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SANTA CRUZ

**AN INTERNATIONAL ENVIRONMENTAL AGREEMENT FOR SPACE DEBRIS  
MITIGATION AMONG ASYMMETRIC NATIONS**

A thesis submitted in partial satisfaction  
of the requirements for the degree of

MASTER OF SCIENCE

in

TECHNOLOGY AND INFORMATION MANAGEMENT

by

**MICHAEL SINGER**

March 2012

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Tyrus Miller  
Vice Provost and Dean of Graduate Studies

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## ABSTRACT

### **AN INTERNATIONAL ENVIRONMENTAL AGREEMENT FOR SPACE DEBRIS MITIGATION AMONG ASYMMETRIC NATIONS**

by

Michael Singer

We investigate how ideas from the International Environmental Agreement (IEA) literature can be applied to the problem of space debris mitigation. Space debris pollution is similar to other international environmental problems in that there is a potential for a “tragedy of the commons” effect: individual nations bear all the cost of their mitigation measures but share only a fraction of the benefit. As a consequence, nations have a tendency to underinvest in mitigation. Coalitions of nations, brought together by IEAs, have the potential to lessen the tragedy of the commons effect by pooling the costs and benefits of mitigation. This work brings together two recent modeling advances: (i) a game theoretic model for studying the potential gains from IEA cooperation between nations with asymmetric costs and benefits, (ii) an orbital debris model that gives the societal cost that specific actions, such as failing to deorbit an inactive spacecraft, have on the environment. We combine these two models with empirical launch-share data for a “proof of concept” of an IEA for a single mitigation measure—deorbiting spacecraft at the end of operational lifetime. Simulations of empirically-derived and theoretical launch distributions among nations suggest the possibility that voluntary coalitions can provide significant deorbiting gains relative to nations acting in the absence of an IEA agreement.

To Janet and her mother, Lois, with thanks for their interest and support



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The second author listed in the above publication directed and supervised the research which forms the basis for the thesis.

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# 1 Problem statement

When actions of individuals affect a shared resource, there is potential for a tragedy of the commons consequence: individual decision-makers under-invest in protection if they see only a fraction of the benefits from the investment. Consequently, a stream of recent literature has sought to understand how nations can form coalitions to counter the potential for tragedy of the commons effects in protecting the environment.

Game-theoretic models in the greenhouse gas (GHG), ozone depletion, and acid rain arenas have shown that when nations (i) recognize asymmetries of marginal costs and benefits of mitigation and (ii) establish coalitions that adjust abatement rates through transfer payments, there can be a substantial increase in global levels of pollution abatement. The size of the increase is a function of the number of parties, the nature of the transfer scheme, and the size and nature of the asymmetries. (See also, e.g., [Barrett, 2001](#); [Carraro et al., 2006](#); [McGinty, 2007](#); [Weikard, 2009](#).)

Our initial focus applies the International Environmental Agreement (IEA) framework to one debris mitigation measure: post-mission deorbiting of spacecraft. We derive marginal benefits from the lifetime-risk metric provided by [Bradley and Wein \(2009\)](#), marginal costs from deorbit cost estimates given by [Wiedemann et al. \(2004a\)](#), and spacecraft ownership data from the [Union of Concerned Scientists \(2009\)](#).

# 2 Background

Five decades of launches have left a substantial population of objects in Earth orbit that pose a risk to present and future operational spacecraft. This population includes rocket bodies, non-operational as well as other operational spacecraft, launch- and mission-related objects (e.g., nose cones, bolts), slag and dust from propellant combustion, fragments from accidental explosions of rocket bodies, and fragments from collisions of all these.

In low Earth orbit (LEO, generally defined as extending to an altitude of 2000 km), there are  $> 10^4$  objects larger than 10 cm in diameter, the smallest size regularly tracked by earth-bound radar ([Liou et al., 2010](#); [Johnson et al., 2001](#)). Models indicate there are  $> 10^5$  objects larger than 1 cm ([Oswald et al., 2006](#)).

To-date, there have been four collisions between tracked objects in LEO, with one a catastrophic

collision involving two spacecraft, one operational and the other non-operational (Kessler et al., 2010). At relative velocities typical of collisions in LEO, much smaller objects can also catastrophically destroy a spacecraft of average mass. The consequent increase in number of objects increases the rate of future collisions which can lead to what has been termed a “collision cascade” or, in popular parlance, the “Kessler Syndrome” (Kessler and Cour-Palais, 1978; Liou and Johnson, 2008).

In response to such events and predictions of cascading increase in object population by debris evolution models, several national space agencies and international organizations have proposed and adopted guidelines to mitigate risk to future spacecraft (Klinkrad et al. 2006, pp. 193-ff; also Johnson 2011). These guidelines share a focus on (a) preventing on-orbit breakups, (b) removing space systems at end of life (EOL), and (c) limiting release of launch- and mission-related objects during normal operations (Kato, 2001).

Some mitigation measures, e.g., deorbiting upper stage rocket bodies, have been substantially adopted, as only “. . . a few rocket launchers remain that do not enable rocket body deorbiting” (Bradley and Wein, 2009).

Efforts are underway to improve object tracking to support collision avoidance. However, such efforts require substantial national or international expenditures and can be inhibited by national security considerations (Shah et al., 2007). Collision avoidance is currently performed by owners for some valuable spacecraft when risk—in view of tracking and orbital prediction accuracy—warrants (Klinkrad et al., 2006).

Measures such as deorbiting spacecraft at end-of-life, while currently technically feasible by various mechanisms (e.g., cold gas propulsion, solid propellant, and electric propulsion), require significant expenditure by spacecraft owners (Janovsky et al., 2003; Wiedemann et al., 2004a; Wiedemann et al., 2004b). Few spacecraft have such capabilities (Liou and Johnson, 2008).

Nicholas Johnson, NASA chief scientist for orbital debris, has commented that “[t]o date, the most frequent violation of space debris mitigation guidelines by small satellites is persistence in the low Earth orbit region following mission termination . . .” (Johnson, 2011). This is consistent with Janovsky’s finding that “Although the absolute effort to install a EOL-deorbit function into a spacecraft increases with the size of the spacecraft, the relative impact is most for the small vehicles. . . . It is found that the spacecraft mass of micro- and nano-satellites can double due to the addition of the de-orbit function” (Janovsky et al., 2003).

For its programs and projects, NASA has mandated a 25-year removal time from LEO to limit “the

growth of the debris environment over the next 100 years while limiting the cost burden to programs and projects." Given that "[d]ebris in orbits with perigee altitudes below 600 km will usually have orbital lifetimes of less than 25 years," this, in effect, requires spacecraft with orbital altitudes higher than 600 km to maneuver to 600 km at end-of-life. "This requirement will have the greatest impact on programs and projects with perigee altitudes above 700 km, where objects may remain in orbit naturally for hundreds of years." (NASA Orbital Debris Program Office, 2007) This requirement has not been imposed on non-NASA U.S. spacecraft (i.e., military, commercial, and non-NASA civilian spacecraft).

Other debris mitigation mechanisms under active exploration include, e.g., retrieval of non-operational spacecraft (see, e.g., Barbee et al. 2011) and laser ablation to deflect fragments to avoid collisions (see, e.g., Mason et al. 2011).

