

Kilometre-scale orbital data centres may clear debris by avoiding rocket bodies and defunct satellites

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Kilometre-scale orbital data centres may clear debris by avoiding rocket bodies and defunct satellites

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Abstract

Companies propose orbital data centres with square kilometres of thin solar arrays in low Earth orbit. Their debris assessments ask how often such a structure is struck, not what it does to the objects crossing it. A model using ESA's MASTER-8 fluxes and the public catalogue shows two opposite effects. Rocket bodies and defunct satellites carry over 90% of the crossing mass, and a crossing deposits more energy than their catastrophic breakup requires. If crossings strip over 0.1–3% of their mass, an unmeasured quantity, a structure that does not avoid them becomes a net source of debris; complete breakup leaves 3–15 times today's lethal population (untrackable but mission-ending objects) after 15 years at 20 GW. If these objects crossed unharmed, the slowing of debris fragments into re-entry would cut that population at 650–1,000 km to a quarter to three-fifths of today's. Avoiding only these few hundred objects makes the structure a net remover, even if every missed crossing breaks the object up, once 93–99.6% of their crossings are screened at 650–1,000 km and over 99% at 550 km, depending on altitude and fragment yield. Screening every catalogued object protects little better at up to ten times the propellant.

Keywords: space debris; orbital data centre; large space structure; hypervelocity impact; collision avoidance; debris environment

Introduction

Demand for computing power for artificial intelligence has led several companies to propose data centres in orbit, where sunlight is nearly continuous and waste heat can be radiated to space. The proposals share a scale measured in gigawatts and square kilometres. Starcloud's white paper describes a 5 GW monolith with a solar array of 4 km by 4 km, radiators of less than half the array's area and compute housed in modules of about 100 t [1]. The same company has applied to the US Federal Communications Commission for up to 88,000 separate satellites in shells between 600 and 850 km [2], SpaceX has applied for up to a million satellites operating as orbital data centres between 500 and 2,000 km [3], and Google's Project Suncatcher studies clusters of 81 satellites flying in formation at about 650 km [4]. All of these architectures use or include dawn–dusk Sun-synchronous orbits [1–4], in heavily used altitude bands where the density of active payloads is approaching that of debris [5]. At gigawatt scale, each would expose square kilometres of thin structure to the debris population.

Debris assessments for such systems ask what the environment does to the structure. The assessment filed with the Starcloud application reports a probability below 0.001 of collision with objects larger than 10 cm and states that no debris will be released during normal operations [2]. The limit comes from the NASA standard for limiting orbital debris, whose rationale is that such a collision breaks the spacecraft up and makes it a source of debris [6]. Analyses of kilometre-scale infrastructure estimate impact probabilities, local fragmentation chains and the feasibility of manoeuvring [7], and studies of orbital data centres themselves

treat debris as a hazard rate for the spacecraft [8] or note qualitatively that such structures could trigger runaway collisions [9]. Work on solar power satellites has modelled projectiles of about 1 cm crossing micrometre-thick membranes largely intact and identified impacts of objects larger than a metre as the next step [10]. A study of uncontrolled membrane reflectors of 19 g/m² in Sun-synchronous orbit treats their impacts as non-fragmenting and assesses the risk to the structure [11]. Models of the environment as a whole derive the collisional cascade [12–14], the critical size of constellations [15], the carrying capacity of low Earth orbit [16,17] and the effect of disposal and of active removal on the long-term population [18,19]. In all of these, the large structure is the potential victim and, if it breaks up, the potential source.

The opposite question, what a structure does to the population of objects that hit it, has been asked mainly for devices built to remove debris. A 1991 patent describes rotating fabric panels that slow debris of intermediate size piercing them enough for it to decay from orbit, while large debris is allowed to pass between the panels to protect them [20]. Later sweeper concepts assume that the sweeper captures or absorbs what it hits [21,22], and one study found that a sweeper large enough to halve the growth of centimetre debris would itself suffer thousands of potentially catastrophic impacts by objects larger than 10 cm [23]. Low-density media, plates meeting debris at low relative velocity and injected dust have also been proposed to slow small debris [24–27], while collisions with drag-sail membranes are classed as non-catastrophic because of the membranes' low density [28,29]. None concerns a square-kilometre structure that is not designed to remove debris yet is crossed every year by both debris fragments and rocket bodies.

A thin solar array neither captures debris nor is destroyed by it. A fragment of 10 cm striking a 0.5 kg/m² sheet at 13–14 km/s is expected to break up while punching a hole, much as a projectile breaks up on the bumper of a Whipple shield [30,31]. The disc of sheet that it punches out is accelerated to the fragment's velocity, so the centre of mass of everything that passes through moves part of the way towards the structure's own velocity, enough for a fragment with a high area-to-mass ratio to lose hundreds of metres per second and re-enter. For a rocket body or a defunct satellite (together, intact objects), the disc it punches out is a small fraction of its mass and the slowdown is tens of metres per second, while the energy that the sheet deposits per unit of the object's mass exceeds the threshold for catastrophic breakup in the standard breakup model [32]. Whether a crossing strips only a small fraction of such an object or breaks it up has not been measured, nor has the number of fragments that the lost mass makes; most of these fragments stay in orbit, and in tests on a modern satellite, breakups produced more than three times the fragments that the standard model predicts [33]. The same structure can therefore clear its altitude shell of one kind of debris while seeding it with another.

Which effect prevails depends on whether the structure avoids the intact objects that cross it. Conjunction screening protects the spacecraft that manoeuvres: it is triggered by the probability of a collision with the spacecraft, sometimes with stricter thresholds for objects whose collision would produce more debris [34,35]. The Starcloud white paper commits a large structure to responsive manoeuvring and state-of-the-art tracking, and notes that small-debris impacts on solar arrays are generally passive [1]. For a thin structure, however, screening designed to protect the spacecraft does not serve the environment. Screened for its own safety, the structure has little reason to avoid a rocket body that would merely cut a hole in a sheet, yet that crossing can shed more lethal fragments than the array removes; screened on collision probability alone, it avoids such objects only together with the debris fragments it would otherwise remove, and at an efficiency set without regard to the environment.

