a satellite}}, \quad [6]$$

where r_s is the per-period rate of return on a single satellite (π/F , where π is the per-period return generated by a satellite and F is the cost of launching a satellite, inclusive of non-launch expenditures such as satellite manufacturing and ground stations) and r is the risk-free interest rate.^{¶¶}

Equation 6 can therefore also be used to calculate the implied internal rate of return (IRR) for satellite investments from observed data on collision risk and satellite returns. r is not observed in our data. When costs and returns are time-varying, equation 6 becomes

$$\begin{aligned} L(S_{t+1}, D_{t+1}) &= 1 + r_{s,t+1} - (1 + r) \frac{F_t}{F_{t+1}} \\ \implies L(S_{t+1}, D_{t+1}) &= \underbrace{\left(r_{s,t+1} - r \frac{F_t}{F_{t+1}} \right)}_{\text{excess return on a satellite}} + \underbrace{\left(1 - \frac{F_t}{F_{t+1}} \right)}_{\substack{\text{capital gains from open access} \\ \text{and satellite launch cost variation}}} \end{aligned} \quad [7]$$

where $r_{s,t+1} = \pi_{t+1}/F_{t+1}$. With time-varying economic parameters, two sources of returns drive the collision risk. One is the excess return realized in $t + 1$ from launching a satellite in t . The other is the capital gain (or loss) due to open access and the change in satellite costs. Since open access drives the value of a satellite down to the total cost of launching and operating it, F_t becomes the cost of receiving F_{t+1} in present value the following period, and the returns are given as percentages of F_{t+1} . Since the discount rate is unobserved, we fix it to be constant over time to facilitate estimation.^{***} While we abstract from the fact that satellite lifetimes are finite, this extension was considered in (?) and shorter planned operational lifetimes were shown to reduce the expected collision risk. We discuss this issue further when describing our calibration methodology in section C.2, including why it is unlikely to affect our estimates of the optimal OUF and the benefits of implementing it.

^{‡‡}“Effective” numbers of fragments measure the number of new fragments weighted by the time they spend inside the volume of interest. This approach is used in the debris modeling literature, for example (?).

^{§§}While we consider LEO as a whole, this approach could be generalized to individual spherical shells within LEO. Such generalization could incorporate the substantial heterogeneity in orbital-use values. For example, some orbits are more valuable because they offer ideal conditions for Earth observation, and will likely need a different fee schedule than orbits which do not offer such conditions.

^{¶¶}More precisely, r is the opportunity cost of funds invested in launching a satellite, and may diverge from the risk-free rate if the satellite launcher’s most-preferred alternate investment is not a risk-free security. This rate is sometimes referred to as the internal rate of return.

^{***}This equation was derived in the Appendix of (?). In that setting the discount rate was not constant over time.

B.3. Optimal orbit use with time-varying aggregate returns and costs. Determining the launch plan to ensure optimal orbit use is more complicated. Economists commonly refer to this type of problem as “the (fleet) planner’s problem”, imagining a planner tasked with maximizing fleet-wide NPV. The fleet planner launches satellites to maximize the value of the entire fleet into the (discounted) infinite future, subject to the laws of motion of satellite and debris stocks. Formally, letting $\beta = (1 + r)^{-1}$ be the discount factor, the planner solves

$$\begin{aligned} W(S, D) &= \max_{X \geq 0} \{ \pi S - FX + \beta W(S', D') \} \\ S' &= S(1 - L(S, D))\mu + X \\ D' &= D(1 - \delta) + G(S, D) + \gamma A + mX. \end{aligned} \quad [8]$$

We drop time subscripts and use primes on a variable’s right to indicate future values, in keeping with the convention for infinite-horizon dynamic programming problems. The economic parameters π and F are allowed to be time-varying in our solution approach, though all other physical and economic parameters are constant over time.

Solving the planner’s problem by taking the first-order condition and applying the envelope condition to recover the unknown functional derivatives, we obtain an expression for the collision risk in period $t + 1$ which characterizes the optimal launch rate in period t :

Combining equation 37 with equation 36 iterated one period forwards, we obtain

$$L(S_{t+1}, D_{t+1}) = 1 + r_{s,t+1} - (1 + r) \frac{F_t}{F_{t+1}} - \xi(S_{t+1}, D_{t+1}), \quad [9]$$

where

$$\begin{aligned} \xi(S_{t+1}, D_{t+1}) &= S_{t+1}L_S(S_{t+1}, D_{t+1})F + \frac{\pi - rF - L(S_t, D_t)F - S_tL_S(S_t, D_t)F}{\beta(1 - \delta + G_D(S_{t+1}, D_{t+1}) + mL_D(S_{t+1}, D_{t+1})S_{t+1})} \\ &\quad - \frac{\beta G_S(S_{t+1}, D_{t+1}) + m(1 - L(S_{t+1}, D_{t+1}) - S_{t+1}L_S(S_{t+1}, D_{t+1}))}{\beta(1 - \delta + G_D(S_{t+1}, D_{t+1}) + mL_D(S_{t+1}, D_{t+1})S_{t+1})} L_D(S_{t+1}, D_{t+1})S_{t+1}F \end{aligned} \quad [10]$$

is defined as the marginal external cost of another satellite. This equation is derived in the Supplementary Equations.

C. Calibration and simulation.

C.1. Physical parameters: deorbit, decay, collisions, and fragments. We calibrate the rate at which satellites deorbit, μ , by estimating the following analog to equation 1 by ordinary least squares (OLS):

$$S_{t+1} = S_t(1 - L(S_t, D_t))\hat{\mu} + X_t. \quad [11]$$

We use hats over variables to indicate a parameter being estimated, e.g. μ is the true (unknown) value while $\hat{\mu}$ is the estimate of μ .

Equation 11 yields an estimated average lifespan of about 30 years, i.e. $\hat{\mu} = 0.967$. This is consistent with an average mission length of 5 years, followed by compliance with the 25-year deorbit guideline issued by the IADC (?). Using this rate in our forward simulations is conservative in the sense that the estimated OUF becomes a lower bound relative to a model with imperfect compliance, given that ?) show full compliance to be optimal.

We calibrate equations 4 and 3 by estimating the following equations:

$$L(S_t, D_t) = 1 - \exp(-\hat{\alpha}_{SS}S_t - \hat{\alpha}_{SD}D_t) + \varepsilon_{Lt} \quad [12]$$

$$D_{t+1} = (1 - \delta)D_t + \hat{\beta}_{SS}(1 - \exp(-\hat{\alpha}_{SS}S_t))S_t + \hat{\beta}_{SD}(1 - \exp(-\hat{\alpha}_{SD}D_t))S_t + \quad [13]$$

$$\gamma A_t + \hat{m}X_t + \varepsilon_{Dt}, \quad [14]$$

where ε_{xt} are mean-zero error terms to minimize and α_{xi} are parameters to estimate. Theory predicts α_{jk} , β_{jk} , and m are nonnegative, and δ is in $(0, 1)$. We constrain the parameter estimates to comply with the theoretical restrictions.

We calibrate equations 12 and 13 in two stages. First, we estimate equation 12 by constrained nonlinear least squares (NLS). Then, using the estimated values of $\hat{\alpha}_{SS}$ and $\hat{\alpha}_{SD}$ to generate $(1 - \exp(-\hat{\alpha}_{SS}S_t))S_t$ and $(1 - \exp(-\hat{\alpha}_{SD}D_t))S_t$, we estimate equation 13 by constrained ridge regression, estimating $(1 - \delta)$ directly.^{†††} We estimate both equations on the sample from 1957-2014. The fitted values for all three equations are shown against the actual values in Extended Data Figure 2.

Tables S1 and S2 show the calibrated parameters for equations 12 and 13. Since our goal is predicting the time series rather than inference on the physical coefficients, we show prediction uncertainty estimates for equations 12 and 13 rather than coefficient standard errors in Extended Data Figure 7.

^{†††}We use ridge regression for the debris equation to improve the model fit, despite bias in the estimated parameters. Ridge estimates are biased toward zero relative to OLS estimates. For a given penalty parameter $\lambda \geq 0$, the relationship between a ridge coefficient estimate $\hat{\beta}^{\text{ridge}}$ and the corresponding OLS estimate $\hat{\beta}^{\text{OLS}}$ is $\hat{\beta}^{\text{ridge}} = \hat{\beta}^{\text{OLS}} / (1 + \lambda)$.

Collision probability parameters:	α_{SS}	α_{SD}
Parameter values:	1.29e-06	2.56e-08

Table S1. Parameter values from estimating equation 12.

Debris law of motion parameters	δ	m	γ	β_{SS}	β_{SD}
Parameter values:	0.49	4.84	144.13	292.72	5026.17

Table S2. Parameter values from estimating equation 13. All values are rounded to two decimal places. The penalty parameter λ was selected through cross-validation.

The estimated physical parameter values are physically plausible, with the values estimated for equation 13 being lower bounds due to ridge estimation bias. For example, the value of m suggests that every satellite launched creates (at least) 4.84 pieces of debris on average, while the value of γ suggests that anti-satellite missile tests create (at least) 144.13 pieces of debris on average. While higher-fidelity physical models which derive these quantities from first principles will yield more accurate results, the estimated values appear to be a reasonable first-order approximation to the true values based on the model fits (shown in Extended Data Figure 2).

C.2. Economic parameters: returns, costs, and discounting. Since the discount rate r is unobserved, we calibrate equation 7 by estimating

$$L(S_t, D_t) = a_{L1} + a_{L2}r_{st} + a_{L3} \frac{F_{t-1}}{F_t} + \varepsilon_{rt}, \quad [15]$$

using OLS on the sample of returns data from 2005-2015, omitting the first observation (for 2005) to construct F_{t-1}/F_t . ε_{rt} is a mean-zero error term, a_{L2} is a scale parameter, and a_{L3} measures the gross IRR, $1 + r$. We do not explicitly incorporate satellite lifetimes net of exogenous failure (the parameter μ) as the coefficient is not separately identifiable — it enters each term in equation 15 as a scalar multiplying the parameters (a_{L1}, a_{L2}, a_{L3}), and does not affect the model's predictions. Table S3 shows the calibrated parameters.