Beyond that, use of certain orbit design paradigms, such as constellations (see, e.g., Marshall 2008; Spencer et al. 2001) and the orbit-slotting scheme of Bilimoria and Krieger (2011), provide a means to reduce risk of debris-generating collision between compliant spacecraft. However, such paradigms would also allow for a significant increase in number of spacecraft in orbit.<sup>1</sup> This, in turn, would require even higher compliance with measures such as EOL de-orbiting to minimize the cumulative impact.

Motivating and ensuring compliance with debris-mitigation guidelines will likely require additional mechanisms for cooperation and governance (Weeden, 2011; Johnson-Freese and Weeden, 2012) that take into account the costs and benefits to all of the parties involved.

## 2.1 Economics of debris mitigation

Wiedemann et al. (2004a) estimate global debris damage and mitigation costs for the coming 100 years under various implementation schedules of debris mitigation guidelines, including deorbiting. Janovsky et al. (2003) estimates deorbit costs for various spacecraft configurations and orbits. Shah et al. (2007) use game-theoretic cooperation archetypes and system dynamics modeling to explore a "partial cooperation" strategy between two nations for sharing tracking data in view of spacecraft and sensor economics and national security concerns.

To assess the benefit of debris mitigation strategies, Bradley and Wein (2009) propose a new metric of

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<sup>1</sup>The picture is further complicated by possible introduction of swarms of small spacecraft as these could represent a collision hazard to other spacecraft both during their operational lifetime and post-mission. Some such swarms, labeled "smart dust" spacecraft, with size on the order of (1 cm × 1 cm × 25 μm) and considered for altitudes between 300 and 1000 km, can be employed in vast numbers (e.g., 10,000) and use electrochromic plating to extend mission lifetime. It might be possible, however, to reduce risk to other spacecraft by changing the reflectivity of their plating in order to limit their orbital phase space domain. In addition, suitable design (i.e., a high area-to-mass ratio) can facilitate deorbiting at end-of-life (Colombo and McInnes, 2010).

“lifetime risk”, which they define as the risk of catastrophic destruction posed to an operational spacecraft launched  $t$  years from present under a particular scenario of launch and mitigation assumptions. They propose the maximum of this lifetime risk over all future time as a metric of “. . . sustainability (loosely defined as the highest utility that can be maintained for all future time), which has gained some popularity as an alternative to economic efficiency (Perman et al., 2003, Ch. 4), particularly for studying resources that—like outer space—have no substitutes and are in the infancy of their exploitation”. They also use lifetime risk to compute the difference in cumulative operational spacecraft destroyed through time  $T$  for compliance and non-compliance with deorbit guidelines, and term the asymptote of this value, “damage”.

Bradley and Wein identify various instruments used in environmental economics to achieve the target pollution level including “technology controls, ceilings or taxes on emissions, subsidies for pollution reduction, tradeable emissions permits, and non-compliance fees.” They use the damage metric described above to generate a fee schedule for failure to deorbit future launched objects, legacy costs for consequences of past launches, and debris from anti-satellite weapon (ASAT) tests. The current work extends that of Bradley and Wein using a game-theoretic IEA framework with abatement trading which is analogous to emissions permit trading in the GHG realm.

## **2.2 IEA model framework**

Game theory is a mathematical method used to study interactions between actors based on behavioral assumptions about their preferences. Given those assumptions, various equilibrium concepts can be applied to obtain predictions about the outcomes of the actors’ strategic interactions. Game-theoretic methods are ideally suited to formally modeling strategic considerations when actions have consequences for a globally shared environmental resource (Finus, 2008).

“Cooperative” game theory studies interactions between parties in situations where binding agreements can be enforced by a third party. However, when there is no third party to enforce cooperation, as is typically the case for International Environmental Agreements, such agreements must be designed to be self-enforcing. “For IEAs to improve management of shared environmental resources, they must make it attractive for countries to sign and carry out the terms of the agreement” (Barrett, 1994). The theory assumes parties act in their own self-interest to maximize their individual net profit (share of benefit from global abatement minus individual cost of environmental abatement). Self-enforcing agreements maintained only by parties acting in their own self-interest are studied in “non-cooperative” game theory. Seminal works in the modeling of such self-enforcing IEAs include the “benchmark” model introduced

by Barrett, Hoel (1992), and Carraro and Siniscalco (1993).

In game-theoretic framing, each actor independently attempts to find a “best response” to other actors’ strategies. If there is a mutual best response where no actor can benefit by individually deviating from that solution, the game solution is a “Nash-equilibrium” (Fudenberg and Tirole, 1991).

The Nash equilibrium solutions of IEA games usually involve coalitions of only a subset of the parties. If for all parties the mutually best action is to not enter a coalition, then the “null coalition” is an equilibrium outcome. If some actors determine their mutual best response is to join, while others determine their mutual best response is to refrain from joining, the result is a “partial” coalition.

These “null” and “partial” Nash equilibria are usually inefficient in that they fail to maximize global profit (i.e., profit summed over all actors). In contrast, complete membership in a “full” coalition yields an efficient or socially optimal outcome that maximizes global profit. The full coalition outcome, however, usually requires a “social hegemon” or legal framework decreeing abatement levels for each actor.

IEA research has focused on evaluating levels of abatement and profit for self-enforcing partial coalitions relative to the null coalition and full coalition under different assumptions of actor characteristics and rules of coalition formation.

For a coalition to be stable (i.e., self-enforcing), two criteria introduced in the cartel formation game of d’Aspremont et al. (1983) must be satisfied:

1. Coalition members individually realize a greater profit under the agreement than they would outside (a condition termed as “internal” stability in economic oligopoly literature).
2. Non-members individually realize a greater profit outside the coalition than they would inside (“external” stability).

Early research (Barrett, 1994) indicated that a partial coalition formed by identical nations (i.e., each nation having identical cost functions and benefit functions for abatement) could neither attain significant membership (no more than three members, depending on the shape of the marginal benefit and cost functions) nor improve significantly upon the null coalition level of global abatement. Later research (Barrett, 1997; Barrett, 2001) indicated potentially greater membership and benefits for self-enforcing coalitions relative to null coalition outcome when there are marginal cost and benefit asymmetries between actors (nations) and side payments to trade abatement responsibilities. A further challenge for IEAs has been finding mechanisms to overcome incentives for nations to “free-ride” on the abatement efforts of others (Finus and Rundshagen, 2001).

These insights have been significantly extended and refined in non-cooperative game theoretic analyses including [McGinty \(2002\)](#); [McGinty \(2007\)](#); [Pintassilgo \(2003\)](#); [Carraro et al. \(2006\)](#); [Weikard \(2009\)](#); and [Fuentes-Albero and Rubio \(2010\)](#).

### 2.3 IEA model

We adopt the non-cooperative game framework referenced above to investigate abatement gains of self-enforcing partial coalitions in contrast with null-coalition and full-coalition behavior.

The global profit function is defined as:

$$\Pi = \sum \pi_i \quad \text{where } \pi_i = B_i(Q) - C_i(q_i). \quad (1)$$

Each nation bears the cost,  $C_i$ , of its own abatement,  $q_i$ , while all nations share the benefits of reduction of harm,  $B_i$ , from global abatement  $Q$ .

In a stable partial coalition, members have a collective profit that is at least as high as the sum of their individual profits operating alone. However, the allocation of abatement levels within the coalition that maximizes the coalition profit might not result in a higher individual profit for each member compared to their profit if they left the coalition.