This paper quantifies both effects for gigawatt-scale orbital data centres and finds that whether the structure avoids intact objects decides which prevails. Without avoidance it is a net source of debris if a crossing strips more than 0.1–3% of an intact object’s mass. Avoiding intact objects alone, rather than every catalogued object, makes it a net remover of debris at a fraction of the propellant, but only at screening efficiencies of 0.93–0.999 if every missed crossing breaks the object up, depending on altitude and fragment yield. Both the mass a crossing strips and the fragments it makes are unmeasured. The model follows four populations in a 100 km shell: intact objects, trackable debris fragments, trackable fragments made by the structure and lethal objects (untrackable objects smaller than 10 cm but heavy enough to end a satellite’s mission), whose number in the shell is called the lethal population. Impact rates and velocities come from ESA’s Meteoroid and Space Debris Terrestrial Environment Reference model, MASTER-8 [36], the split of the trackable population from the public catalogue, fragmentation from hypervelocity-impact data and the NASA standard breakup model [30,32], and the orbits of impact products (fragments, flakes and remnants) from momentum conservation and an orbit-averaged drag integration. Twenty-three uncertain parameters are varied in a Monte Carlo analysis, the stripped mass fraction is scanned from zero to complete breakup, and a fleet of separate satellites is evaluated for comparison.

Results

Unless stated otherwise, results are for 20 GW installed in the shell, in one or several structures, operating for 15 years at altitudes of 550, 650, 850 and 1,000 km. They use the 1.47 g lethal threshold and the fragment yield of the NASA standard breakup model, and are medians over 1,000 Monte Carlo draws (designs in Table 1, results by altitude in Table 2); screening-efficiency scans and sensitivity cases use the first 150 draws. Because sources hold today’s population steady, a structure is a net remover if the population ends below today’s and a net source if it ends above. Shares of draws above today’s population describe the spread over the sampled parameter ranges, not a probability.

Debris fragments are slowed into re-entry

Each gigawatt of array (3.2 km²) is crossed every year by a few intact objects, about ten trackable debris fragments and tens to hundreds of lethal objects (Fig. 1b; Table 2). By number, nearly all crossings are by debris fragments and small lethal objects; by mass, nearly all are by intact objects, which carry 93–98% of the mass that crosses the array. A 5 GW structure of the size in the Starcloud white paper would be crossed by about 10–23 of them every year. The momentum shared with the punched-out disc separates the two classes (Fig. 1a, c). For a trackable debris fragment, the sheet crossed is typically a few per cent to tens of per cent of its mass, and the centre of mass of fragment and disc loses enough speed that, for 90–100% of the fragments, the new perigee lies below 200 km; a compact lethal object of 1 cm loses about 1.1 km/s (Supplementary Note 4). For an intact object the sheet crossed is about 1% of its mass or less, and the object loses only 36–145 m/s, depending on its area-to-mass ratio, and most such objects stay in orbit, moved to lower altitudes rather than removed.

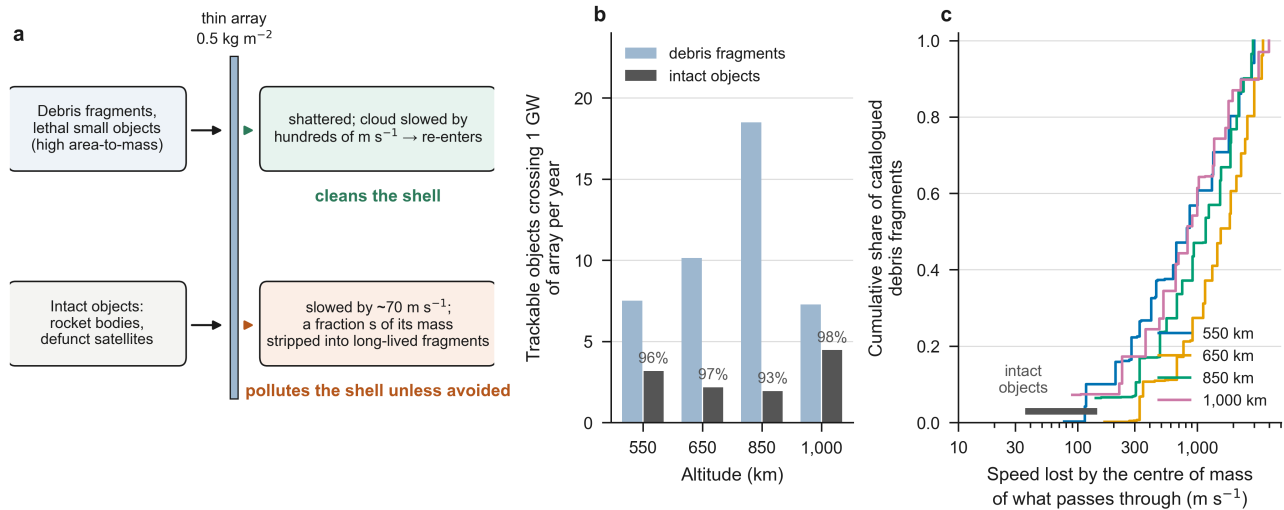


Fig. 1 | A thin array slows debris fragments into re-entry but can break up the intact objects that cross it. a, Debris fragments and small lethal objects, which have high area-to-mass ratios, are shattered and slowed by hundreds of metres per second through the momentum they share with the punched-out disc; intact objects are slowed by a median of about 70 m/s (36–145 m/s) and may lose a fraction s of their mass to fragments that stay in orbit. **b**, Trackable debris fragments and intact objects crossing 1 GW of array (3.2 km^2) per year; percentages give the share of the crossing mass carried by intact objects. **c**, Distribution of the speed lost by the centre of mass of a trackable debris fragment and its punched-out disc at the median impact speed, averaged over incidence angles; the grey bar marks intact objects with area-to-mass ratios of $0.003\text{--}0.012 \text{ m}^2/\text{kg}$.

Table 2. Main results by altitude for 20 GW over 15 years (lethal threshold 1.47 g; medians over 1,000 draws, share of draws above today's population in brackets; standard fragment yield, sheet momentum shared by the whole object and screening efficiency 0.99 unless stated).