Economic calibration parameters:	a_{L1}	a_{L2}	a_{L3}
Parameter values:	0.004	0.009	-0.0004
Standard errors:	0.002	0.002	0.001

Table S3. Parameter values from estimating equation 15. All values are rounded to the first non-zero digit.

If our data perfectly measured the costs and returns of satellite ownership, and our theoretical model held exactly, we would expect $a_{L1} = 1$, $a_{L2} = 1$, and $a_{L3} < -1$. Our estimates therefore suggest that our returns and cost series are measured with error or that our theoretical model is missing some important factors, such as constraints on the number of launches possible each period. In this situation, using the raw economic data with the theoretical model could yield overly-pessimistic predictions. To account for this, we adjust our satellite launch cost data to be consistent with the simple open access model by using the estimated parameter values from the economic calibration. Extended Data Table 3 compares the adjusted data to the original series. The adjusted cost data are of the same magnitude as the unadjusted data, but typically smaller. This suggests that the unmodeled factors include cost efficiencies in satellite production, launch, and management, or constraints on launch services available each period, which are consistent with the analytical features we abstract from in our theoretical model.

The open access model described so far assumes that any firm which wants to launch a satellite can do so. If launches are limited, as they are in practice, this assumption will be violated. The limits will prevent open access launching from equating the excess return on a satellite with the risk of its destruction. In this way, firms which are able to launch earn rents from having a satellite while the collision risk is below the excess return. The wedge between the collision risk and excess return will reflect the value of those rents. To get a sense of how a binding launch constraint would affect our estimates, we adapt the flow-controlled equilibrium condition from (?) to our situation with time-varying parameters.

$$L(S_{t+1}, D_{t+1}) = \left(1 - \frac{p_t}{F_{t+1} + p_{t+1}}\right) + \frac{\pi_{t+1}}{F_{t+1} + p_{t+1}} - (1 + r_t) \frac{F_t}{F_{t+1} + p_{t+1}}, \quad [16]$$

p_t can be interpreted in two ways. It can be viewed as the implied rent received by a firm which already owns a satellite in t due to launches in t being restricted. It can also be viewed as the implied launch fee paid by a firm which is allotted a launch slot in t . In either view, a binding launch constraint results in positive values of p_t and p_{t+1} , biasing the coefficients from regression 7. a_{L1} is biased toward negative infinity, while a_{L2} and a_{L3} are biased toward zero. If the data were free of measurement error and an atomistic homogeneous open access model with a constant discount rate r was correct, we would have $a_{L3} = -(1 + r)$. We set the discount rate to be 5% ($r = 0.05$, implying a discount factor of $\beta = (1 + r)^{-1} \approx 0.95$).

Regardless of the factors missing from the theoretical model, we use equation 15 to recursively calculate the sequence of launch costs implied by the combination of open access, observed launch rates, and observed satellite returns as

$$L(S_t, D_t) = a_{L1} + a_{L2}r_{st} + a_{L3}\frac{F_{t-1}}{F_t} + \varepsilon_{rt}$$

$$\implies \hat{F}_t = \frac{a_2\pi_t + a_3F_{t-1}}{L_t - a_1}. \quad [17]$$

This “adjusted cost” accounts for these missing factors for the historical period. When it exceeds the observed costs, it is likely that the missing factors tend to reflect unobserved costs to launching satellites, such as limited launch availability. When it is below the observed costs, it is likely that the missing factors tend to reflect unobserved returns to launching satellites, such as returns to scale.

Extended Data table 3 shows the observed satellite returns (π_t), observed launch costs (F_t), and implied launch costs (\hat{F}_t). The adjusted costs can be interpreted as the costs such that observed launch patterns result from open access under a non-binding launch constraint and with no other unmeasured factors impacting launch costs. Using the adjusted costs instead of the observed costs in the historical sample ensures that our parameter estimates are consistent with our model of open access.^{†††}

C.3. Algorithms for open access and optimal policy functions. We generate two sequences of policy functions: one function for each period under consideration, and one sequence for each management regime type. We compute each sequence through backwards induction: beginning at the final period in our projection horizon, and iteratively working backwards to the initial period. This procedure implies “perfect foresight” planning under each management regime, i.e. that all agents under any management regime are able to perfectly forecast the sequence of returns, costs, interest rates, launch rates, and other model objects. The perfect foresight assumption is clearly unrealistic, but our purpose is not to show how uncertainty in economic parameters propagates over time. Rather, our purpose is to show how an optimal OUF would vary over time and the time paths of orbital aggregate stocks under different management regimes. Such assumptions are used in integrated assessment models of climate change with similar rationales, e.g. the models studied in ? ? ?). Our work here is conceptually similar to integrated assessment modeling.

To compute the open access time path, we first generate a grid of satellite and debris levels, ($grid_S, grid_D$). We generate this grid as an expanded Chebyshev grid to reduce numerical errors from interpolation, provide higher fidelity near boundaries, and economize on overall computation time. In contrast to a standard Chebyshev grid, an expanded Chebyshev grid allows for computation (rather than extrapolation) at the boundary points. The formula for the k^{th} expanded Chebyshev node on an interval $[a, b]$ with n points is

$$x_k = \frac{1}{2}(a+b) + \frac{1}{2}(b-a)\sec\left(\frac{\pi}{2n}\right)\cos\left(\frac{k}{n} - \frac{1}{2n}\right)$$

We set different values of a and b for S and D , creating a rectangular grid. The main issue in setting b is ensuring that the time paths we solve for (described in section C.4) do not run into or beyond the boundary. To avoid this issue while minimizing the number of points in regions the time paths never reach, we set different a and b bounds for open access and the optimal plan, with the open access grid being strictly larger in both dimensions than the optimal plan grid.

In general, computing decentralized solutions under open access is simpler than computing the planner’s solutions. This is because open access simplifies the continuation value to the cost of launching a satellite. We use R for all simulations, parallelizing where possible. To facilitate convergence of policy and value functions, we normalize the returns and costs parameters so that $\pi_1 = 1$ during computation, and rescale the parameters after the time paths have been generated.

We compute optimal value functions by value function iteration on a grid of the state variables S and D . We initialize the algorithm with a guess of the value and policy functions. Then, at each point on the grid, we solve the first-order condition for the planner’s problem (equation 9). Since there may be multiple solutions, only one of which leads to a global maximum, we then evaluate the value function at each solution (including zero) and select the launch rate attached to the largest level of the value function. Algorithm ?? describes how we compute the optimal policy and value functions for a given grid and given value function guess $guess(S, D)$, while algorithm 2 describes how we compute the open access policy and value functions.

We construct our initial guess of the planner’s value function as the terminal value of the fleet. In the penultimate period, we assume it is not optimal to launch any satellites ($X_{T-1}^* = 0$), making the final fleet size

$$S_T = S_{T-1}(1 - L(S_T, D_T)).$$

In the final period (T), the payoff of the fleet is πS_T . Our assumption that it is not optimal to launch any satellites in the penultimate period implies that the one-period returns of a satellite do not cover the cost of building and launching ($\beta\pi_T < F_{T-1}$), which we verify to hold in every period of our data. We use the implied series of F_t given the observed π_t and launch rate series in solving for open access and optimal policies.

^{†††}Estimating the economic parameters using an open access model with a binding launch constraint is challenging as equation 6 becomes an inequality, giving sets of open access-consistent parameters rather than a unique combination.

Use a numerical rootfinder to find the X_{t-1}^o which solves

$$L(S_t, D_t) = a_{L1} + a_{L2} \hat{r}_{st} + a_{L3} \frac{\hat{F}_{t-1}}{\hat{F}_t}, \text{ using the estimated law of motion for}$$

S_t and D_t as functions of X_{t-1} , and the estimated function for $L(S_t, D_t)$.

Approximate $W_i^\infty(S, D) = \sum_{t=1}^\infty \beta^{t-1} (\pi S_t - \hat{F} X_t^o)$ as $W_i^T(S, D) = \sum_{t=1}^{T-1} \beta^{t-1} (\pi S_t - \hat{F} X_t^*)$ by backwards induction, using the estimated laws of motion for S_{t+1} and D_{t+1} and the estimated function for $L(S_t, D_t)$. We use $T = 500$.
algorithm[Open access launch plan computation]Open access launch plan computation

271
272 **C.4.**
273 **Projected**
274 **time**
275 **paths.**
276
277 We
278 use
279 algorithms
280 ??
281 and
282 [2](#)
283 to
284 compute
285 policy
286 and
287 value
288 functions
289 in
290 each
291 period,
292 and
293 run
294 them
295 sequentially
296 from
297 the
298 final
299 period
300 to
301 the
302 first
303 period
304 to
305 generate
306 a
307 series
308 of
309 policy
310 and
311 value
312 functions
313 for
314 each
315 period's
316 set
317 of
318 economic
319 parameters.
320 Algorithm
321 ??
322 describes
323 this
324 process.