To overcome this problem, a transfer payment scheme redistributes the net burden among members. The “burden-sharing” rule ensures that the profit each nation receives as a coalition member exceeds what they receive outside the coalition. Nations that abate an amount greater than required under the agreement would receive a positive transfer, while nations that purchase permits are able to meet their abatement responsibilities under the agreement at a lower cost. Net transfers are zero-sum.

[Weikard \(2009\)](#) presents a family of sharing rules that satisfy the internal and external stability requirements cited above. We adopt one rule from this set: the allocation rule for abatement requirements under a system of tradable pollution permits followed by [McGinty \(2007\)](#). This rule proposes transfers between coalition members that are “just sufficient to quell any incentive to deviate from the agreement” and distributes the remaining coalition surplus in proportion to the members’ benefit share-to-cost ratio.

### 3 Application of IEA Model to Debris Mitigation

For this initial model of an IEA for space debris mitigation, we examine the effect of a self-enforcing market mechanism on parties' choices regarding a single type of abatement action: deorbiting of spacecraft after mission lifetime. We do not consider other actions parties might take that would affect the rate of debris generation such as active removal of debris, collision avoidance, or anti-satellite weaponry.

#### 3.1 Elements of the model

An IEA model requires the following elements:

- An environmental resource and a pollutant.
- Actors and actions that affect the environmental resource.
- An estimate of harm to the environmental resource from pollutant generation and benefits to actors for their own and others' abatement of harm.
- An estimate of costs to each actor for abating harm.

We specify the elements as follows for a space debris mitigation IEA:

##### 3.1.1 Environmental resource and pollutant

The environmental resource is taken to be the 900–1000 km altitude shell-of-interest (SOI) analyzed by [Bradley and Wein \(2009\)](#). This is the region of near-Earth space with the highest object density. (The 700–900-km shell has a higher density of operational spacecraft but lower overall object density.) The “pollutant” is the population of orbital objects that might catastrophically collide with operational spacecraft, and thereby includes all objects from fragments through non-operational spacecraft as well as other operational spacecraft. Of particular concern is the future introduction of spacecraft that are launched but not deorbited from the SOI after completion of their operational lifetimes.<sup>2</sup>

##### 3.1.2 Actors and actions

Since our analysis relies on the long-term debris evolution model of Bradley and Wein, we adopt their baseline assumption of a total annual launch rate of three operational spacecraft per year to the 900–1000-

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<sup>2</sup>The Bradley and Wein model assumes a rapid deorbiting out of the SOI at end-of-life to an altitude of 600 km, in accordance with the NASA policy discussed earlier.



km SOI (Bradley and Wein, 2009).

For a set of actors, we look at ownership data, by nation, for recent LEO spacecraft whose orbits enter this SOI as indicated in the UCS database of operational spacecraft (Union of Concerned Scientists, 2009). We use a recent eight-year period<sup>3</sup> and ignore spacecraft in orbits UCS classifies as “elliptical” (i.e., with eccentricity 0.14 and higher) because these spend only a small fraction of time in the SOI. (See Appendix: Spacecraft in the Shell of Interest.)

We focus only on the pattern of launch distribution among nations (as “owners”), and ignore temporal variation in the ownership set. The one spacecraft identified as “international” we treat as having a single owner, and the one spacecraft with two identified co-owners we allocate equally between them. The resulting set contains seven actors, and we scale the launch distribution to match the total launch rate above.

Reliance on the historical launch rates to the SOI results in a small set of actors, while the trend is arguably toward broader participation. Given this, we consider the seven-actor empirical distribution to be our Case I, and construct a “plausible” distribution for a larger set of actors, which we call Case II. We construct this pattern from UCS data for a broader LEO shell, from 700 to 1000 km. There were 15 single-nation “owners” of spacecraft recently launched to this shell.<sup>4</sup> Of these nations, nine launched only one spacecraft. As benefit and cost in our model are both functions only of the parties’ launch rates, this launch distribution would yield a subset of nine identical actors out of the 15. To incorporate some measure of variety in this larger, hypothetical set of actors, we weight the distribution launches by orbit fraction in this larger shell. Figures 1 and 2 show share of eight-year launch rates for Cases I and II, listed in order from highest (designated as #1) to lowest.

In Case III, we provide a preliminary sensitivity analysis of the relationship between coalition outcomes, number of nations,  $n$ , and the benefit and cost asymmetry by considering launch patterns based on the zeta distribution with a range of “steepness” parameters  $s$  (explained below).

### 3.1.3 Harm

Bradley and Wein (2009), in the exposition of their debris environment model, introduce several important performance metrics relevant to environmental risk assessment. The model, a mean-field approximation set of ordinary differential equations, computes rates of change of spacecraft, rocket bodies, and

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<sup>3</sup> 7/1/01 to 7/1/09. Use of an eight-year launch period follows practice for long-term debris models (Martin et al., 2004; Liou and Johnson, 2005).

<sup>4</sup>For tractability of assigning ownership interests, we exclude the seven multi-nation owner sets.

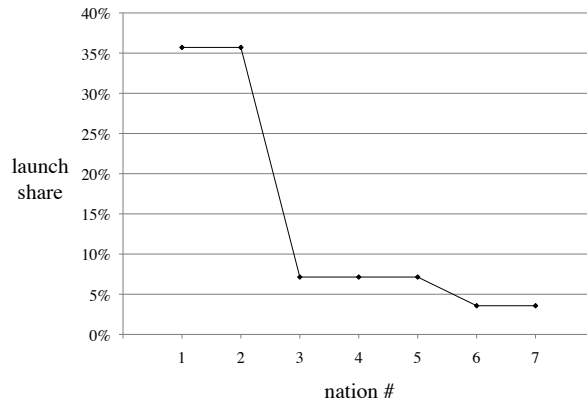


Figure 1: Projected share of launch rate to the shell of interest (SOI) for our proxy Case I of seven spacecraft-owning nations, sorted high to low [derived from the UCS database].

fragments in a SOI for  $T \in [0, \infty)$ , where 0 is the present. The model categorizes spacecraft as operational or no longer operational, with or without deorbit capability; rocket bodies with or without deorbit capability; and fragments as hazardous or benign in collision with other objects depending on collision velocity and fragment characteristics. Parameters for the differential equations are expectations over the same distributions that govern an object-by-object simulation.

The model’s primary metric is “lifetime risk”, which Bradley and Wein define as “the probability that a spacecraft launched at time  $t$  will be destroyed (via an intact-intact or catastrophic intact-fragment collision) while it is still operational” (p. 1376). Fig. 3 shows lifetime risk for an operational spacecraft launched at time  $t$  in the SOI given a baseline set of parameters (launch rates, existing debris flux, spacecraft characteristics, fraction of spacecraft deorbited, etc.). Risk increases at a modest rate for the next several hundred years, increases rapidly starting at about year 500, then levels off ca. 3000 years.<sup>5</sup>

The time frame explored in Bradley and Wein’s paper and herein (e.g., 10,000 years in Fig. 3) is substantially longer than that explored by most debris evolution models. (Object-by-object evolution models generate predictions for periods extending up to 200 years (Liou and Johnson, 2008; Oswald et al., 2006). The extended time horizon is necessary to provide a “debris footprint” or quantification of the full consequence (or lack thereof) of a mitigation measure.