Quantity	550 km	650 km	850 km	1,000 km
Crossings per GW of array per year: intact objects / trackable debris / lethal objects	3.2 / 7.5 / 62	2.2 / 10.1 / 162	1.9 / 18.5 / 318	4.5 / 7.3 / 182
Lethal population relative to today, no avoidance, $s = 0$	0.84 (22%)	0.61 (4%)	0.31 (1%)	0.26 (6%)
Threshold s^* , no avoidance; stripped material takes the momentum	0.13%; 3.5%	1.0%; 4.1%	3.3%; 8.2%	0.24%; 3.0%
Lethal population relative to today, no avoidance, $s = 1$	11 (100%)	5.0 (100%)	3.1 (94%)	15 (100%)
Same, along-track radiators	5.7 (100%)	1.62 (80%)	0.51 (17%)	2.27 (82%)
Lethal population relative to today, structure avoids intact objects, $s = 1$	1.18 (72%)	0.80 (21%)	0.41 (2%)	0.80 (38%)
Screening efficiency at which the median for $s = 1$ equals today's (first 150 draws): standard fragment yield / 3.5 times the yield	0.994 / 0.999	0.977 / 0.994	0.926 / 0.981	0.985 / 0.996
Trackable population relative to today, $s = 0$: avoiding intact objects / every catalogued object	0.77 / 0.92	0.67 / 0.88	0.30 / 0.68	0.49 / 0.80
Lethal population relative to today, modules not avoided, $s = 0$: expected / if no module breaks up	1.64 (100%) / 0.86 (26%)	1.04 (56%) / 0.62 (5%)	0.63 (21%) / 0.32 (1%)	1.62 (76%) / 0.28 (7%)
$P(\geq 1$ module breakup in 15 years), stripped fraction sampled: no avoidance / structure and modules avoiding	40% / 0.84%	31% / 0.61%	39% / 0.72%	62% / 1.4%
Propellant for whole-structure avoidance, 5 GW (t per GW per year), position uncertainty 0.1–0.3 km: intact objects / every catalogued object	2.0–8.4 / 6.7–28	1.3–5.7 / 7.6–32	1.2–5.3 / 13–55	2.8–12 / 7.3–33
Same, position uncertainty 3 km	1,020–1,540 / 3,430–5,170	693–1,040 / 3,920–5,910	669–1,010 / 7,040–10,600	1,630–2,460 / 4,290–6,460

If intact objects crossed without losing mass, the structure would clear debris from its shell. The median lethal population after 15 years would be 0.26–0.61 times today's at 650–1,000 km, where natural decay is

slow and removal by the structure dominates the balance, and 0.84 times today's at 550 km (Fig. 2). The removal rests on the slowdown of the centre of mass: without momentum exchange the lethal population would be 1.0–1.5 times today's (Supplementary Note 6). It is also an upper estimate, because the shell is taken as fully mixed. If only the objects whose orbits reach the altitude band of the structure can be struck (about two-fifths to three-quarters of today's objects), the lethal population at 650–1,000 km rises to 0.37–0.68 times today's (Supplementary Note 6). With a lower lethal threshold of 0.108 g the removal is weaker still, leaving 0.52–0.95 times today's population at the four altitudes, because flakes of the sheet itself then count as lethal (Supplementary Table 6). This removal is only potential: it is realised only if intact objects cross the structure unharmed or not at all.

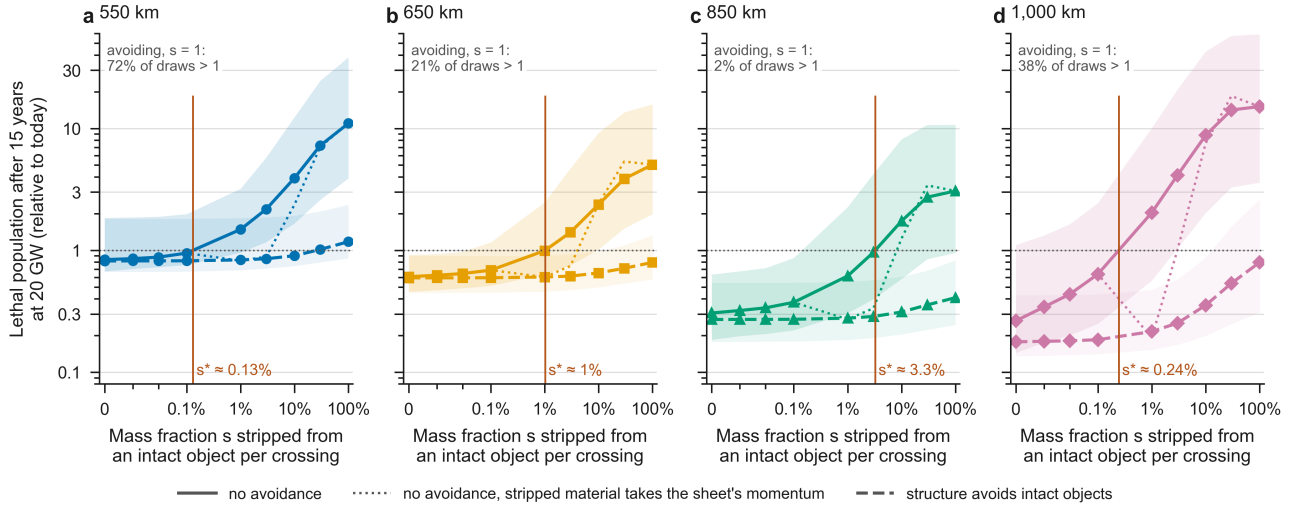


Fig. 2 | Lethal population against the stripped fraction. Lethal untrackable population of the shell after 15 years at 20 GW, relative to today, against the stripped fraction s , for a monolith of thin surfaces without avoidance (solid) and with the whole structure avoiding catalogued intact objects at a screening efficiency of 0.99 (dashed), with the standard fragment yield; Fig. 3c gives the efficiency required with a higher yield. Lines are medians and bands 5th–95th percentiles over 1,000 Monte Carlo draws, with the sheet's momentum shared by the whole object; the dotted line gives the median without avoidance when the momentum goes to the stripped material alone. Vertical lines mark the threshold s^* at which the solid median equals today's population; the note in each panel gives the share of draws above today's population with avoidance and complete breakup. The left end of each axis corresponds to $s = 0$.

Intact objects can reverse the effect

Intact objects are unlikely to cross unharmed. An aluminium wall 2–5 mm thick facing the sheet makes up 3–8% of the mass of an intact object with an area-to-mass ratio of 0.006 m²/kg. A 0.5 kg/m² sheet striking such an object at the median impact speed of 13.6 km/s deposits about 280 J per gram of the object, seven times the threshold for catastrophic breakup in the standard breakup model [32]. Membranes of a few to a few tens of grams per square metre, such as drag sails or reflectors, deposit one to two orders of magnitude less energy per unit mass of the struck object, consistent with their impacts being classed as non-catastrophic [11,28,29]. By that criterion an intact object crossing the array would break up, although whether a distributed impact by a thin sheet delivers its energy to the whole object, or melts and fragments only its outer layer, has not been measured. Confined to the facing wall, the same energy would amount to 3.4–8.6 kJ per gram of wall, several times what it takes to melt aluminium, and the impulse of the sheet would drive the wall into the object at about a kilometre per second, which suggests that a crossing strips at least the wall.