325 It
326 is

327 important
328 to
329 note
330 that
331 when
332 obtaining
333 the
334 sequence
335 of
336 policy
337 functions
338 we
339 do
340 not
341 do
342 backwards
343 induction
344 within
345 each
346 economic
347 time
348 period
349 prior
350 to
351 the
352 final
353 period.
354 Instead,
355 we
356 hold
357 the
358 continuation
359 value
360 $(W(S_{t+1}, D_{t+1}))$
361 fixed
362 and
363 iterate
364 on
365 the
366 policy
367 functions,
368 using
369 previous
370 iterations'
371 policies
372 as
373 starting
374 points.
375 This
376 ensures
377 that
378 the
379 continuation
380 value
381 incorporates
382 each
383 period's
384 returns
385 and
386 costs
387 only

388 once
389 until
390 the
391 final
392 period,
393 while
394 allowing
395 for
396 any
397 numerical
398 errors
399 in
400 initial
401 policy
402 solves
403 to
404 be
405 corrected.
406 This
407 type
408 of
409 “policy
410 iteration”
411 typically
412 takes
413 1-
414 2
415 iterations
416 to
417 converge
418 to
419 within
420 $1e-$
421 3.
422 Backwards
423 induction
424 on
425 the
426 value
427 function
428 in
429 the
430 final
431 period
432 treats
433 that
434 period’s
435 costs
436 and
437 returns
438 as
439 steady
440 state
441 values.
442 This
443 is
444 why
445 we
446 change
447 the
448 notation

449 for
450 the
451 fleet
452 value
453 function
454 for
455 algorithm
456 **??**,
457 indexing
458 by
459 time
460 to
461 indicate
462 that
463 the
464 launch
465 cost
466 and
467 satellite
468 per-
469 period
470 return
471 are
472 changing
473 in
474 each
475 period.
476

477 Once
478 we
479 have
480 a
481 sequence
482 of
483 policy
484 functions
485 for
486 each
487 period's
488 economic
489 parameters,
490 we
491 generate
492 time
493 paths
494 by
495 picking
496 a
497 starting
498 condition
499 (S_0, D_0) ,
500 computing
501 the
502 launch
503 rate
504 X_0
505 by
506 thin-
507 plate
508 spline
509 interpolation

510 of
511 the
512 policy
513 function,
514 using
515 the
516 launch
517 rate
518 to
519 compute
520 the
521 next-
522 period
523 state
524 variables,
525 and
526 repeating
527 the
528 process
529 until
530 the
531 terminal
532 period.
533 Extended
534 Data
535 figure
536 4
537 shows
538 the
539 simulated
540 open
541 access
542 and
543 optimal
544 paths
545 of
546 launches,
547 satellites,
548 debris,
549 and
550 collision
551 risk
552 over
553 the
554 in-
555 sample
556 period,
557 2005-
558 2015,
559 as
560 well
561 as
562 projections
563 from
564 2016-
565 2040.

566
567 **C.5.**
568 **Accounting**
569 **for**
570 **launch**

571 **availability**
572 **constraints.**
573

574 The
575 maximum
576 number
577 of
578 satellites
579 which
580 can
581 be
582 launched
583 in
584 a
585 year
586 are
587 limited
588 by
589 a
590 variety
591 of
592 factors,
593 including
594 weather,
595 availability
596 of
597 rockets,
598 and
599 availability
600 of
601 launch
602 sites.
603 We
604 estimate
605 this
606 “launch
607 constraint”
608 from
609 the
610 observed
611 data
612 for
613 the
614 historical
615 period,
616 and
617 extrapolate
618 it
619 forward
620 for
621 the
622 projection
623 period.
624 To
625 prevent
626 the
627 model
628 from
629 violating
630 the
631 limited

632 availability
633 of
634 launches,
635 we
636 estimate
637 the
638 launch
639 constraint
640 from
641 the
642 observed
643 historical
644 data
645 and
646 then
647 project
648 it
649 forward.
650 In
651 each
652 historical
653 period,
654 we
655 calculate
656 the
657 maximum
658 number
659 of
660 satellites
661 which
662 can
663 be
664 launched
665 as
666 the
667 cumulative
668 maximum
669 of
670 launch
671 attempts
672 (successes+failures).
673 From
674 the
675 historical
676 calculation,
677 we
678 project
679 the
680 launch
681 constraint
682 forward
683 with
684 a
685 linear
686 time
687 trend
688 and
689 an
690 intercept.
691 Table
692 [S4](#)

693 shows
694 the
695 estimated
696 coefficients,
697 and
698 Extended
699 Data
700 figure
701 6
702 shows
703 the
704 projected
705 launch
706 constraint
707 time
708 path.
709

<i>Launch constraint model parameters:</i>	Intercept	Time trend
<i>Parameter values:</i>	30.13	12.5
<i>Standard errors:</i>	16.43	2.65

table[Parameter values from linear model of launch constraint]Parameter values

from linear model of launch constraint. All values are rounded to two decimal places. We estimate these coefficients using OLS on the historical launch constraint.

710 In
711 the
712 historical
713 period,
714 we
715 use
716 the
717 adjusted
718 launch
719 costs
720 (described
721 in
722 section
723 [C.2](#))
724 When
725 the
726 zero-
727 profit
728 or
729 optimal
730 number
731 of
732 launches
733 exceeds
734 the
735 launch
736 constraint
737 in
738 the
739 projection
740 period,
741 we
742 impose
743 the
744 constraint.
745 If
746 the
747 constraint

748 binds
749 for
750 both
751 the
752 planner
753 and
754 open
755 access
756 firms,
757 then
758 the
759 estimated
760 optimal
761 OUF
762 will
763 be
764 zero.
765 If
766 the
767 constraint
768 binds
769 on
770 open
771 access
772 firms
773 but
774 not
775 on
776 the
777 planner,
778 the
779 optimal
780 OUF
781 will
782 be
783 lower
784 than
785 if
786 the
787 constraint
788 had
789 not
790 bound
791 open
792 access
793 firms.
794 If
795 we
796 impose
797 the
798 constraint
799 when
800 in
801 reality
802 it
803 would
804 not
805 bind,
806 we
807 will
808 underestimate

809 the
810 optimal
811 OUF.
812

813
814 **D.**
815 **Sensitivity**
816 **analyses**
817 **of**
818 **physical**
819 **equation**
820 **calibration.**

821 To
822 study
823 the
824 sensitivity
825 of
826 our
827 conclusions
828 to
829 uncertainty
830 in
831 our
832 physical
833 parameter
834 estimates,
835 we
836 conduct
837 a
838 sensitivity
839 analysis
840 of
841 the
842 model
843 simulations
844 given
845 different
846 physical
847 parameter
848 values.
849

850 We
851 use
852 a
853 residual
854 bootstrap
855 procedure
856 to
857 obtain
858 sets
859 of
860 alternative
861 parameter
862 values.
863

864 First,
865 we
866 estimate
867 equations
868 [12](#)
869 and

870 13
871 as
872 described
873 above.
874 Then,
875 we
876 sample
877 from
878 the
879 distribution
880 of
881 residuals
882 to
883 generate
884 “bootstrap
885 worlds”.
886 We
887 add
888 these
889 residuals
890 to
891 the
892 estimated
893 models
894 to
895 generate
896 bootstrap
897 world
898 outcome
899 variables.
900 Finally,
901 we
902 re-
903 estimate
904 the
905 model
906 using
907 the
908 bootstrap
909 world
910 outcomes
911 to
912 generate
913 alternate
914 sets
915 of
916 physical
917 parameter
918 estimates,
919 and
920 simulate
921 the
922 model
923 under
924 a
925 random
926 sample
927 of
928 those
929 estimates.
930 Algorithm

931 ??
932 describes
933 our
934 procedure
935 precisely.

936

937 One
938 issue
939 to
940 note
941 is
942 that,
943 because
944 we
945 estimate
946 equation
947 [12](#)
948 with
949 a
950 constrained
951 procedure
952 and
953 the
954 coefficients
955 are
956 near
957 one
958 of
959 the
960 constraint
961 boundaries,
962 the
963 asymptotic
964 properties
965 of
966 this
967 procedure
968 are
969 difficult
970 to
971 obtain
972 (?
973).
974 Since
975 our
976 goal
977 is
978 not
979 asymptotic
980 analysis
981 of
982 standard
983 errors
984 but
985 rather
986 to
987 generate
988 alternate
989 parameter
990 sets
991 in

992 a
993 principled
994 way
995 for
996 counterfactual
997 simulations,
998 we
999 select
1000 the
1001 main
1002 model
1003 estimates
1004 as
1005 the
1006 mean
1007 of
1008 the
1009 bootstrap
1010 world
1011 parameters.
1012 This
1013 ensures
1014 that
1015 our
1016 sensitivity
1017 analysis
1018 selects
1019 parameters
1020 around
1021 the
1022 main
1023 model
1024 estimates.
1025 Ultimately
1026 this
1027 is
1028 inconsequential
1029 for
1030 the
1031 outcomes
1032 of
1033 interest
1034 —
1035 collision
1036 risk
1037 under
1038 open
1039 access
1040 and
1041 optimal
1042 management,
1043 and
1044 the
1045 resulting
1046 OUF
1047 —
1048 since
1049 the
1050 outcomes
1051 are
1052 endogenous

1053 variables
1054 which
1055 satisfy
1056 economic
1057 conditions
1058 irrespective
1059 of
1060 the
1061 specific
1062 physical
1063 parameter
1064 values.
1065 The
1066 physical
1067 parameter
1068 values
1069 affect
1070 the
1071 specific
1072 paths
1073 of
1074 launches,
1075 satellites,
1076 and
1077 debris,
1078 but
1079 only
1080 such
1081 that
1082 the
1083 collision
1084 risk
1085 continues
1086 to
1087 satisfy
1088 the
1089 economic
1090 conditions.

1091
1092 **E.**
1093 **Projecting**
1094 **the**
1095 **optimal**
1096 **OUF**
1097 **path.**
1098 With
1099 the
1100 calibrated
1101 parameter
1102 values,
1103 we
1104 turn
1105 to
1106 projecting
1107 the
1108 optimal
1109 OUF
1110 path.
1111 We
1112 split
1113 this

1114 process
1115 into
1116 two
1117 stages.
1118 In
1119 the
1120 first
1121 stage,
1122 we
1123 compute
1124 the
1125 time
1126 paths
1127 of
1128 the
1129 satellite
1130 stock,
1131 debris
1132 stock,
1133 and
1134 launch
1135 rate,
1136 given
1137 the
1138 open
1139 access
1140 and
1141 fleet
1142 planner
1143 models
1144 of
1145 orbit
1146 use.
1147 These
1148 describe
1149 the
1150 projected
1151 evolution
1152 of
1153 the
1154 orbital
1155 aggregates.
1156 In
1157 the
1158 second
1159 stage,
1160 we
1161 use
1162 the
1163 computed
1164 time
1165 paths
1166 with
1167 the
1168 estimated
1169 collision
1170 probability
1171 function
1172 and
1173 launch
1174 cost

1175 path
1176 to
1177 calculate
1178 the
1179 optimal
1180 OUF.
1181 The
1182 OUF
1183 is
1184 derived
1185 from
1186 the
1187 same
1188 open
1189 access
1190 and
1191 fleet
1192 planner
1193 models.
1194 It
1195 describes
1196 the
1197 amount
1198 which
1199 a
1200 satellite
1201 owner
1202 would
1203 have
1204 to
1205 be
1206 charged
1207 every
1208 year,
1209 beginning
1210 from
1211 the
1212 projection
1213 horizon's
1214 initial
1215 conditions,
1216 in
1217 order
1218 to
1219 align
1220 their
1221 incentives
1222 with
1223 the
1224 fleet
1225 planner's.^{\$\$\$}
1226 We
1227 show
1228 the
1229 in-
1230 sample
1231 fit
1232 of
1233 our
1234 open

^{\$\$\$} This can also be thought of as "How much of the profits from orbit use currently reflect resource rents which should not have been dissipated?"