From the lifetime-risk metric, Bradley and Wein derive a second metric, “sustainable lifetime risk” defined as the maximum of the lifetime risk over all future times. Fig. 4 shows how the lifetime risk

<sup>5</sup>See Bradley and Wein (2009) pp. 1375-76 for discussion of qualitative agreement of model results at 200 years with those reported in Liou and Johnson (2008) for LEGEND; pp. 1374-75 for long-term behavior; pp. 1380-81 for difference in bounds on the number of fragments relative to Kessler (2001).

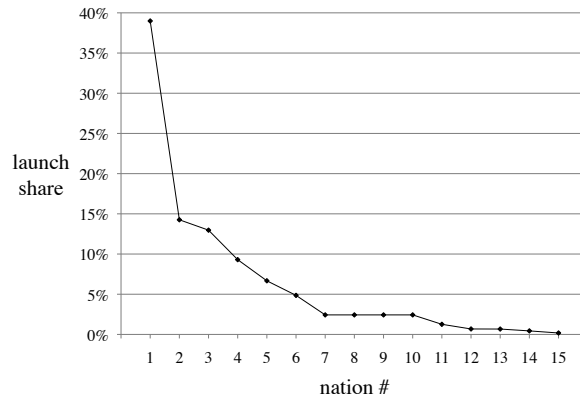


Figure 2: Projected share of launch rate to the shell of interest (SOI) for our proxy Case II of 15 spacecraft-owning nations, sorted high to low [derived from ownership of spacecraft launched to the broader 700-1000 km altitude shell, per the UCS database].

at 200 years (dashed line) and the sustainable lifetime risk (solid curve) vary as a function of deorbit compliance rate. The former value is relatively insensitive and the latter strongly sensitive to deorbit compliance.

From the lifetime-risk metric, Bradley and Wein also derive the measure of harm most directly relevant to our current purposes, the additional operational spacecraft destroyed up until time  $T$  by a failure to deorbit one “extra” spacecraft (i.e., a launch that represents a perturbation above a given launch rate), shown as “ $S_n$  insertion” in Fig. 5.<sup>6</sup>

An interesting feature of the figure is that actions representing break-ups at  $T = 0$  show the largest peak difference relative to baseline, since the effects of that early breakup cause risk to rise sooner and more rapidly, and dissipate sooner. Launch of a spacecraft or rocket body without deorbiting capability does not represent a current break-up but, instead, has an attendant risk of break-up at some future epoch. These curves, “ $R$  insertion” and “ $S_n$  insertion” show, respectively, a smaller peak and no significant peak in operational spacecraft destroyed relative to baseline. The figure also shows operational spacecraft expected to be destroyed due to currently orbiting spacecraft and debris, and the future harm expected from the most recent anti-satellite weapon test.

<sup>6</sup>The subscript “ $n$ ” signifies an addition to the non-operational spacecraft population, i.e., a spacecraft not deorbited after operational lifetime.

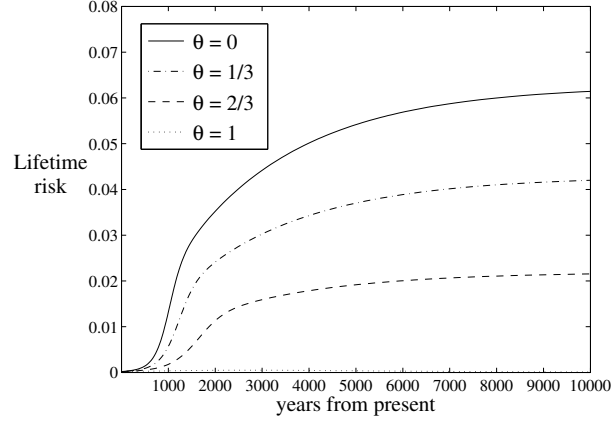


Figure 3: Risk to a spacecraft of catastrophic destruction during its operational lifetime as a function of deorbit compliance rate.

### 3.1.4 Benefit from abatement of harm

We derive benefit from abatement of harm attributable to the deorbit of one spacecraft from Bradley and Wein’s third metric provided by the “ $S_n$  insertion” of Fig. 5. Until one reaches a very high level of compliance (> 94 %), the marginal benefit of deorbiting has a relatively low dependence on the rate of deorbit compliance. We therefore assume a linear benefit function with constant marginal benefits of deorbiting.

As a first approximation, the present value (PV) of the incremental benefit from avoiding spacecraft destroyed, relative to baseline, is a function of discount rate:

$$PV_{\text{benefit}} = \frac{1}{2} \text{cost of harm per spacecraft destroyed} \times \int_0^{\infty} e^{-rt} \left[ \frac{d(\text{spacecraft destroyed})}{dt} \right] dt \quad (2)$$

The factor of 1/2 reflects an assumption that, on average, those spacecraft that are destroyed will have survived that portion of their lifetime (Wiedemann et al., 2004a).

Models in the GHG arena typically compute future harm for a period of 100 years and adopt discount rates on the order of 2% (Dellink et al., 2008). Some GHG models explore periods of up to 400 years and employ various declining discount rate formulations (Weitzman, 2001; Guo et al., 2006; HM Treasury,

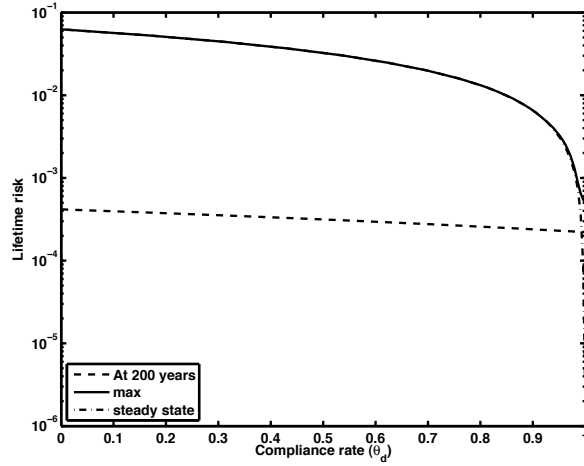


Figure 4: Sustainable lifetime risk (solid curve) and lifetime risk at 200 years (dashed line) to an operational spacecraft as a function of fraction of launched spacecraft that are deorbited at the end of operational life. [Bradley and Wein (2009), Fig. 5, reprinted with permission]

2003).

For the present analysis, we limit consideration of harm to average spacecraft replacement cost, which, for simplicity, we take to be a constant \$200M in future-year dollars. We compute the PV of benefit using the Weitzman “step” discount formulation with a 4% near-term discount rate, stepping down to 0.1% for the period beyond 300 years. This yields a PV which we round to \$1M and assign to the benefit parameter  $b$  in the benefit function. The resulting benefit function for actor  $i$  is

$$B_i(Q) = b \alpha_i Q \quad (3)$$

We allocate abatement benefits to nations in accordance with their exposure in the SOI through the parameter  $\alpha_i$ , which represents their share of launches (Figures 1 and 2).

A full accounting of the PV of benefit (i.e., reduced harm), here represented by the benefit parameter,  $b$ , should arguably account for costs beyond the replacement value of spacecraft destroyed, e.g., earning capability of commercial spacecraft; social, environmental, and national security costs; harm to human spacefarers; and disruption or degradation of operations due to damage from debris or performance of additional collision avoidance. Conversely, most discount schemes considered in the environmental economics literature cited above would reduce the PV of benefit. Such changes might also lead to a more complex benefit function with nonlinear marginal benefits.