Each crossing by an intact object therefore adds the fragments stripped from it, and most of these stay in the shell. The lethal population rises steeply with the stripped fraction s (Fig. 2) and reaches today's at a

threshold s^* of 0.13% at 550 km, where removal is weakest; 0.24% at 1,000 km, where intact objects are most numerous relative to debris; and 1.0% and 3.3% at 650 and 850 km. If the sheet's momentum goes to the stripped material alone, which then leaves the shell more readily, the thresholds rise to 3–8%; the two momentum cases are not bounds, because material splashed back from the wall would stay in orbit longer than in either (Supplementary Note 8). A stripping yield proportional to s , which removes the excess fragments of repeated small strips, raises s^* two- to twentyfold on a coarser grid of stripped fractions (Supplementary Note 6), but at every altitude s^* with the default stripping yield is at or below the mass fraction of the facing wall. If intact objects break up completely, the lethal population is 3.1–15 times today's, above it in 94–100% of the draws (Table 2), and the trackable population 5–27 times.

These figures follow the standard breakup model. Hypervelocity tests on a modern satellite have produced more than three times the fragments of 2 mm and larger that the model predicts [33]; with the yield of lethal fragments multiplied by 3.5, complete breakup gives 9–44 times today's lethal population in the first 150 draws, against 2.7–13 with the standard yield, and, on the same coarser grid, s^* falls three- to twenty-sevenfold (Supplementary Note 6). A smaller installation is not safer: each intact object breaks up only once, while the removal that offsets the harm grows with the structure, so a single 5 GW structure, the size in the white paper, gives 4.6–21 times today's lethal population for complete breakup, more than 20 GW does. With the stripped fraction sampled, the population matrix becomes supercritical at 20 GW or less in 12% of the draws at 850 and 1,000 km, so that the population keeps growing after 15 years; with avoidance no draw does below about 40 GW (Supplementary Note 8). Without avoidance, a structure built mainly of thin arrays is therefore a net source of debris once crossings strip more than 0.1–3% of an intact object's mass, no more than the share held by its facing wall.

What the structure must avoid

Avoidance changes the balance because it takes intact objects out of the crossings while leaving the debris fragments that the structure removes. With the standard fragment yield, if the whole structure screens crossings by catalogued intact objects with an efficiency of 0.99, the median lethal population after 15 years stays below today's at 650–1,000 km even if every remaining crossing breaks the object up, and exceeds it by about a fifth at 550 km (Fig. 2, dashed lines; Table 2); whether 0.99 is enough depends on that yield (next section). The margin is thin: at 650 and 1,000 km a fifth to two-fifths of the draws still exceed today's population.

Which objects are screened matters less for the lethal population than for what else the structure removes and what avoidance costs. Screening every catalogued object, as conjunction screening for a spacecraft would, lowers the lethal population little further, by at most 5% (Table 1), because the additional objects it avoids are debris fragments that the structure would otherwise remove. It gives up most of the removal of trackable debris (Fig. 3a) and multiplies the manoeuvres and the propellant, by 2.6 at 1,000 km and by about 10 at 850 km, where debris fragments outnumber intact objects nine to one (Fig. 3b). The objects to avoid form a short list: the 250–600 rocket bodies and defunct satellites in a 100 km shell.

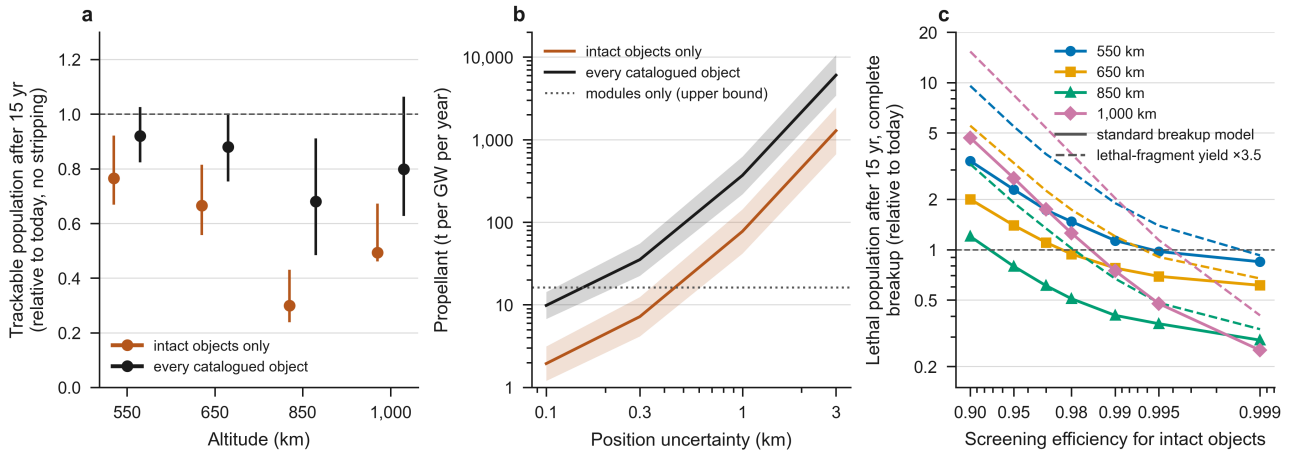


Fig. 3 | What a thin structure must avoid, and at what cost. **a**, Trackable population after 15 years without stripping when the structure avoids intact objects only or every catalogued object; points are medians and bars 5th–95th percentiles. **b**, Propellant per gigawatt per year for a 5 GW structure avoiding intact objects only or every catalogued object, screened by the point where each object crosses the array plane, against the position uncertainty of the screened orbits; lines are geometric means and bands the range over altitudes and screening thresholds of 10^{-4} – 10^{-5} ; the dotted line is the upper bound for the clustered compute modules alone. **c**, Lethal population after 15 years at 20 GW relative to today against the efficiency with which the whole structure screens catalogued intact objects, for complete breakup of the remaining crossings, with fragments from the standard breakup model (solid, markers) and with a lethal-fragment yield 3.5 times higher (dashed); medians over the first 150 draws, so values at 0.99 differ slightly from Fig. 2, which uses all 1,000.

Table 1. Designs, the architectures they represent and the lethal population after 15 years at 20 GW relative to today (threshold 1.47 g; standard fragment yield; medians, ranges over altitudes of 550–1,000 km; screening efficiency 0.99). s^* is the stripped fraction at which the median equals today’s population, with the sheet’s momentum shared by the whole object and, for the first design in brackets, given to the stripped material. Designs with modules count module breakups at their expected rate; module-breakup probabilities and the fleet use the stripped fraction sampled log-uniformly. With 3.5 times the lethal fragments of the standard model, an efficiency of 0.99 does not keep the lethal population for complete breakup below today’s at 550, 650 and 1,000 km (Table 2; Supplementary Note 6).