1235 access
 1236 projections
 1237 to
 1238 establish
 1239 that
 1240 our
 1241 approach
 1242 can
 1243 approximate
 1244 the
 1245 observed
 1246 history,
 1247 and
 1248 then
 1249 use
 1250 predictions
 1251 of
 1252 space
 1253 economy
 1254 revenues
 1255 and
 1256 costs
 1257 from
 1258 (?)
 1259)
 1260 to
 1261 project
 1262 out
 1263 the
 1264 open
 1265 access
 1266 and
 1267 optimal
 1268 launch
 1269 rates
 1270 given
 1271 those
 1272 predictions.

1273
 1274 We
 1275 calculate
 1276 the
 1277 time
 1278 path
 1279 of
 1280 an
 1281 optimal
 1282 OUF
 1283 from
 1284 equation
 1285 18:

$$\tau_t = (L(S_{t+1}^o, D_{t+1}^o) - L(S_{t+1}^*, D_{t+1}^*)) F_{t+1},$$

1286 [18]
 1287 where
 1288 S_{t+1}^o
 1289 and
 1290 D_{t+1}^o
 1291 are
 1292 satellite
 1293 and

1294 debris
 1295 stocks
 1296 in
 1297 $t +$
 1298 1
 1299 under
 1300 open
 1301 access
 1302 management,
 1303 and
 1304 S_{t+1}^*
 1305 and
 1306 D_{t+1}^*
 1307 are
 1308 satellite
 1309 and
 1310 debris
 1311 stocks
 1312 in
 1313 $t +$
 1314 1
 1315 under
 1316 optimal
 1317 management.
 1318 The
 1319 optimal
 1320 OUF
 1321 is
 1322 positive
 1323 whenever
 1324 the
 1325 planner
 1326 would
 1327 maintain
 1328 a
 1329 lower
 1330 collision
 1331 probability
 1332 than
 1333 firms
 1334 under
 1335 open
 1336 access
 1337 would.
 1338 The
 1339 planner,
 1340 in
 1341 turn,
 1342 will
 1343 maintain
 1344 a
 1345 lower
 1346 collision
 1347 probability
 1348 if
 1349 the
 1350 lifetime
 1351 returns
 1352 from
 1353 another
 1354 satellite

1355 in
1356 orbit
1357 are
1358 less
1359 than
1360 that
1361 satellite's
1362 expected
1363 future
1364 damages
1365 to
1366 other
1367 satellites
1368 in
1369 the
1370 fleet.
1371 By
1372 charging
1373 open
1374 access
1375 firms
1376 the
1377 marginal
1378 external
1379 cost
1380 of
1381 their
1382 satellite
1383 as
1384 an
1385 OUF,
1386 their
1387 incentives
1388 are
1389 aligned
1390 with
1391 those
1392 of
1393 the
1394 planner
1395 despite
1396 the
1397 institutional
1398 differences.
1399 With
1400 their
1401 incentives
1402 aligned,
1403 their
1404 decisions
1405 to
1406 launch
1407 or
1408 not
1409 are
1410 shifted
1411 to
1412 optimize
1413 the
1414 total
1415 intertemporal

1416 economic
1417 value
1418 from
1419 orbit
1420 use
1421 rather
1422 than
1423 their
1424 own
1425 individual
1426 profit.
1427

1428 Formally,
1429 equation
1430 [18](#)
1431 can
1432 be
1433 derived
1434 by
1435 comparing
1436 the
1437 open
1438 access
1439 equilibrium
1440 condition
1441 (equation
1442 [7](#))
1443 to
1444 the
1445 fleet
1446 planner's
1447 optimality
1448 condition
1449 for
1450 launching
1451 (the
1452 first-
1453 order
1454 condition
1455 of
1456 system
1457 of
1458 equations
1459 [8](#)).
1460 These
1461 conditions
1462 can
1463 be
1464 written
1465 to
1466 express
1467 the
1468 expected
1469 loss
1470 in
1471 satellite
1472 value
1473 (collision
1474 probability
1475 multiplied
1476 by

1477 replacement
1478 cost)
1479 in
1480 terms
1481 of
1482 economic
1483 and,
1484 in
1485 the
1486 case
1487 of
1488 the
1489 optimality
1490 condition,
1491 physical
1492 parameters.
1493 Those
1494 economic
1495 parameters
1496 include
1497 terms
1498 for
1499 the
1500 current
1501 excess
1502 return
1503 on
1504 a
1505 satellite
1506 in
1507 addition
1508 to
1509 the
1510 capital
1511 gain
1512 or
1513 loss
1514 from
1515 changes
1516 in
1517 the
1518 cost
1519 of
1520 a
1521 replacement
1522 satellite.
1523 By
1524 subtracting
1525 the
1526 optimal
1527 expected
1528 loss
1529 from
1530 the
1531 open
1532 access
1533 expected
1534 loss,
1535 we
1536 recover
1537 the

1538 additional
1539 physical
1540 and
1541 economic
1542 term
1543 the
1544 social
1545 planner
1546 accounts
1547 for
1548 —
1549 the
1550 marginal
1551 external
1552 cost
1553 of
1554 a
1555 satellite.
1556 The
1557 marginal
1558 external
1559 cost
1560 is
1561 the
1562 optimal
1563 OUF
1564 value
1565 to
1566 levy
1567 on
1568 each
1569 satellite.
1570

1571
1572 **F.**
1573 **Projecting**
1574 **the**
1575 **effects**
1576 **of**
1577 **active**
1578 **debris**
1579 **removal**
1580 **under**
1581 **open**
1582 **access.**
1583 Finally,
1584 we
1585 consider
1586 the
1587 effects
1588 of
1589 active
1590 debris
1591 removal
1592 technologies
1593 on
1594 the
1595 NPV
1596 losses
1597 due
1598 to

1599 open
1600 access,
1601 shown
1602 in
1603 Extended
1604 Data
1605 figure
1606 5.
1607 We
1608 assume
1609 that
1610 debris
1611 removal
1612 is
1613 available
1614 for
1615 zero
1616 cost,
1617 and
1618 that
1619 50%
1620 of
1621 all
1622 debris
1623 is
1624 removed
1625 from
1626 orbit
1627 each
1628 period
1629 once
1630 the
1631 technology
1632 is
1633 available.
1634 For
1635 example,
1636 in
1637 a
1638 scenario
1639 where
1640 removal
1641 begins
1642 in
1643 2030,
1644 we
1645 assume
1646 that
1647 50%
1648 of
1649 all
1650 debris
1651 in
1652 orbit
1653 is
1654 removed
1655 every
1656 year
1657 beginning
1658 in
1659 2030.

1660 We
1661 assume
1662 debris
1663 is
1664 removed
1665 before
1666 it
1667 collides
1668 with
1669 any
1670 other
1671 orbiting
1672 object,
1673 and
1674 that
1675 implementing
1676 the
1677 removal
1678 technology
1679 does
1680 not
1681 require
1682 any
1683 additional
1684 satellites.
1685

1686 These
1687 assumptions
1688 help
1689 us
1690 bound
1691 a
1692 “best
1693 case”
1694 removal
1695 scenario.
1696 In
1697 reality,
1698 removal
1699 will
1700 cost
1701 more
1702 than
1703 \$0
1704 per
1705 unit
1706 removed,
1707 will
1708 require
1709 some
1710 additional
1711 satellites
1712 on
1713 orbit
1714 to
1715 implement,
1716 and
1717 will
1718 not
1719 be
1720 guaranteed

1721 to
 1722 be
 1723 successful
 1724 in
 1725 all
 1726 cases.
 1727 Since
 1728 debris
 1729 removal
 1730 in
 1731 LEO
 1732 is
 1733 not
 1734 commercially
 1735 available
 1736 yet,
 1737 we
 1738 experiment
 1739 with
 1740 different
 1741 removal
 1742 start
 1743 years
 1744 between
 1745 2021–
 1746 2034.
 1747

The
 laws
 of
 motion
 with
 debris
 removal
 are

$$S_{t+1} = S_t(1 - L(S_t, D_t(1 - R_t)))\mu + X_t$$

[19]

$$D_{t+1} = D_t(1 - R_t)(1 - \delta) + G(S_t, D_t(1 - R_t)) + \gamma A_t + mX_t,$$

[20]

1748 where
 1749 $R_t =$
 1750 0.5
 1751 if
 1752 removal
 1753 technologies
 1754 are
 1755 available
 1756 and
 1757 0
 1758 otherwise.
 1759

The
 open
 access
 equilibrium
 condition
 is
 unchanged
 from
 the

condition
without
(equation
7).
The
planner's
optimality
condition
with
freely-
provided
debris
removal
is
similar
to
the
condition
without
(equation
9),
but
with
(1 −
 R_t)
terms
scaling
the
debris
variable
and
all
derivatives
with
respect
to
debris:

$$W_{D,t}(S_t, D_t(1 - R_t)) = -S_t L_D(S_t, D_t(1 - R_t))(1 - R_t)F_t + \beta[1 - \delta + G_D(S_t, D_t(1 - R_t))(1 - R_t) + mS_t L_D(S_t, D_t(1 - R_t))(1 - R_t)]W_{D,t+1}(S_{t+1}, D_{t+1}(1 - R_{t+1})),$$

[21]

where

$$W_{D,t}(S_t, D_t(1 - R_t)) = \left[\frac{F_{t-1}}{\beta} - \pi_t - (1 - L(S_t, D_t(1 - R_t)) - S_t L_S(S_t, D_t(1 - R_t)))F_t - \left(\frac{G_S(S_t, D_t(1 - R_t)) - m(1 - L(S_t, D_t(1 - R_t)) - S_t L_S(S_t, D_t(1 - R_t)))}{1 - \delta + G_D(S_t, D_t(1 - R_t))(1 - R_t) + mL_D(S_t, D_t(1 - R_t))(1 - R_t)} \right) \cdot L_D(S_t, D_t(1 - R_t))(1 - R_t)S_t F_t \right] \cdot \left[\frac{G_S(S_t, D_t(1 - R_t)) - m(1 - L(S_t, D_t(1 - R_t)) - S_t L_S(S_t, D_t(1 - R_t)))}{1 - \delta + G_D(S_t, D_t(1 - R_t))(1 - R_t) + mL_D(S_t, D_t(1 - R_t))(1 - R_t)} + m \right]^{-1}.$$

[22]

1. Supplementary Equations

A.