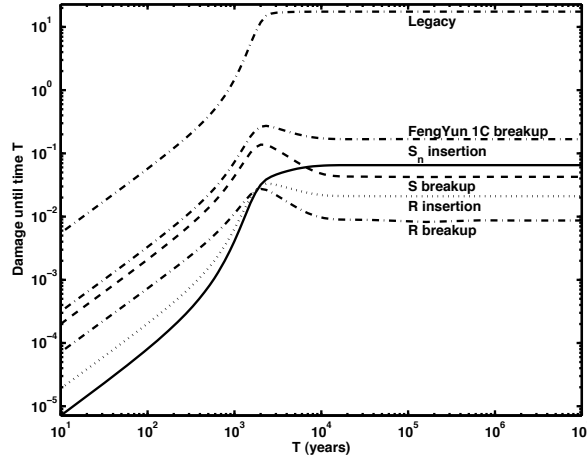


Figure 5: Operational spacecraft destroyed, relative to baseline, up until time  $T$  by launch at  $T=0$  of an additional spacecraft or rocket body without deorbit capability; a breakup at  $T=0$ ; damage expected from current spacecraft and debris, and legacy damage due to the most recent anti-satellite weapon test. Of key interest here is the “ $S_n$  insertion” curve representing harm caused by failure to deorbit a spacecraft. All curves shown assume a  $2/3$  deorbit compliance rate. [Bradley and Wein (2009), Fig. 6, reprinted with permission]

### 3.1.5 Abatement costs

Actual deorbiting costs vary as a function of orbit, mass, and other variables, in particular whether a spacecraft’s mission already requires it to have maneuvering capabilities (Janovsky et al., 2003). Such a spacecraft would typically have a lower additional cost to add de-orbit capabilities than a spacecraft not already carrying fuel and thrusters for its mission.

Given the paucity of data regarding mission plans and spacecraft designs individually or in the aggregate by actor, we suppose that a nation’s marginal costs for deorbiting spacecraft are uniformly distributed between \$0 and \$1M, for an average cost of \$0.5M.<sup>7</sup>

We assume (i) each nation chooses to add deorbit capability to those spacecraft for which addition is least costly and (ii) the marginal cost of deorbiting increases linearly with the fraction of spacecraft a nation deorbits. That is, the cost function for each nation  $i$  deorbiting a quantity  $q_i$  of spacecraft, is

$$C_i(q_i) = \frac{c_i q_i^2}{2}. \quad (4)$$

Given a maximum deorbiting cost of  $c = \$1M$ , the cost coefficient for nation  $i$  is  $c_i = c/n_i$ ; the

<sup>7</sup>This is the value Bradley and Wein extrapolate (p. 1378) from Wiedemann et al. (2004a) for the cost of deorbiting an “average” spacecraft (800 kg) from their shell-of-interest (900–1000 km).

marginal cost is  $c q_i/n_i$ ; and total cost for nation  $i$  is  $c q_i^2/2n_i$ . Deorbiting all  $n_i$  of their spacecraft launched per year would cost a nation  $\$0.5M \times n_i$ .

Technology improvements, e.g., in use of solar sails for propulsion (Johnson et al., 2010), offer the possibility of substantial reductions in cost of deorbiting. Fuller consideration of expected technology developments and choices by actors might also warrant a more complex cost function.

## 3.2 Simulation

The simulation computes global and individual abatement and profit for the null and full coalition (social optimum) outcomes. It also computes, for each partial coalition chosen from the power set of all possible coalitions:

- Profit and abatement by members.
- Profit by members if they were to leave the coalition.

The simulator then checks stability of each partial coalition. For each stable partial coalition, the simulator computes:

- Transfer payments among members (and member profits after transfer).
- Profit and abatement by non-members.

Finally, for each scenario with a stable partial coalition, the simulator computes global (total summed over members and non-members) abatement  $Q$  and profit  $\Pi$  and identifies those partial coalitions that generate the highest global abatement (which we deem the “best partial coalition”) and highest global profit. (If there is more than one “best partial coalition”, we select one to represent the class in the figures.)

## 4 Results

### 4.1 Case I

In the simulation of our seven-actor Case I with parameterization as above<sup>8</sup>, there are 30 stable coalitions out of  $2^7 = 128$  possible coalitions. Three coalitions, each with four members, tie for generation of the

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<sup>8</sup> $b = \$1M$ ,  $\{\alpha_i\}$  from Figs. 1 and 2,  $c_i = \$1M/n_i$

highest global abatement. These coalitions consist of the two highest launch rate nations and any two of the three mid-level nations:  $\{1,2,3,4\}, \{1,2,3,5\}, \{1,2,4,5\}$ .

Fig. 6 shows global abatement (deorbited/year) for the null, best partial, and full coalition cases. Typically, the full coalition level of abatement can be achieved only if actors can be compelled to do what is socially optimal. The best partial coalitions for our Case I make up 65% of the difference between the null and full coalition levels of abatement.

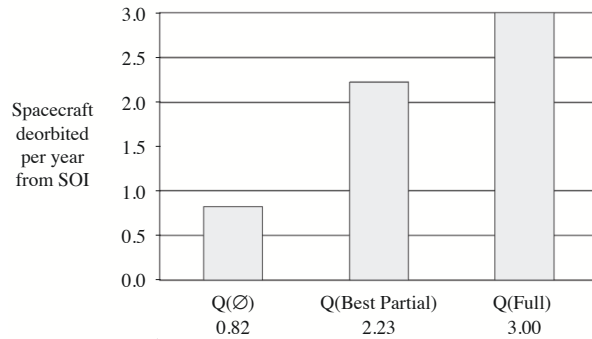


Figure 6: Global abatement for null, best partial, and full coalitions for Case I.

Fig. 7 shows global profit (\$M/year) for the null, best partial, and full coalition cases. The best partial coalitions make up 73% of the difference in total payoffs between the null and full coalitions. While there are parameter settings for which this is not the case, here the partial coalitions that achieve the highest global abatement are the same as those that achieve the highest global profit. There are no higher-membership stable partial coalitions than those which achieve the highest abatement and profit.

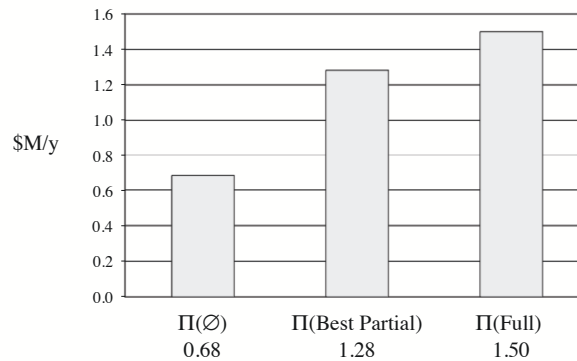


Figure 7: Global profit for null, best partial, and full coalitions for Case I.



Fig. 8 shows profit achieved by each nation in the null and best partial coalition cases. Each member nation individually achieves a higher profit in the best partial coalitions than they would in the null coalition case. This confirms that membership in the coalition is consistent with parties' self-interest.