Design	Represents	No stripping	s^*	Complete breakup	Module or satellite breakups
Thin surfaces, radial radiators, no avoidance	Arrays and radiators of the Starcloud white paper [1], without avoidance	0.26–0.84	0.13–3.3% (3.0–8.2%)	3.1–15	—
Thin surfaces, along-track radiators, no avoidance	Radiator orientation as a design choice	0.11–0.75	0.4–9%; not reached at 850 km	0.51–5.7	—
Thin surfaces, structure avoids intact objects	Selective whole-structure avoidance	0.18–0.82; trackable 0.30–0.77	26% at 550 km; not reached elsewhere	0.41–1.18	—
Thin surfaces, structure avoids every catalogued object	Conventional screening of every catalogued object	0.17–0.80; trackable 0.68–0.92	37% at 550 km; not reached elsewhere	0.40–1.12	—
Thin surfaces and compute modules, no avoidance	Geometry of the Starcloud white paper [1] without the avoidance it calls for	0.63–1.64	already exceeded at $s = 0$ at 550, 650 and 1,000 km; 1.1% at 850 km	3.3–16	Module: $P(\geq 1$ in 15 years) 31–62%
Thin surfaces and modules, structure avoids intact objects, modules avoid every catalogued object	Monolith with selective and module avoidance	0.20–0.84	22% at 550 km; not reached elsewhere	0.42–1.20	Module: $P(\geq 1$ in 15 years) 0.61–1.4%

Design	Represents	No stripping	s^*	Complete breakup	Module or satellite breakups
Fleet of separate satellites avoiding catalogued objects	Starcloud licence application [2]; Google Project Suncatcher scaled to gigawatts [4]	—	—	—	11–26 satellite-body breakups; lethal population 1.4–1.9

The efficiency required depends on what a crossing does

The benefit depends, to first order, on the screening efficiency, and the efficiency required depends on the two unmeasured quantities (Fig. 3c). If every remaining crossing breaks the object up and the fragments follow the standard breakup model, the median lethal population at 20 GW falls to today's once the efficiency reaches 0.93 at 850 km, 0.98 at 650 km, 0.985 at 1,000 km and 0.994 at 550 km. With the fragment yield of the modern-satellite tests the requirements rise to 0.98, 0.994, 0.996 and 0.999. If crossings strip a tenth of the object rather than break it up, the requirements fall to 0.98 or less with the standard model and to 0.994 or less with the higher yield. At 0.999 the structure removes debris at all four altitudes under either yield. Because these thresholds are medians, about half of the draws still exceed today's population there, so a design needs a margin.

Two further factors make the highest requirements harder to meet. Radiators facing radially account for 0.1–1.2% of the intact-object crossings, rising with altitude, and lie outside the screening geometry of the array, so where the efficiency required is 0.99 or more they would have to be screened as well. At 550 km a 5 GW structure would also meet several hundred active satellites a year; even if 99% of these encounters were avoided, the remaining crossings would outnumber those of intact objects after selective avoidance, so the results there hold only if operators coordinate their manoeuvres (Supplementary Note 8).

What avoidance costs

The cost of avoidance by the whole structure is set by how well the orbits of intact objects are known (Fig. 3b; Supplementary Note 5). Because a Sun-pointing array lies close to its own orbital plane, a manoeuvre only has to move the array along its track until the point where the object will cross that plane is clear. If the orbits of intact objects are known to 100–300 m, a 5 GW structure needs up to two manoeuvres a week and 1.2–12 t of propellant per gigawatt per year, with thrusters of a few kilonewtons drawing a few per cent of its output. With the 3 km uncertainty of poorly determined public orbits the propellant rises by two orders of magnitude, to 8–28% of the structural mass every year.

Compute modules add a second hazard

The compute modules of a monolithic design are dense targets. A 100 t module struck at 13–14 km/s by an object of about 45 kg or more receives more than 40 J per gram of its mass and breaks up. Without avoidance, the probability of at least one module breakup within 15 years is 31–62% (Fig. 4a), and a single breakup raises the shell's lethal population to 2.7–11 times today's immediately after the event (Fig. 4b). In histories without a module breakup the lethal population stays close to that of the thin-surface design, but averaged over histories the modules raise it to or above today's at 550, 650 and 1,000 km even without stripping (Table 2), and the average conceals that a single event more than doubles it.

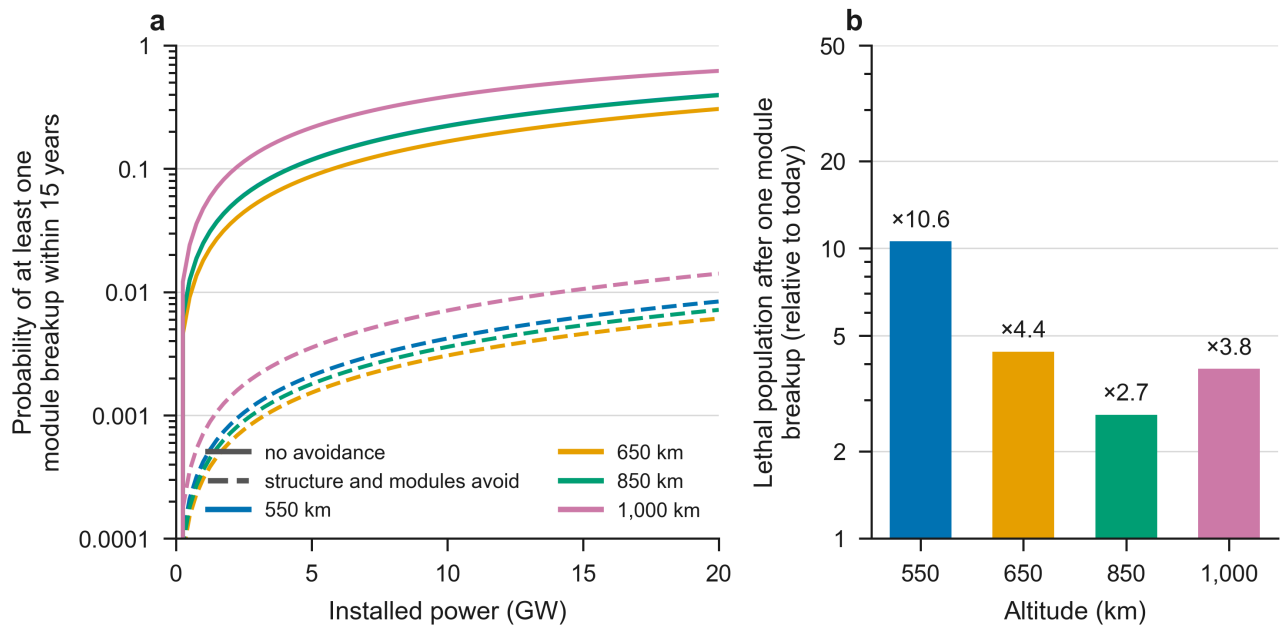


Fig. 4 | Compute modules. **a**, Probability of at least one module breakup within 15 years against installed power, without avoidance (solid) and with the structure avoiding intact objects and the modules avoiding every catalogued object (dashed); without avoidance the lines for 550 and 850 km coincide. **b**, Lethal population of the shell immediately after one module breakup relative to today, counting each fragment by the fraction of its orbit spent in the shell.