1764 **Derivation**
 1765 **of**
 1766 **the**
 1767 **optimal**
 1768 **launch**
 1769 **rate.**

In
 this
 section
 we
 derive
 the
 equations
 characterizing
 the
 planner's
 launch
 rule,
 equations

9

and

37.

Period

t

values

are

shown

with

no

subscript,

and

period

$t +$

1

values

are

marked

with

a

,

e.g.

$S_t \equiv$

$S, S_{t+1} \equiv$

S' .

The

fleet

planner's

problem

is

$$W(S, D) = \max_{X \geq 0} \{ \pi S - FX + \beta W(S', D') \}$$

[23]

$$\text{s.t. } S' = S(1 - L(S, D)) + X$$

[24]

$$D' = D(1 - \delta) + G(S, D) + \gamma A + mX.$$

[25]

1770 The
 1771 fleet
 1772 planner's
 1773 launch

1774 plan
1775 will
1776 satisfy

$$X^* : \beta[W_S(S', D') + mW_D(S', D')] = F,$$

17[26]

1778 that
1779 is,
1780 the
1781 planner
1782 will
1783 launch
1784 until
1785 the
1786 marginal
1787 value
1788 to
1789 the
1790 fleet
1791 of
1792 a
1793 new
1794 satellite
1795 plus
1796 the
1797 marginal
1798 value
1799 to
1800 the
1801 fleet
1802 of
1803 its
1804 launch
1805 debris
1806 is
1807 equal
1808 to
1809 the
1810 launch
1811 cost.

1812
Assuming
an
optimal
policy
function
 $X^* =$
 $H(S, D)$
exists
and
applying
the
envelope
condition,
we
have
the
following
expressions
for
the
fleet's

marginal
value
of
another
satellite
and
another
piece
of
debris:

$$W_S(S, D) = \pi + \beta[W_S(S', D')(1 - L(S, D) - SL_S(S, D)) + W_D(S', D')G_S(S, D)]$$

[27]

$$W_D(S, D) = \beta[W_D(S', D')(1 - \delta + G_D(S, D)) + W_S(S', D')(-SL_D(S, D))]$$

[28]

1813 Rewriting
1814 equation
1815 26,
1816 we
1817 have

$$W_S(S', D') = \left[\frac{F}{\beta} - mW_D(S', D') \right]$$

18[29]

Plugging
equation
29
into
equations
27
and
28,

$$W_S(S, D) = \pi + F(1 - L(S, D) - SL_S(S, D)) - \beta W_D(S', D')[m(1 - L(S, D) - SL_S(S, D)) - G_S(S, D)]$$

[30]

$$W_D(S, D) = (-SL_D(S, D))F + \beta W_D(S', D')[1 - \delta + G_D(S, D) - m(-SL_D(S, D))]$$

[31]

Define
the
following
quantities:

$$\begin{aligned}\alpha_1(S, D) &= \pi + (1 - L(S, D) - SL_S(S, D))F \\ \alpha_2(S, D) &= -SL_D(S, D)F \\ \Gamma_1(S, D) &= G_S(S, D) - m(1 - L(S, D) - SL_S(S, D)) \\ \Gamma_2(S, D) &= 1 - \delta + G_D(S, D) + mSL_D(S, D).\end{aligned}$$

These
allow
us
to
rewrite
equations
30
and
31
as

$$W_S(S, D) = \alpha_1(S, D) + \beta \Gamma_1(S, D)W_D(S', D')$$

[32]

$$W_D(S, D) = \alpha_2(S, D) + \beta \Gamma_2(S, D)W_D(S', D').$$

[33]

1819 As
 1820 long
 1821 as
 1822 $\delta <$
 1823 1,
 1824 $\Gamma_2(S, D) \neq$
 1825 $0 \forall (S, D),$
 1826 allowing
 1827 us
 1828 to
 1829 rewrite
 1830 equation
 1831 33
 1832 as

$$W_D(S', D') = \frac{W_D(S, D) - \alpha_2(S, D)}{\beta \Gamma_2(S, D)}.$$

[34]
 Plugging
 equation
 34
 into
 equation
 32,
 we
 get

$$\begin{aligned} W_S(S, D) &= \alpha_1(S, D) + \beta \Gamma_1(S, D) \frac{W_D(S, D) - \alpha_2(S, D)}{\beta \Gamma_2(S, D)} \\ &= \alpha_1(S, D) + \frac{\Gamma_1(S, D)}{\Gamma_2(S, D)} (W_D(S, D) - \alpha_2(S, D)) \\ \implies W_S(S, D) &= \alpha_1(S, D) - \frac{\Gamma_1(S, D)}{\Gamma_2(S, D)} \alpha_2(S, D) + \frac{\Gamma_1(S, D)}{\Gamma_2(S, D)} W_D(S, D) \end{aligned}$$

[35]

Iterating
 equation
 29
 one
 period
 backwards
 and
 plugging
 it
 into
 equation
 32,
 we
 get

$$\begin{aligned} \frac{{}'F}{\beta} - m W_D(S, D) &= \alpha_1(S, D) - \frac{\Gamma_1(S, D)}{\Gamma_2(S, D)} \alpha_2(S, D) + \frac{\Gamma_1(S, D)}{\Gamma_2(S, D)} W_D(S, D) \\ \implies W_D(S, D) &= \left[\frac{{}'F}{\beta} - \alpha_1(S, D) - \frac{\Gamma_1(S, D)}{\Gamma_2(S, D)} \alpha_2(S, D) \right] \left[\frac{\Gamma_1(S, D)}{\Gamma_2(S, D)} + m \right]^{-1}. \end{aligned}$$

[36]

Substituting
 in
 the
 forms
 for
 $\alpha_1(S, D), \alpha_2(S, D), \Gamma_1(S, D),$

and
 $\Gamma_2(S, D)$,
equation
33
yields
equation
9
and
equation
36
yields

$$W_D(S, D) = \left[\frac{F}{\beta} - \pi - (1 - L(S, D) - SL_S(S, D))F - \frac{G_S(S, D) - m(1 - L(S, D) - SL_S(S, D))}{1 - \delta + G_D(S, D) + mL_D(S, D)} L_D(S, D)SF \right] \cdot \left[\frac{G_S(S, D) - m(1 - L(S, D) - SL_S(S, D))}{1 - \delta + G_D(S, D) + mL_D(S, D)} + m \right]^{-1}.$$

[37]

Combining
equation
37
with
equation
36
iterated
one
period
forwards,
we
obtain

$$L(S', D') = 1 + r'_s - (1 + r) \frac{F}{F'} - \xi(S', D'),$$

where

$$\xi(S', D') = S' L_S(S', D') F' + \frac{\pi - rF - L(S, D)F - SL_S(S, D)F}{\beta(1 - \delta + G_D(S', D') + mL_D(S', D')S')} - \frac{\beta G_S(S', D') + m(1 - L(S', D') - S' L_S(S', D'))}{\beta(1 - \delta + G_D(S', D') + mL_D(S', D')S')} L_D(S', D') S' F'.$$

2. Supplementary Discussion

A. Interpreting the optimal OUF and long-run industry value paths.

Figure
2
in
the
main
text
shows

1854 the
1855 NPV
1856 gains
1857 from
1858 beginning
1859 optimal
1860 management
1861 in
1862 different
1863 years,
1864 and
1865 the
1866 permanent
1867 orbit
1868 use
1869 value
1870 losses
1871 in
1872 2040
1873 from
1874 delaying
1875 optimal
1876 management.
1877 The
1878 permanent
1879 orbit
1880 use
1881 value
1882 is
1883 the
1884 discounted
1885 value
1886 of
1887 the
1888 satellite
1889 fleet
1890 over
1891 the
1892 long-
1893 run,
1894 accounting
1895 for
1896 losses
1897 and
1898 replacements.