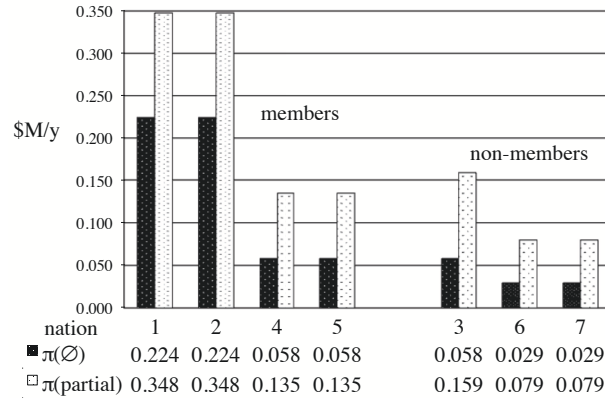


Figure 8: Profit for null and best partial coalitions for Case I. Coalition members are displayed on the left and non-members on the right.

Fig. 9 shows abatement performed vs. abatement “responsibility” for each nation in the best partial coalition case. The difference between these two quantities is the number of “permits” the member sells (or buys) within the coalition. In this case, nations 1 and 2, which have equally high exposure to debris risk—and therefore gain the most from debris abatement—pay the other two coalition members to increase abatement from the levels they would execute according to their individual cost-benefit analyses.

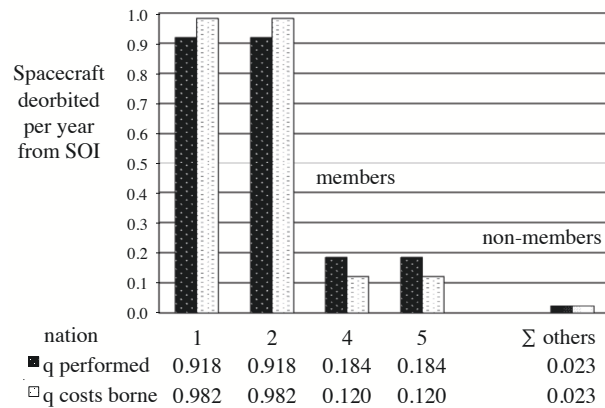


Figure 9: Abatement effected vs abatement costs borne for best partial coalition for Case I. Coalition members are displayed on the left, with one summary entry for non-members on the right.

Fig. 10 shows abatement responsibility (after transfer payments) nation-by-nation for the null and best partial coalition cases. This figure shows that the parties with the highest exposure in the SOI dramatically increase their abatement over their null coalition levels, while still achieving the higher profit shown in Fig. 8.

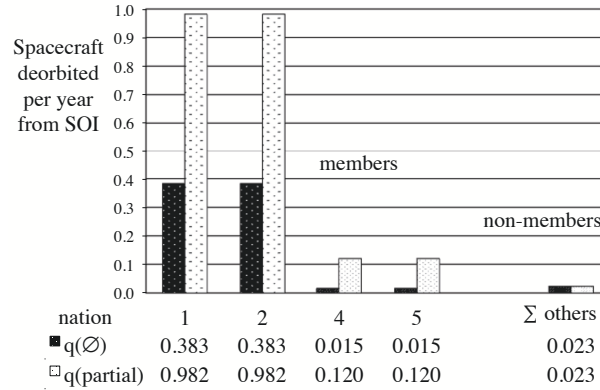


Figure 10: Quantity of abatement: null vs best partial coalition for Case I. Coalition members are displayed on the left, with one summary entry for non-members on the right.

## 4.2 Case II

In the simulation of our 15-nation Case II, there are 448 stable coalitions out of the  $2^{15} = 32768$  possible coalitions. The best partial coalitions are those consisting of the three highest launch rate countries, one of the four symmetric mid-rate nations, and nation #12 out of our set of 15:  $\{1, 2, 3, 7, 12\}$ ,  $\{1, 2, 3, 8, 12\}$ ,  $\{1, 2, 3, 9, 12\}$ ,  $\{1, 2, 3, 10, 12\}$ .

Fig. 11 shows global abatement (deorbited/year) for the null, best partial, and full coalition cases. The best partial coalitions for our Case II achieve 37% of the difference between null and full coalition abatement and 48% of the difference between null and full coalition profit. As in Case I, the partial coalitions that achieve the highest global profit are the same as those that achieve the highest global abatement. In contrast with Case I, larger stable coalitions can form (up through 10 actors). However, abatement and profit for these coalitions are substantially lower than that for the best partial coalitions.

Fig. 12 shows abatement nation-by-nation for the null and best partial coalition cases. Again, in the presence of the coalition mechanism, members effect substantially higher abatement while achieving at least as high a profit as they would in the absence of the coalition.

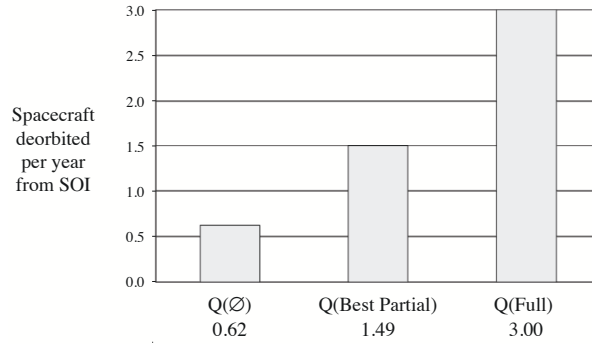


Figure 11: Global abatement for null, best partial, and full coalitions for Case II

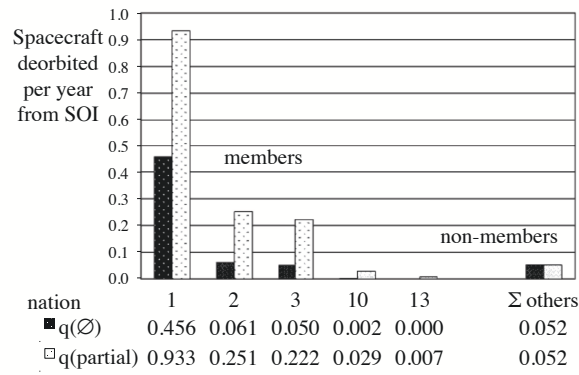


Figure 12: Quantity of abatement: null vs best partial coalition for Case II. Coalition members are displayed on the left, with one summary entry for non-members on the right.

### 4.3 Case III

To systematically explore the effects of asymmetry and number of actors on coalition performance, we use for Case III an analytic distribution which approximates the 15-nation Case II launch distribution we derived from the UCS database for the 700-1000 km shell in LEO.

This curve roughly follows a power law, a type of distribution often seen in, e.g., the allocation of wealth across a population. In economics, this is modeled as a Pareto distribution. The zeta distribution is a discretized version of the Pareto distribution, with density function

$$f_s(k) = k^{-s} / \zeta(s) \quad (5)$$

where  $\zeta(s)$  is the Riemann zeta function

$$\zeta(s) = \sum_{n=1}^{\infty} 1/n^s \quad s > 0, s \neq 1.$$

The  $k$  parameter of the zeta distribution takes integer values which we use to represent the ordinal number for each actor. As the zeta distribution is defined for an infinite population, we truncate to 15 actors and normalize the sum to unity. Increasing values of  $s$  steepen the distribution among actors relative to a symmetric distribution at  $s = 0$ . Fig. 13 shows our Case II launch distribution fitted to a zeta distribution with a value of  $s = 1.25$ , with a root mean square error of 0.0138.