The modules can be protected in the same way as the structure, because every object able to destroy one, of about 45 kg or more, is large enough to be catalogued. With the structure avoiding intact objects and the modules avoiding every catalogued object, the probability of a module breakup within 15 years falls to about 1%, and a monolith with modules performs close to the thin-surface design (Table 1). A module, however, is small compared with the uncertainty in the position of what approaches it, so this requires orbits known to 100–200 m for every object of tens of kilograms or more; at 1 km the modules' screening efficiency falls well below 0.99 (Supplementary Note 5). Avoidance by the compute modules, screened as one cluster, costs at most 16 t of propellant per gigawatt per year.

Denser surfaces facing the flow slow intact objects too

The division between the two classes is set by the ratio of the sheet mass crossed to the mass of the object, not by the class itself, so the surfaces of the structure are a further lever. Radiators of 3 kg/m² facing along the flight direction (along-track radiators) are crossed far more often than radial ones and slow an intact object by 210–770 m/s. That takes it out of the shell, in most cases into re-entry, together with whatever is stripped from it. With such radiators the lethal population for complete breakup falls two- to sevenfold, to below today's at 850 km, but it stays above today's at the other three altitudes (Table 2); a 3 kg/m² array has a similar effect (Supplementary Note 6). The benefit extends to partial stripping only if the stripped material moves with the rest of the object. Denser surfaces cost mass, and glass along-track radiators create a chain of millimetre ejecta between structures in opposite dawn–dusk planes that becomes self-sustaining above 2–4 GW at 850 km and about 1 GW at 1,000 km (Supplementary Note 7).

A fleet moves the hazard to satellite bodies

Distributing the same capacity over 88,000 satellites of 1–3 t spreads the crossings over many small arrays and moves the risk to the satellite bodies. The bodies present 9–120 times as much dense cross-section per

gigawatt as the compute modules of a monolith and can be destroyed by debris of about a kilogram, of which only part is catalogued. Even with every satellite avoiding catalogued objects, the model gives 11–26 body breakups in 15 years at 20 GW. With the stripped fraction sampled, the lethal population is then 1.4–1.9 times today's, above it at every altitude, and two to six times that of a monolith that avoids intact objects (Supplementary Tables 4 and 5). Because the satellite mass and cross-section are assumptions of this paper, these figures illustrate the order of magnitude rather than assess a specific design.

Discussion

A kilometre-scale orbital data centre acts on its shell in two opposite ways, and which prevails is decided by whether it avoids the rocket bodies and defunct satellites that would cross it. Without avoidance, a structure built mainly of thin arrays is a net source of debris if crossings strip more than 0.1–3% of an intact object's mass, no more than the share held by its facing wall, and compute modules that do not avoid catalogued objects add a 31–62% chance of a breakup that would more than double the shell's lethal population. With intact objects avoided reliably enough, the slowdown of debris fragments and small lethal objects makes it a net remover. Both the sign without avoidance and the efficiency required with it rest on two quantities that have not been measured.

This runs against current practice, in which conjunction screening serves the manoeuvring spacecraft, at best weighted by the consequence of a collision [34,35]. Screening sized for the structure's own safety gives it little reason to avoid the objects that make it a source; screening every catalogued object protects hardly better than screening intact objects alone, because the structure reduces the lethal population mainly by slowing objects too small to be catalogued. It also gives up most of the removal of trackable debris and costs up to ten times as much. The structure should avoid intact objects, for the sake of the environment rather than its own, and let debris fragments through. Letting catalogued debris fragments cross the structure on purpose departs from current limits on collision probability [6] and from the guideline to avoid intentional destruction and other harmful activities [37]; it is a design option that regulators would have to accept, not one that an operator could adopt alone. The sweeper patent let large debris pass to protect its panels [20], and consequence-weighted thresholds already favour avoiding objects whose collision would create more debris [34,35]. What differs here is that the structure survives the crossing, the harm comes from the crossing object alone and the efficiency required is set by the environment rather than by damage tolerance. Nudging derelicts apart to prevent collisions between them has been proposed as a third-party service [38–40]; a thin structure would have to do the equivalent for itself.

Analytical and evolutionary models commonly assume that active satellites fail to avoid 1% of their conjunctions [15,41]. For a thin structure this miss rate, $1 - \epsilon$, is a design requirement, and it is demanding: the largest miss rate at which the shell is no worse than today's (median, complete breakup) is 2–7% of intact-object crossings at 850 km, depending on the fragment yield, 0.4–2.3% at 650 and 1,000 km and 0.1–0.6% at 550 km. For a target of square kilometres the Gaussian tail of the screening rule misses about one crossing in ten thousand, so the efficiency achieved is set by failures outside the Gaussian model: unrealistic covariances, the lead time that a structure of tens of thousands of tonnes needs to decide on and execute a manoeuvre, objects lost from the catalogue and errors in execution. Whether a kilometre-scale structure can reach these efficiencies against a few hundred well-tracked objects, with manoeuvres requiring a few kilonewtons of thrust up to twice a week applied to a structure of thin membranes, is an operational question that the proposals have not yet quantified [1].

The design priorities follow. First, the whole structure should screen catalogued intact objects selectively, with an efficiency set by its altitude and with margin for the fragment yield; because the propellant rises by two orders of magnitude as the position uncertainty grows from hundreds of metres to kilometres, the cost favours tracking those few hundred objects to a few hundred metres. Second, the compute modules should avoid every catalogued object able to destroy them, which requires the orbits of objects of tens of kilograms and more to be known to 100–200 m; otherwise their mass and layout should limit the consequence of a breakup. Third, the areal density and orientation of radiators and arrays should be chosen with intact objects in mind, and glass along-track radiators need structures at the same altitude to share one dawn–dusk plane. Among the altitudes considered, 850 km is the most forgiving and 550 km, where removal is weakest and active satellites are most numerous, the least. A fleet of separate satellites does not avoid the problem but moves the hazard to their bodies (Supplementary Tables 4 and 5).