1900 The
1901 discontinuous
1902 jumps
1903 in
1904 NPV
1905 in
1906 figure
1907 2
1908 reflect
1909 the
1910 immediate
1911 effect
1912 of
1913 reducing
1914 launch

1915 activity
1916 while
1917 the
1918 satellite
1919 and
1920 debris
1921 stocks
1922 are
1923 suboptimally
1924 high.
1925 The
1926 change
1927 in
1928 launch
1929 activity
1930 increases
1931 the
1932 NPV
1933 by
1934 reducing
1935 the
1936 cost
1937 outflows
1938 each
1939 year.
1940 Since
1941 open
1942 access
1943 launching
1944 results
1945 in
1946 excess
1947 satellites
1948 and
1949 debris,
1950 the
1951 benefits
1952 of
1953 optimal
1954 management
1955 continue
1956 to
1957 accrue
1958 gradually
1959 as
1960 the
1961 satellite
1962 and
1963 debris
1964 stocks
1965 draw
1966 down.
1967 Extended
1968 Data
1969 figure
1970 4
1971 shows
1972 these
1973 launch
1974 rate
1975 dynamics

1976 for
1977 a
1978 2006
1979 optimal
1980 management
1981 start.
1982

1983 The
1984 fact
1985 that
1986 the
1987 optimal
1988 OUF,
1989 shown
1990 in
1991 Extended
1992 Data
1993 figure
1994 10,
1995 rises
1996 over
1997 time
1998 is
1999 an
2000 indication
2001 of
2002 the
2003 restored
2004 value
2005 of
2006 orbit
2007 use
2008 due
2009 to
2010 optimal
2011 management
2012 (orbital
2013 rents).
2014 Intuitively,
2015 firms
2016 fully
2017 dissipate
2018 orbital
2019 rents
2020 in
2021 an
2022 open
2023 access
2024 equilibrium,
2025 as
2026 those
2027 rents
2028 act
2029 as
2030 an
2031 incentive
2032 to
2033 enter.
2034 To
2035 counter
2036 the

2037 growth
2038 in
2039 the
2040 incentive
2041 to
2042 enter
2043 due
2044 to
2045 restored
2046 orbital
2047 rents,
2048 the
2049 OUF
2050 must
2051 also
2052 rise
2053 over
2054 time.
2055 A
2056 firm
2057 which
2058 enters
2059 the
2060 commons
2061 early
2062 on
2063 (say,
2064 2020)
2065 will
2066 pay
2067 a
2068 lower
2069 initial
2070 fee
2071 than
2072 a
2073 firm
2074 which
2075 enters
2076 later
2077 on
2078 (say,
2079 2030)
2080 because
2081 the
2082 early
2083 entrant
2084 is
2085 paying
2086 to
2087 use
2088 a
2089 more
2090 congested
2091 environment.
2092

2093 Though
2094 our
2095 modeling
2096 procedure
2097 abstracts

2098 from
2099 many
2100 economic
2101 and
2102 physical
2103 complications,
2104 our
2105 optimal
2106 OUF
2107 and
2108 long-
2109 run
2110 industry
2111 value
2112 estimates
2113 are
2114 likely
2115 robust
2116 to
2117 these
2118 limitations
2119 and
2120 on
2121 the
2122 correct
2123 order
2124 of
2125 magnitude
2126 with
2127 the
2128 correct
2129 qualitative
2130 features.
2131 On
2132 the
2133 OUF
2134 side,
2135 given
2136 that
2137 the
2138 projected
2139 optimal
2140 launch
2141 path
2142 beginning
2143 from
2144 the
2145 projected
2146 2020
2147 state
2148 of
2149 LEO
2150 involves
2151 cessation
2152 of
2153 launch
2154 activity,
2155 the
2156 estimated
2157 OUF
2158 in

2159 2020
2160 needs
2161 only
2162 to
2163 be
2164 large
2165 enough
2166 to
2167 deter
2168 launches,
2169 particularly
2170 those
2171 likely
2172 to
2173 generate
2174 large
2175 and
2176 suboptimal
2177 increases
2178 in
2179 collision
2180 risk.
2181 While
2182 satellite
2183 operators
2184 in
2185 LEO
2186 are
2187 heterogeneous
2188 and
2189 represent
2190 diverse
2191 interests,
2192 we
2193 estimate
2194 an
2195 optimal
2196 averaged-
2197 across-
2198 LEO-
2199 use-
2200 cases
2201 per-
2202 satellite
2203 per-
2204 year
2205 fee
2206 beginning
2207 at
2208 approximately
2209 \$13,500
2210 USD
2211 and
2212 growing
2213 over
2214 time.
2215 (?
2216)
2217 identify
2218 that
2219 the

2220 majority
2221 of
2222 collision
2223 risk
2224 increases
2225 in
2226 the
2227 near
2228 future
2229 will
2230 be
2231 driven
2232 by
2233 satellite
2234 constellation
2235 operators.
2236 For
2237 an
2238 entity
2239 planning
2240 to
2241 launch
2242 a
2243 constellation
2244 of
2245 600
2246 satellites,
2247 our
2248 OUF
2249 amounts
2250 to
2251 an
2252 additional
2253 yearly
2254 expenditure
2255 beginning
2256 at
2257 \$8.1
2258 million
2259 USD
2260 —
2261 likely
2262 enough
2263 to
2264 prompt
2265 serious
2266 reconsideration
2267 of
2268 the
2269 size
2270 and
2271 nature
2272 of
2273 the
2274 constellation.
2275 On
2276 the
2277 industry
2278 value
2279 side,
2280 the

2281 global
2282 satellite
2283 sector
2284 currently
2285 produces
2286 approximately
2287 \$0.15
2288 trillion
2289 USD
2290 in
2291 revenues,
2292 and
2293 is
2294 anticipated
2295 to
2296 grow
2297 to
2298 \$2
2299 trillion
2300 USD
2301 in
2302 revenues
2303 and
2304 costs
2305 by
2306 2040
2307 (?
2308).
2309 A
2310 decrease
2311 in
2312 collision
2313 risk
2314 which
2315 leads
2316 to
2317 a
2318 10%
2319 increase
2320 in
2321 the
2322 per-
2323 year
2324 economic
2325 value
2326 of
2327 the
2328 satellite
2329 sector
2330 would
2331 immediately
2332 add
2333 10%
2334 to
2335 the
2336 sector's
2337 NPV.
2338 Our
2339 model
2340 projects
2341 that

2342 collision
2343 risk
2344 in
2345 2040
2346 will
2347 decrease
2348 by
2349 roughly
2350 33%
2351 (compared
2352 to
2353 BAU)
2354 under
2355 an
2356 optimal
2357 management
2358 plan
2359 beginning
2360 in
2361 2020.
2362 This
2363 reduction
2364 collision
2365 risk
2366 would
2367 cut
2368 collision-
2369 related
2370 replacement
2371 costs,
2372 increase
2373 the
2374 expected
2375 lifespan
2376 of
2377 satellites
2378 in
2379 orbit,
2380 and
2381 reduce
2382 collision-
2383 related
2384 disruptions
2385 in
2386 the
2387 stream
2388 of
2389 satellite-
2390 related
2391 economic
2392 returns.
2393 Given
2394 this,
2395 long-
2396 run
2397 industry
2398 value
2399 in
2400 2040
2401 on
2402 the

2403 order
2404 of
2405 single-
2406 digit
2407 trillions
2408 of
2409 USD
2410 seems
2411 plausible.

2412
2413 **B.**
2414 **Open**
2415 **access**
2416 **and**
2417 **active**
2418 **debris**
2419 **removal.**

2420 The
2421 introduction
2422 of
2423 debris
2424 removal
2425 makes
2426 both
2427 open
2428 access
2429 firms
2430 and
2431 the
2432 planner
2433 launch
2434 additional
2435 satellites.
2436 However,
2437 the
2438 planner
2439 launches
2440 considerably
2441 fewer
2442 additional
2443 satellites
2444 than
2445 open
2446 access
2447 firms.
2448 The
2449 immediate
2450 decrease
2451 in
2452 debris
2453 when
2454 removal
2455 becomes
2456 available
2457 induces
2458 new
2459 launches
2460 until
2461 the
2462 collision
2463 risk

2464 is
2465 once
2466 again
2467 equated
2468 with
2469 the
2470 excess
2471 return
2472 on
2473 a
2474 satellite.
2475 Extended
2476 Data
2477 figure
2478 5a–
2479 d
2480 shows
2481 the
2482 effects
2483 of
2484 debris
2485 removal
2486 beginning
2487 in
2488 2029
2489 on
2490 satellite
2491 and
2492 debris
2493 accumulation
2494 under
2495 open
2496 access
2497 and
2498 a
2499 range
2500 of
2501 optimal
2502 management
2503 paths.
2504 The
2505 removal-
2506 induced
2507 additional
2508 launching
2509 leads
2510 to
2511 a
2512 higher
2513 steady-
2514 state
2515 satellite
2516 stock
2517 and
2518 a
2519 lower
2520 steady-
2521 state
2522 debris
2523 stock
2524 under

2525 open
2526 access
2527 and
2528 optimal
2529 management.
2530 The
2531 amount
2532 of
2533 debris
2534 removed
2535 in
2536 our
2537 “50%
2538 removal”
2539 scenario
2540 is
2541 substantially
2542 larger
2543 under
2544 open
2545 access
2546 than
2547 the
2548 optimal
2549 plan
2550 as
2551 there
2552 is
2553 more
2554 debris
2555 in
2556 orbit
2557 under
2558 open
2559 access.
2560

2561 Though
2562 debris
2563 removal
2564 allows
2565 open
2566 access
2567 to
2568 sustain
2569 more
2570 satellites
2571 in
2572 orbit,
2573 over
2574 time
2575 collision
2576 risk
2577 returns
2578 to
2579 the
2580 equilibrium
2581 level.
2582 The
2583 costs
2584 of
2585 additional

2586 launches
2587 erodes
2588 some
2589 of
2590 the
2591 NPV
2592 gains
2593 due
2594 to
2595 reduced
2596 risk.
2597 Extended
2598 Data
2599 figure
2600 5e
2601 shows
2602 the
2603 percentage
2604 change
2605 in
2606 open-
2607 access
2608 NPV
2609 loss
2610 due
2611 to
2612 the
2613 introduction
2614 of
2615 debris
2616 removal
2617 in
2618 2029,
2619 as
2620 a
2621 fraction
2622 of
2623 the
2624 potential
2625 gain
2626 from
2627 implementing
2628 the
2629 optimal
2630 plan
2631 in
2632 2020.
2633 Extended
2634 Data
2635 figure
2636 5f
2637 summarizes
2638 the
2639 minimum,
2640 mean,
2641 and
2642 maximum
2643 changes
2644 in
2645 long-
2646 run

2647 industry
2648 value
2649 losses
2650 due
2651 to
2652 open
2653 access
2654 with
2655 removal
2656 beginning
2657 in
2658 each
2659 year
2660 in
2661 2021–
2662 2034.
2663 On
2664 average,
2665 debris
2666 removal
2667 beginning
2668 in
2669 the
2670 2021–
2671 2034
2672 window
2673 reduces
2674 open
2675 access
2676 NPV
2677 losses
2678 by
2679 about
2680 1.65%
2681 relative
2682 to
2683 a
2684 counterfactual
2685 world
2686 without
2687 removal.
2688 When
2689 optimal
2690 management
2691 begins
2692 ahead
2693 of
2694 debris
2695 removal,
2696 the
2697 NPV
2698 losses
2699 tend
2700 to
2701 be
2702 reduced
2703 (negative
2704 changes).
2705 When
2706 optimal
2707 management