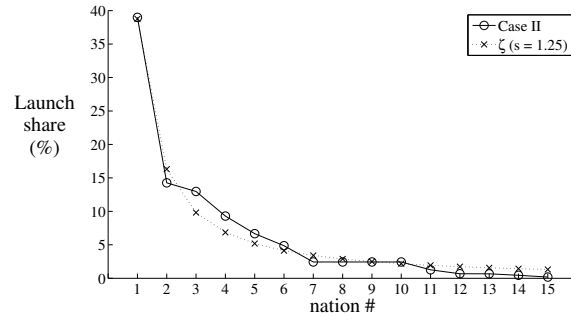


Figure 13: Comparison of Case II launch shares with values based on zeta distribution for  $s=1.25$ . (Connecting lines are included for ease of viewing.)

Fig. 14 shows that % abatement gain— $Q^*$ %, computed as the percentage of difference between the null and full coalition abatement levels obtained by the best partial coalition—decreases as the number of actors in the distribution increases. For the value of  $s$  fitting Case II above, 1.25,  $Q^*$ % decreases from ca. 60% for 6 actors to 35% for 15 actors, consistent with findings of prior research (Barrett, 1994; McGinty, 2007).

Fig. 15 shows  $Q^*$ % levels obtained by the best partial coalition as a function of zeta distribution  $s$  parameter for 15 actors.  $Q^*$ %, increases monotonically from ca. 1.5% to 100% at  $s \approx 2.15$ . The lowest  $Q^*$ % corresponds to the case of symmetric actors (where the zeta distribution becomes the uniform distribution at  $s=0$ ). For the steepest distributions ( $s \geq 2.15$ ), representing the greatest asymmetry

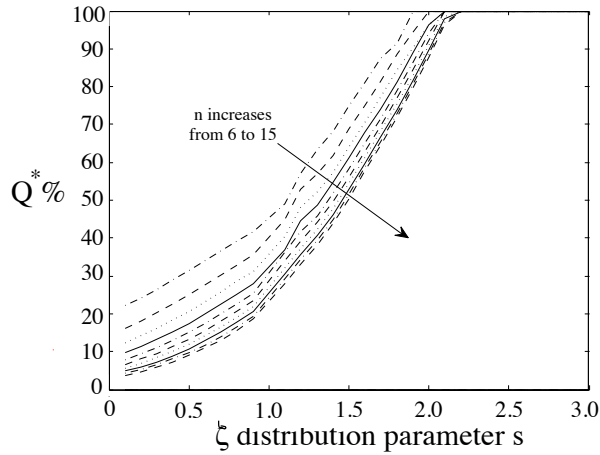


Figure 14: Percentage abatement gain,  $Q^*\%$ , for the best partial coalition as a function of zeta distribution  $s$  parameter for various sizes,  $n$ , of actor sets.

in launch rates to the SOI, the best partial coalition is equivalent to the full coalition. This comports with McGinty’s observation that “increasing the variance of the [benefit share] and [cost coefficient] distributions increases both abatement and payoff gain” (McGinty, 2007).

Fig. 15 also shows the change in best partial coalition membership, indicated as vertical sets of circles, for  $s=\{0.05, 0.10, \dots, 2.25\}$ . (No set appears for  $s = 1$  because the zeta distribution is not defined for that value.) The first derivative of abatement is discontinuous when membership shifts. For the symmetrical distribution ( $s=0$ ), the best partial coalition consists of any two members. For all asymmetric zeta distributions, all best partial coalitions include the two highest launch rate actors. For  $0 < s < 0.9$ , the best partial coalition consists of the top three actors. At  $s \approx 0.9$ , a pattern emerges where lower ranked actors join the coalition, usually in addition to, but sometimes in lieu of the third highest launch rate actor.

## 5 Discussion

Abatement levels are higher with coalitions because the coordinating and burden-sharing mechanism of the IEA effectively multiplies the benefit each party obtains from the deorbits they perform and/or pay for.

Our profit function yields “% abatement gain”—percentage of difference between the null and full coalition abatement levels obtained by the best partial coalition—that is a function of launch distribution

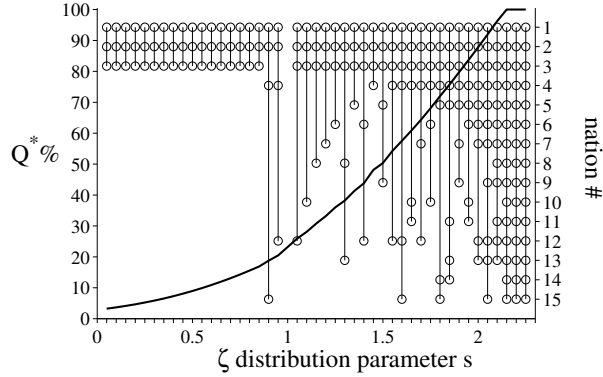


Figure 15: Percentage abatement gain for the best partial coalition as a function of zeta distribution  $s$  parameter for 15 actors. Each vertical set of circles shows coalition membership, with key along the right vertical axis, with nations numbered in decreasing order of launch rate. Asymmetry increases as  $s$  increases. The zeta distribution is not defined for  $s=1$ .

pattern among nations and is independent of the levels of  $b$  and  $c$ . Membership in the best-performing partial coalition is also independent of  $b$  and  $c$ .<sup>9</sup>

Two fundamental concerns about the % abatement gain the best partial coalition can achieve are (i) “free-riding” by non-members, and (ii) the decrease in % abatement gain as the number of actors (here, the number of nations launching spacecraft to the SOI) increases.

In our linear benefits model, non-members do not reduce their abatement in the presence of the increased abatement by the coalition. As noted by McGinty (2007), linear benefit functions result in orthogonal reaction functions for non-members, so IEA abatement does not influence non-member abatement (citing Barrett, 1997; Mäler, 1989; and Hoel, 1992).

For an IEA where benefits are effectively additive in the regime of interest, active free-riding—in the sense of a counter-productive decrease of non-members’ abatement that offsets an increase in members’ abatement—may not be a problem. However, free-riding through “undeserved” benefit spillovers enjoyed by non-coalition members may be some impediment to coalition formation. The extent to which non-members benefit from abatement generated by the coalition can be seen in Fig. 8.

The zeta-distribution analysis of the effect of the number of actors on  $Q^*$  % achieved by the best partial coalitions is consistent with the results of Case I and Case II. As per McGinty, “Allowing for asymmetry does not overturn the fundamental result that there is a tradeoff between the gains to an IEA

<sup>9</sup>Our model of linear benefits and quadratic costs yields null, partial, and full coalition levels of abatement that are all directly proportional to the value of benefit parameter  $b$ , and inversely proportional to the cost parameter  $c$ .

and the number of signatories."

## 6 Conclusions and Future Work

This simulation was a successful proof of concept of an International Environmental Agreement for debris mitigation. The results suggest that a coordination mechanism allowing for transfer payments between self-interested parties can provide a means of increasing compliance with debris mitigation guidelines. However, it also confirmed the tradeoff between the gains to an IEA and the number of signatories.

In view of the heterogeneity of orbit selection and space debris density, the present work suggests that a promising route for debris mitigation might be development of a set of IEAs, each formulated for a modestly-sized orbital shell of interest to a limited numbers of actors. Such IEAs, dealing with local concerns over non-uniformly dispersed pollutants, could achieve significantly higher  $Q^*$ % than a single large IEA. This possibility stands in contrast to the GHG scenario, where the pollutant is rapidly dispersed through the environment, affecting a large number of nations.