For assessment and regulation, the collision probability with objects larger than 10 cm says little about such a structure. A 5 GW array is crossed every year by 50–100 non-maneuvrable objects of that size (Table 2) and reaches the 0.001 limit within minutes of operation [6]; what matters is what happens to the objects that cross it. Table 3 lists the quantities that a debris assessment of such a structure should report instead.

Table 3. Aspects that a debris assessment of a monolithic orbital data centre should report, the quantities with which each can be evaluated and the measurements or models that would support them.

Aspect	What to report and how to evaluate it	Basis in this work	Measurement or model needed
Crossings by intact objects	Rate per year, $k_f N_I$ per surface, and the outcome assumed for each crossing	Fig. 1b, Table 2	Catalogue-based rates for the chosen orbit
Outcome for the crossing object	Ratio of crossed sheet mass to object mass and the resulting slowdown for each surface; stripped fraction assumed, compared with s^* and with the mass of the facing wall	Fig. 2, Table 2	Wall sections fired through thin sheets at 7–8 km/s and above; validated hydrocode
Fate of debris that crosses the structure	Centre-of-mass slowdown, breakup below the lethal mass, cloud expansion, fraction re-entering, flux into lower shells	Fig. 1c, Supplementary Note 4	Tests of centimetre to decimetre fragments against thin sheets
What is avoided	Object classes screened; trackable debris removal retained or forgone	Fig. 3a, Table 1	—
Screening efficiency	Fraction of intact-object crossings screened, compared with the efficiency required at the chosen altitude	Fig. 3c, Table 2	Covariance realism and missed-detection statistics for the screened objects
Avoidance cost	Manoeuvres per year, Δv , propellant, thrust and power for the whole structure and the modules, against the position uncertainty of the screened orbits	Fig. 3b, Supplementary Note 5	Operational concept for manoeuvring a kilometre-scale structure; dedicated tracking
Dense elements	Probability and consequence of a compute-module breakup, with and without avoidance	Fig. 4	Breakup model for modules of tens to hundreds of tonnes
Areal density and orientation of crossed surfaces	Slowdown of intact objects by each surface; ejecta chain between opposite planes	Table 2, Supplementary Note 7	Impact tests on array and radiator assemblies
Damage to the structure itself	Tearing of membranes beyond the hole, failure of trusses struck by large objects, fragments released by the structure	Supplementary Note 8	Structural response to decimetre and larger impacts
Active satellites and end of life	Coordination with operators whose satellites cross the shell; disposal of about 8,900 t of structure per gigawatt	Discussion	Shared ephemerides and manoeuvre rules; disposal concept

Two measurements would settle most of what the model leaves open: how much mass an intact object sheds into orbit when it crosses a thin sheet at orbital speed, and how many lethal fragments that mass makes. The

first decides whether a structure without avoidance pollutes; the second, together with the first, sets the screening efficiency an avoiding structure needs. In the frame of the object, the sheet is a thin flyer striking its wall at 13–14 km/s. In a light-gas gun, wall sections of upper stages and satellites could be fired through stationary, tensioned sheets of 0.5–3 kg/m², with fragments collected in low-density foam and tracer materials distinguishing wall from sheet. This would measure the yield of lethal fragments per square metre of cross-section crossed; a ballistic pendulum or flash X-ray imaging of the debris cloud would show how the sheet’s momentum divides [31]. Light-gas guns reach 7–8 km/s, below the 13–14 km/s of orbital crossings, so validated hydrocode simulations would be needed to extrapolate. The only recorded impact on a solar array in orbit with a known effect, an object of about 1 cm that struck an array of Sentinel-1A in a dawn–dusk orbit near 700 km, measured its effect on the satellite but not on the impactor [42]. The experiments need to resolve stripped fractions from about a tenth of a per cent to a few tens of per cent. Tests of centimetre debris fragments crossing such sheets would test the slowdown on which the removal rests.

The model has limitations whose direction of bias is known (Supplementary Note 8). It balances each shell on its own and holds sources at today’s level. Mixing the shell fully overstates both the removal and the harm, which fall by about a sixth and by two-fifths to three-fifths respectively when only objects that reach the structure’s altitude band are struck, without changing the direction of any result (Supplementary Note 6). Intact objects that cross a thin array without being destroyed are mostly moved below the shell rather than removed: 78–97% of them keep perigees above 180 km and cross the shells beneath on every orbit until drag lowers their apogee, so a structure without avoidance harms lower altitudes as well as its own shell; with avoidance few intact objects cross. Fragments made by the structure are treated as catalogued at once, which favours the designs that screen every catalogued object and the avoidance by the modules. Fluxes come from MASTER rather than NASA’s ORDEM, whose fluxes of small debris differ [43]. Pieces of the structure itself, such as severed trusses, are not counted; they would lower s^* and raise the required screening efficiencies. Product counts are calibrated for steady production and overstate products where production falls steeply, which affects chiefly complete breakup without avoidance (Methods; Supplementary Note 6). Besides switching off the momentum exchange, two modelling variants raise the population with avoidance and complete breakup above today’s at some altitudes: steady-state product weights (which overstate long-lived eccentric products) at 550 and 1,000 km, and unrescaled catalogue area-to-mass ratios at 1,000 km, where it reaches 1.1 times today’s (Supplementary Note 6). The multiples describe the shell after 15 years of operation: the removal ends when the structure stops operating while the fragments it has made remain, and a structure that fails without disposal would itself become a target that cannot avoid anything. Coupling the source terms derived here to a whole-orbit evolutionary model is the next step.

Within these limits, whether an orbital data centre sweeps or pollutes low Earth orbit is a design choice. It can be made before such structures are built, once two quantities have been measured (the mass that a crossing strips from an intact object and the fragments it makes), and checked once the first kilometre-scale structure shows the screening efficiency it can reach.