2708 begins
2709 after
2710 debris
2711 removal,
2712 the
2713 NPV
2714 losses
2715 tend
2716 to
2717 be
2718 increased
2719 (positive
2720 changes).
2721 The
2722 increase
2723 in
2724 NPV
2725 losses
2726 in
2727 the
2728 latter
2729 scenario
2730 is
2731 driven
2732 by
2733 the
2734 costs
2735 of
2736 additional
2737 launching
2738 under
2739 open
2740 access,
2741 both
2742 immediately
2743 following
2744 the
2745 initial
2746 debris
2747 reduction
2748 and
2749 to
2750 sustain
2751 the
2752 larger
2753 satellite
2754 population.
2755 Due
2756 to
2757 open
2758 access,
2759 firms
2760 will
2761 take
2762 advantage
2763 of
2764 lower
2765 collision
2766 risk
2767 due
2768 to

2769 debris
2770 removal
2771 by
2772 launching
2773 satellites
2774 until
2775 there
2776 are
2777 no
2778 more
2779 profits
2780 from
2781 launching
2782 new
2783 satellites.
2784 When
2785 the
2786 planner
2787 is
2788 in
2789 charge
2790 of
2791 launching
2792 before
2793 debris
2794 removal
2795 begins,
2796 they
2797 do
2798 not
2799 waste
2800 resources
2801 by
2802 launching
2803 to
2804 dissipate
2805 the
2806 gains
2807 from
2808 debris
2809 removal.

2810
2811 **C.**
2812 **Unmodeled**
2813 **physical**
2814 **and**
2815 **economic**
2816 **factors.**

2817
2818 In
2819 addition
2820 to
2821 the
2822 limitations
2823 imposed
2824 by
2825 modeling
2826 spatially
2827 and
2828 temporally
2829 heterogeneous

2830 physical
2831 and
2832 economic
2833 processes
2834 at
2835 an
2836 aggregated
2837 level,
2838 there
2839 are
2840 three
2841 main
2842 analytical
2843 limitations
2844 pertaining
2845 to
2846 unobservables
2847 in
2848 the
2849 past
2850 and
2851 present
2852 and
2853 unknowables
2854 in
2855 the
2856 future:
2857 launch
2858 market
2859 frictions,
2860 constellations
2861 (coordinated
2862 systems
2863 of
2864 satellites
2865 intended
2866 to
2867 serve
2868 a
2869 common
2870 purpose),
2871 and
2872 satellite
2873 placement.
2874 These
2875 limitations
2876 may
2877 make
2878 our
2879 OUF
2880 estimates
2881 lower
2882 bounds
2883 on
2884 the
2885 true
2886 values
2887 required
2888 to
2889 induce
2890 optimal

2891 orbit
2892 use,
2893 as
2894 we
2895 describe
2896 below.
2897
2898 Our
2899 conclusions
2900 about
2901 the
2902 suboptimality
2903 of
2904 open
2905 access
2906 to
2907 orbit
2908 and
2909 the
2910 necessity
2911 of
2912 a
2913 globally-
2914 coordinated
2915 OUF
2916 (or
2917 policies
2918 equivalent
2919 to
2920 one)
2921 are
2922 robust
2923 to
2924 these
2925 limitations.
2926 The
2927 fundamental
2928 problem
2929 creating
2930 the
2931 need
2932 for
2933 policies
2934 equivalent
2935 to
2936 a
2937 globally-
2938 coordinated
2939 OUF
2940 is
2941 the
2942 lack
2943 of
2944 legally-
2945 enforceable
2946 property
2947 rights
2948 over
2949 orbits.

^{TTT}The geostationary belt is the exception to this statement. In general, however, there is no globally-coordinated procedure for allocating orbital paths, or even a globally-agreed-upon definition of an orbital path property right.

2950 The
2951 lack
2952 of
2953 property
2954 rights
2955 prevents
2956 satellite
2957 owners
2958 from
2959 internalizing
2960 the
2961 costs
2962 they
2963 impose
2964 on
2965 others
2966 through
2967 collision
2968 risk
2969 and
2970 debris
2971 creation.
2972 The
2973 same
2974 issue
2975 manifests
2976 in
2977 other
2978 common-
2979 resource
2980 settings,
2981 such
2982 as
2983 fisheries
2984 (?
2985).
2986

2987 Our
2988 economic
2989 model
2990 is
2991 founded
2992 on
2993 the
2994 assumption
2995 that
2996 all
2997 agents
2998 who
2999 want
3000 to
3001 launch
3002 satellites
3003 are
3004 able
3005 to
3006 do
3007 so
3008 with
3009 no
3010 frictions.

3011 In
3012 practice,
3013 there
3014 are
3015 factors
3016 other
3017 than
3018 orbital
3019 property
3020 rights
3021 and
3022 willingness-
3023 to-
3024 pay
3025 which
3026 limit
3027 agents'
3028 access
3029 to
3030 orbit,
3031 such
3032 as
3033 limited
3034 availability
3035 of
3036 launch
3037 windows
3038 and
3039 rockets.
3040 These
3041 factors
3042 constrain
3043 humanity's
3044 ability
3045 to
3046 launch
3047 satellites.
3048 To
3049 ensure
3050 that
3051 our
3052 simulations
3053 do
3054 not
3055 violate
3056 this
3057 launch
3058 constraint
3059 in
3060 observed
3061 years,
3062 we
3063 calculate
3064 the
3065 launch
3066 constraint
3067 in
3068 each
3069 observed
3070 period
3071 as

3072 the
3073 cumulative
3074 maximum
3075 number
3076 of
3077 launches
3078 observed
3079 so
3080 far.
3081 The
3082 shadow
3083 value
3084 of
3085 the
3086 launch
3087 constraint
3088 is
3089 recovered
3090 in
3091 the
3092 economic
3093 parameter
3094 calibration
3095 process,
3096 but
3097 the
3098 individual
3099 factors
3100 are
3101 not
3102 identifiable
3103 from
3104 the
3105 data.
3106 We
3107 then
3108 fit
3109 a
3110 linear
3111 time
3112 trend
3113 to
3114 the
3115 observed
3116 launch
3117 constraint,
3118 and
3119 project
3120 it
3121 into
3122 the
3123 future.
3124 To
3125 the
3126 extent
3127 that
3128 the
3129 launch
3130 constraint
3131 will
3132 be

3133 relaxed
3134 faster
3135 than
3136 a
3137 linear
3138 trend
3139 would
3140 predict,
3141 our
3142 estimates
3143 are
3144 economically
3145 conservative,
3146 i.e.
3147 we
3148 assume
3149 fewer
3150 launches
3151 than
3152 may
3153 occur,
3154 which
3155 biases
3156 our
3157 estimated
3158 OUF
3159 downward.
3160

3161 Our
3162 economic
3163 model
3164 is
3165 also
3166 founded
3167 on
3168 the
3169 simplifying
3170 assumption
3171 of
3172 “one
3173 satellite
3174 per
3175 firm”.
3176 In
3177 practice,
3178 there
3179 are
3180 a
3181 number
3182 of
3183 firms
3184 which
3185 own
3186 constellations
3187 or
3188 fleets
3189 of
3190 satellites.
3191 However,
3192 unless
3193 a

3194 single
3195 firm
3196 owned
3197 all
3198 satellites
3199 in
3200 orbit,
3201 orbit
3202 users
3203 would
3204 not
3205 internalize
3206 the
3207 full
3208 scope
3209 of
3210 the
3211 externality
3212 they
3213 impose
3214 on
3215 others.
3216 To
3217 the
3218 extent
3219 that
3220 the
3221 observed
3222 data
3223 reflects
3224 agents
3225 internalizing
3226 those
3227 externalities
3228 due
3229 to
3230 ownership
3231 of
3232 multiple
3233 satellites,
3234 our
3235 economic
3236 parameter
3237 estimates
3238 would
3239 entangle
3240 those
3241 factors
3242 with
3243 the
3244 estimated
3245 launch
3246 constraint
3247 shadow
3248 value.
3249 Our
3250 projections
3251 of
3252 single-
3253 satellite-
3254 owning

3255 firms’
3256 responses
3257 to
3258 increases
3259 in
3260 satellite
3261 profitability
3262 would
3263 therefore
3264 be
3265 attenuated
3266 toward
3267 zero,
3268 making
3269 our
3270 projections
3271 environmentally
3272 conservative,
3273 i.e.
3274 closer
3275 to
3276 an
3277 environmental
3278 “worst-
3279 case”
3280 analysis.
3281 However,
3282 the
3283 same
3284 assumption
3285 also
3286 increases
3287 the
3288 optimal
3289 OUF
3290 we
3291 estimate.
3292

3293 Lastly,
3294 our
3295 model
3296 abstracts
3297 entirely
3298 away
3299 from
3300 the
3301 question
3302 of
3303 satellite
3304 placement.
3305 That
3306 is,
3307 two
3308 orbital
3309 objects
3310 within
3311 a
3312 given
3313 volume
3314 shell
3315 can

3316 be
3317 placed
3318 in
3319 orbits
3320 such
3321 that
3322 at
3323 one
3324 extreme
3325 they
3326 are
3327 guaranteed
3328 to
3329 collide,
3330 or
3331 at
3332 the
3333 other
3334 extreme
3335 they
3336 will
3337 never
3338 collide.
3339 Our
3340 projections
3341 are
3342 based
3343 on
3344 collision
3345 rate
3346 estimates
3347 which
3348 are
3349 calculated
3350 using
3351 historical
3352 placement
3353 patterns.
3354 Thus,
3355 our
3356 projections
3357 assume
3358 that
3359 the
3360 systematic
3361 factors
3362 which
3363 resulted
3364 in
3365 current
3366 object
3367 placements
3368 will
3369 continue
3370 into
3371 the
3372 future.
3373 While
3374 technology
3375 and
3376 constellation