## Appendix: Spacecraft in the Shell of Interest

Spacecraft launched 7/1/01–7/1/09 with orbits crossing 700–1000 km from the Union of Concerned Scientists (UCS) Satellite Database, July 1, 2009

<b>Spacecraft</b>	<b>Nation</b>	<b>Orbit Class</b>	<b>Perigee (km)</b>	<b>Apogee (km)</b>	<b>Launch Date</b>
PCSat	USA	LEO	790	801	09/30/01
Keyhole 4	USA	LEO	202	1041	10/05/01
Maroc Tubsat	Morocco-Germany	LEO	985	1014	12/10/01
Badr 2	Pakistan	LEO	985	1014	12/10/01
Envisat-1	ESA-Belgium	LEO	784	790	03/01/02
Spot 5	France-Belgium	LEO	816	818	05/04/02
Fengyun 1D	China (PR)-Brazil	LEO	851	871	05/15/02
Ofeq 5	Israel	LEO	367	764	05/28/02
Parus 93	Russia	LEO	949	1016	05/28/02
NOAA-17	USA	LEO	806	821	06/24/02
Alsat-1	Algeria	LEO	680	744	11/28/02
LatinSat B	Argentina	LEO	631	701	12/20/02
Coriolis	USA	LEO	391	846	01/06/03
Molniya-1T	Russia	Elliptical	623	40644	04/02/03
Parus 94	Russia	LEO	970	1014	06/04/03
Molniya 3-53	Russia	Elliptical	631	39788	06/19/03
MOST	Canada	LEO	831	855	06/30/03
MIMOSA	Czech Republic	LEO	316	845	06/30/03
Cubesat XI-IV	Japan	LEO	822	828	06/30/03
Cute-1	Japan	LEO	819	831	06/30/03
IRS-P6	India	LEO	802	875	10/17/03
DMSP 5D-3 F16	USA	LEO	843	852	10/18/03
CBERS 2	China (PR)-Brazil	LEO	773	774	10/21/03
Chuangxin 1	China (PR)-ESA	LEO	686	758	10/21/03
SERVIS-1	Japan	LEO	984	1015	10/30/03
Formosat-2	Taiwan-USA	LEO	725	743	05/21/04
LatinSat-C	Argentina	LEO	687	753	06/29/04
DEMETER	France	LEO	685	712	06/29/04
Unisat-3	Italy	LEO	700	779	06/29/04
Saudicomsat-1	Saudi Arabia	LEO	699	734	06/29/04
Saudicomsat-2	Saudi Arabia	LEO	699	764	06/29/04
Saudisat-2	Saudi Arabia	LEO	686	723	06/29/04
Amsat-Echo	USA	LEO	698	799	06/29/04
EOS-CHEM Aura	USA	LEO	702	703	07/15/04
Parus-95	Russia	LEO	951	1006	07/22/04
Double Star 2	China (PR)-ESA	Elliptical	272	38352	07/25/04
SDS III-4	USA	Elliptical	500	39850	08/31/04
Shiyan 2	China (PR)	LEO	694	711	11/18/04
PARASOL	France-USA	LEO	705	705	12/18/04
Parus-96	Russia	LEO	910	967	01/20/05
XSS-11	USA	LEO	800	800	04/11/05
Lacrosse/Onyx 5	USA	LEO	713	716	04/30/05

Continued on next page



<b>Spacecraft</b>	<b>Nation</b>	<b>Orbit Class</b>	<b>Perigee (km)</b>	<b>Apogee (km)</b>	<b>Launch Date</b>
NOAA-18	USA	LEO	847	866	05/20/05
Keyhole 5	USA	LEO	264	1050	10/19/05
BeijinGalaxy-1	China (PR)	LEO	682	705	10/27/05
Sina-1	Iran	LEO	682	704	10/27/05
Cubesat XI-V	Japan	LEO	682	708	10/27/05
Topsat	United Kingdom	LEO	682	707	10/27/05
ALOS	Japan	LEO	697	700	01/24/06
Astro-F	Japan-Germany	LEO	707	716	02/21/06
COSMIC-A	Taiwan-USA-USA	LEO	800	800	04/15/06
COSMIC-B	Taiwan-USA-USA	LEO	800	800	04/15/06
COSMIC-C	Taiwan-USA-USA	LEO	800	800	04/15/06
COSMIC-D	Taiwan-USA-USA	LEO	800	800	04/15/06
COSMIC-E	Taiwan-USA-USA	LEO	800	800	04/15/06
COSMIC-F	Taiwan-USA	LEO	800	800	04/15/06
Calipso	France-USA	LEO	701	704	04/28/06
Cloudsat	USA	LEO	701	704	04/28/06
US-KS Oko 87	Russia	Elliptical	542	39807	07/21/06
Kompsat-2	South Korea	LEO	675	702	07/28/06
MetOp-A	Multinational	LEO	813	830	10/19/06
DMSP 5D-3 F17	USA	LEO	842	855	11/04/06
CoRoT	International	LEO	895	906	12/27/06
THEMIS 1	International	Elliptical	461	87304	02/17/07
THEMIS 2	International	Elliptical	458	87298	02/17/07
THEMIS 3	International	Elliptical	459	87054	02/17/07
THEMIS 4	International	Elliptical	467	87260	02/17/07
THEMIS 5	International	Elliptical	474	87526	02/17/07
Haiyang 1B	China (PR)-Brazil	LEO	783	813	04/11/07
Saudicomsat-3	Saudi Arabia	LEO	653	717	04/17/07
Saudicomsat-4	Saudi Arabia	LEO	650	750	04/17/07
Saudicomsat-5	Saudi Arabia	LEO	652	728	04/17/07
Saudicomsat-6	Saudi Arabia	LEO	649	761	04/17/07
Saudicomsat-7	Saudi Arabia	LEO	651	739	04/17/07
CAPE-1	USA	LEO	646	793	04/17/07
Tselina-2	Russia	LEO	850	880	06/29/07
Parus-97	Russia	LEO	956	999	09/11/07
CBERS 2B	China (PR)-Brazil	LEO	778	778	09/19/07
Globalstar MO66	USA	LEO	917	935	10/20/07
Globalstar MO67	USA	LEO	919	934	10/20/07
Globalstar MO68	USA	LEO	914	937	10/20/07
US-KS Oko 88	Russia	Elliptical	512	39849	10/23/07
SDS III-5	USA	Elliptical	400	39966	12/10/07
Radarsat-2	Canada	LEO	792	799	12/14/07
C/NOFS	USA	LEO	406	853	04/16/08
Fengyun 3A	China (PR)	LEO	825	829	05/27/08
Theos	Thailand	LEO	620	700	10/01/08
THEOS	Thailand	LEO	824	826	10/01/08
Chuangxin 2	China (PR)	LEO	786	805	11/05/08

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<b>Spacecraft</b>	<b>Nation</b>	<b>Orbit Class</b>	<b>Perigee (km)</b>	<b>Apogee (km)</b>	<b>Launch Date</b>
Shiyan 3	China (PR)	LEO	788	803	11/05/08
US-KS Oko 89	Russia	Elliptical	667	39697	12/02/08
NOAA-19	USA	LEO	845	868	02/06/09
SPIRALE-A	France	Elliptical	608	35717	02/11/09
SPIRALE-B	France	Elliptical	627	35697	02/11/09
STSS ATRR	USA	LEO	867	879	05/05/09
Meridian-2	Russia	Elliptical	280	36471	05/20/09

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