3377 ownership
3378 are
3379 likely
3380 to
3381 lead
3382 to
3383 improvements
3384 in
3385 placement
3386 patterns
3387 our
3388 collision
3389 risk
3390 projections
3391 would
3392 be
3393 biased
3394 for
3395 both
3396 the
3397 open
3398 access
3399 and
3400 optimal
3401 launch
3402 paths.
3403 However,
3404 the
3405 magnitude
3406 of
3407 the
3408 gap
3409 between
3410 open
3411 access
3412 and
3413 optimal
3414 collision
3415 risk
3416 may
3417 actually
3418 be
3419 understated
3420 by
3421 this
3422 issue.
3423 To
3424 the
3425 extent
3426 that
3427 economic
3428 agents
3429 have
3430 the
3431 placement
3432 margin
3433 available
3434 to
3435 them
3436 it
3437 is

3438 induces
3439 another
3440 externality,
3441 similar
3442 in
3443 spirit
3444 but
3445 different
3446 in
3447 detail
3448 to
3449 the
3450 orbit
3451 use
3452 externality
3453 we
3454 describe
3455 in
3456 this
3457 article,
3458 wherein
3459 firms
3460 do
3461 not
3462 account
3463 for
3464 the
3465 full
3466 magnitude
3467 of
3468 orbital-
3469 use
3470 efficiency
3471 losses
3472 due
3473 to
3474 their
3475 placement.
3476 A
3477 fleet
3478 planner
3479 who
3480 coordinated
3481 all
3482 satellites
3483 in
3484 orbit
3485 would
3486 account
3487 for
3488 such
3489 placement-
3490 related
3491 externalities.
3492 By
3493 taking
3494 advantage
3495 of
3496 any
3497 efficiencies
3498 in

3499 placement,
3500 would
3501 be
3502 able
3503 to
3504 reduce
3505 collision
3506 rates
3507 below
3508 what
3509 open
3510 access
3511 satellite
3512 owners
3513 would
3514 have
3515 an
3516 incentive
3517 to
3518 consider.
3519 Thus,
3520 while
3521 the
3522 inclusion
3523 of
3524 a
3525 placement
3526 margin
3527 may
3528 reduce
3529 levels
3530 of
3531 collision
3532 risk,
3533 the
3534 differences
3535 in
3536 collision
3537 risk
3538 between
3539 open
3540 access
3541 and
3542 optimal
3543 use
3544 may
3545 increase,
3546 which
3547 would
3548 make
3549 our
3550 OUF
3551 estimates
3552 a
3553 lower
3554 bound
3555 on
3556 average.¹⁷

3557

¹⁷While some regimes in a spatially-differentiated orbit model may have lower OUF values than the ones we calculate here, the average OUF value across all regimes will likely be larger.

3558 **D.**
3559 **Consequences**
3560 **of**
3561 **measurement**
3562 **error**
3563 **and**
3564 **misspecification.**

3565
3566 ***D.1.***
3567 ***Measurement***
3568 ***error***
3569 ***in***
3570 ***satellite***
3571 ***and***
3572 ***debris***
3573 ***counts.***

3574
3575 Limitations
3576 of
3577 sensor
3578 technology
3579 suggest
3580 that
3581 the
3582 debris
3583 counts
3584 are
3585 lower-
3586 bound
3587 estimates.
3588 To
3589 the
3590 extent
3591 that
3592 this
3593 biases
3594 the
3595 collision
3596 probability
3597 and
3598 debris
3599 counts
3600 downward,
3601 it
3602 will
3603 bias
3604 the
3605 estimated
3606 decay
3607 rate,
3608 collision
3609 probability
3610 parameters,
3611 fragmentation
3612 parameters,
3613 and
3614 launch
3615 debris
3616 weakly
3617 downwards.
3618 Since

3619 downward
3620 bias
3621 in
3622 the
3623 physical
3624 parameters
3625 makes
3626 collisions
3627 and
3628 missile
3629 tests
3630 appear
3631 to
3632 cause
3633 less
3634 congestion
3635 than
3636 they
3637 actually
3638 do,
3639 the
3640 open
3641 access
3642 and
3643 optimal
3644 launch
3645 rates
3646 will
3647 be
3648 inflated.
3649

3650 Downward
3651 bias
3652 in
3653 the
3654 collision
3655 probability
3656 data
3657 will
3658 bias
3659 the
3660 economic
3661 parameter
3662 estimates
3663 weakly
3664 downwards
3665 as
3666 well.
3667 This
3668 will
3669 to
3670 some
3671 degree
3672 offset
3673 the
3674 inflation
3675 in
3676 the
3677 launch
3678 rate
3679 caused

3680 by
3681 the
3682 physical
3683 parameter
3684 underestimation,
3685 though
3686 the
3687 exact
3688 extent
3689 of
3690 the
3691 offset
3692 is
3693 not
3694 clear.

3695
3696 In
3697 general,
3698 measurement
3699 error
3700 in
3701 the
3702 collision
3703 probability
3704 data
3705 also
3706 causes
3707 the
3708 nonnegativity
3709 constraint
3710 on
3711 the
3712 collision
3713 probability
3714 parameters
3715 (α_{SS}
3716 and
3717 α_{SD})
3718 to
3719 bind
3720 in
3721 some
3722 bootstrap
3723 replications.
3724 This
3725 causes
3726 issues
3727 of
3728 the
3729 type
3730 described
3731 in
3732 (?)
3733)
3734 in
3735 obtaining
3736 asymptotic
3737 standard
3738 errors.

3739
3740 **D.2.**

3741 ***Collision***
3742 ***probability***
3743 ***model***
3744 ***misspecification.***

3745 We
3746 assume
3747 that
3748 the
3749 collision
3750 probability
3751 model
3752 has
3753 constant
3754 parameters.
3755 Changes
3756 in
3757 patterns
3758 of
3759 satellite
3760 placement,
3761 construction,
3762 and
3763 ownership
3764 structures
3765 lead
3766 to
3767 changes
3768 over
3769 time
3770 in
3771 the
3772 physical
3773 primitives
3774 reflected
3775 in
3776 α_{SS}
3777 and
3778 α_{SD} .
3779 The
3780 “net”
3781 convexity
3782 or
3783 concavity
3784 of
3785 the
3786 time
3787 path
3788 of
3789 the
3790 primitives
3791 will
3792 determine
3793 whether
3794 the
3795 constant
3796 approximations
3797 over
3798 or
3799 understate
3800 the
3801 true

3802 time-
3803 varying
3804 parameters
3805 in
3806 any
3807 period
3808 on
3809 average.
3810 A
3811 convex
3812 time
3813 path
3814 —
3815 low
3816 values
3817 initially
3818 and
3819 high
3820 values
3821 later
3822 on
3823 —
3824 will
3825 be
3826 overestimated
3827 on
3828 average,
3829 while
3830 a
3831 concave
3832 time
3833 path
3834 —
3835 high
3836 values
3837 initially,
3838 with
3839 slow
3840 increases
3841 over
3842 time
3843 —
3844 will
3845 be
3846 underestimated
3847 on
3848 average.
3849

3850 The
3851 misspecification
3852 causes
3853 two
3854 problems
3855 with
3856 simulation
3857 and
3858 inference.
3859 First,
3860 underestimation
3861 will
3862 inflate

3863 launch
3864 rate
3865 projections
3866 and
3867 overestimation
3868 will
3869 deflate
3870 them.
3871 However,
3872 because
3873 the
3874 deflation
3875 affects
3876 both
3877 open
3878 access
3879 and
3880 optimal
3881 launch
3882 rates
3883 in
3884 the
3885 same
3886 way,
3887 the
3888 simulated
3889 optimal
3890 OUF
3891 will
3892 not
3893 be
3894 affected.
3895 Second,
3896 underestimation
3897 may
3898 cause
3899 the
3900 nonnegativity
3901 constraint
3902 on
3903 the
3904 collision
3905 probability
3906 parameters
3907 to
3908 bind
3909 in
3910 some
3911 bootstrap
3912 replications,
3913 causing
3914 the
3915 same
3916 types
3917 of
3918 asymptotic
3919 issues
3920 as
3921 measurement
3922 error.

3923

3924 **D.3.**
3925 **Measurement**
3926 **error**
3927 **in**
3928 **returns**
3929 **and**
3930 **costs.**
3931

3932 We
3933 take
3934 the
3935 returns
3936 and
3937 costs
3938 of
3939 satellite
3940 ownership
3941 from
3942 the
3943 data
3944 used
3945 in
3946 ?
3947),
3948 which
3949 aggregate
3950 revenues
3951 from
3952 all
3953 commercial
3954 satellites
3955 in
3956 orbit.
3957 By
3958 including
3959 more
3960 than
3961 just
3962 LEO
3963 satellites,
3964 the
3965 direct
3966 returns
3967 and
3968 costs
3969 data
3970 overstate
3971 the
3972 returns
3973 to
3974 LEO
3975 paths.
3976 The
3977 economic
3978 parameter
3979 estimates
3980 therefore
3981 reflect
3982 a
3983 “LEO
3984 share”

3985 coefficient
3986 on
3987 the
3988 revenue
3989 data
3990 between
3991 0
3992 and
3993 1.
3994 The
3995 LEO
3996 share
3997 coefficient
3998 attenuates
3999 the
4000 estimates
4001 of
4002 a_{L1} ,
4003 a_{L2} ,
4004 and
4005 a_{L3} .



Image

figure[First figure]First figure



figure[Second figure]Second figure

4006 **Additional**
4007 **data**
4008 **table**
4009 **S1**
4010 **(dataset_**
4011 **one.**
4012 **txt)**
4013 Type
4014 or
4015 paste
4016 caption
4017 here.

4018 **Additional**
4019 **data**
4020 **table**
4021 **S2**
4022 **(dataset_**
4023 **two.**
4024 **txt)**
4025 Type
4026 or
4027 paste
4028 caption
4029 here.
4030 Adding
4031 longer
4032 text
4033 to
4034 show
4035 what
4036 happens,
4037 to
4038 decide
4039 on
4040 alignment
4041 and/or
4042 indentations
4043 for
4044 multi-
4045 line
4046 or
4047 paragraph
4048 captions.