Methods

Shell, populations and sources

Each altitude h_0 (550, 650, 850 and 1,000 km) is represented by a spherical shell 100 km thick, centred on h_0 . Four populations are followed: intact objects I (rocket bodies and defunct satellites), trackable debris fragments D , new trackable fragments R produced by impacts on the structure, and lethal untrackable objects

L , whose number is the lethal population of the shell. An object is trackable if its characteristic length is at least 10 cm, and lethal untrackable if it is smaller than 10 cm and has a mass of at least m_L . The main threshold, $m_L = 1.47$ g, is the mass of a 1 cm object in MASTER's size–density relation; an alternative of 0.108 g, close to the impactor mass at which impacts begin to end satellite missions [44], is reported in the Supplementary Information (Supplementary Note 2). Initial populations follow from MASTER-8.2.3 fluxes [36] (population reference epoch February 2026) on circular dawn–dusk Sun-synchronous targets: the number in the shell is the flux times the shell volume divided by the mean impact speed, and the trackable population is split between I and D by the composition of non-operational, near-circular catalogued objects in the shell [45]. Each population g has a constant source $S_g = N_g(0)/\tau_g$ that holds today's population in steady state, where τ_g is its residence time in the shell; R has no external source. Populations and residence times are listed in Supplementary Table 3.

Structure and impact rates

Per gigawatt, the structure carries 3.2 km² of solar array with an areal density of 0.5 kg/m² and 1.6 km² of radiator with 3 kg/m², following the 4 km by 4 km, 5 GW array of the Starcloud white paper and taking its statement that radiators are smaller than half of the array as an upper value [1]. Compute modules number 25 per gigawatt with a mass of 100 t each and a total cross-section of 750–2,500 m² per gigawatt. The fraction of a population that strikes surface j per gigawatt per year is $k_j = \bar{v}A_j\eta_j/V$, where A_j is the one-sided area of the surface, V the shell volume, $\bar{v}$ the mean impact speed and η_j the ratio of the flux through both faces of the oriented surface to that on a sphere of equal cross-section, computed with MASTER-8 (0.41–0.50 for a Sun-pointing array). Radiators face radially or along the flight direction (along-track radiators). Every impact is evaluated at five equally weighted impact speeds spanning the 10th to 90th percentiles of the MASTER distribution, whose median is 13.5–13.6 km/s.

Momentum exchange and product orbits

An object of mass m that punches through a sheet of areal density σ at incidence angle Θ removes a disc of mass $m_d = \sigma\pi D_h^2/(4\cos\Theta)$, where the hole diameter D_h is $\lambda_h d$ for debris fragments and lethal objects of diameter d (λ_h from 1 to 2) and, for intact objects, the diameter d of a circle with the object's cross-section. Each impact is averaged over the flux-weighted distribution of incidence on a plate, $p(\cos\Theta) = 2\cos\Theta$, with a six-point Gauss–Legendre quadrature; a variant uses instead a single effective incidence per surface for which the sheet mass crossed is σ/η_j (Supplementary Note 6). Impactor and disc share momentum, so the centre of mass moves with

$$\mathbf{v}_{cm} = \mathbf{v}_o + f(\mathbf{v}_s - \mathbf{v}_o), \quad f = \frac{Q}{1+Q}, \quad Q = \frac{m_d}{m},$$

where $\mathbf{v}_o$ and $\mathbf{v}_s$ are the velocities of the object and the structure, both circular at the impact radius with speed v_c and meeting at a horizontal angle ϕ set by the relative speed. The new velocity is horizontal, with speed $|\mathbf{v}_{cm}| = v_c [1 - 2f(1-f)(1 - \cos\phi)]^{1/2}$. Fragments and flakes move with $\mathbf{v}_{cm}$ plus an isotropic expansion velocity $\mathbf{u}$ (100–1,500 m/s for fragmenting projectiles and crater ejecta, 50–500 m/s for material stripped from intact objects and for module breakups) sampled over 48 directions, while remnants move with $\mathbf{v}_{cm}$; the perigee and apogee of each direction follow from the full velocity vector at the impact radius by conservation of energy and angular momentum.

The time a product spends in the shell, $T_{in}(h_p, h_a; B)$ for perigee and apogee altitudes h_p and h_a and ballistic coefficient B , is obtained by integrating the orbit-averaged effect of drag on semi-major axis and eccentricity and accumulating the time spent inside the shell until the perigee falls below 180 km or the apogee below the shell (Supplementary Note 4). The density profile reproduces circular decay times computed with NRLMSIS 2.0 [46] with global-mean densities under a solar cycle $F_{10.7} = 120 + 50\sin(2\pi t/11 \text{ yr} + \psi_0)$, averaged over eight phases ψ_0 . Because the number of objects in a shell is a spatial density times the shell volume, a product counts, right after it is made, as the fraction f_0 of its new orbit spent in the shell, and keeps that count for a duration T_{in}/f_0 . Products enter compartments of the population they join, binned by this duration from 0.1 to 30,000 years, each decaying at the inverse of its representative time, so that one that has left the shell no longer counts; bins of 1–300 years are chains of three compartments, whose survival is closer to a fixed duration than a single exponential. Drag lowers the apogee of an eccentric product towards the shell, so the fraction of its orbit spent there grows with time, and a count held at f_0 would understate products with durations of 10–30 years by up to half. Each product’s count is therefore scaled so that the object-years it contributes within 15 years equal those of the drag integration. For products made at a constant rate this reproduces the integration; if production falls about eightfold over the 15 years, as for intact objects destroyed by complete breakup without avoidance, it overstates products with durations of 3–30 years by up to about 50% and understates some by up to 20% (Supplementary Note 4). Products whose perigee falls below 180 km receive no weight. The impactor is removed from its population, and its remnant, if any, is re-added in the same way with its new orbit.

Fragmentation and stripping

For debris fragments and lethal objects, the ratio of areal densities $Q_a = \sigma(A/m)/\cos\Theta$, with A the cross-section, decides whether the impactor breaks up; the threshold and the size of the largest remnant follow Piekutowski’s tests [30], and the remaining mass is distributed with the standard model’s mass–size relation [32] (Supplementary Note 3). These relations were obtained for bumpers thicker, relative to the projectile, than a 0.5 kg/m² array, and their use here is an extrapolation whose uncertainty enters through the sampled threshold and remnant exponent. The disc breaks into flakes with area-to-mass ratio $1/(2\sigma)$. Area-to-mass ratios of trackable debris come from catalogue ballistic coefficients rescaled so that rocket bodies in the same shell match intact-object values of 0.003–0.012 m²/kg (Supplementary Note 1). Lethal objects present today and those created by the structure share one scaling of the area-to-mass ratio, from that of compact aluminium spheres to the standard-model median, which sets their residence time and their momentum exchange.

No data exist for a thin sheet striking a rocket body or a satellite. A crossing strips a fraction s of the object’s mass, defined for normal incidence on a 0.5 kg/m² sheet and scaled with the sheet mass actually crossed (radiators and oblique incidence), capped at 1. The stripped mass breaks up like a standard-model breakup of that mass, $N(> L_c) = 0.1 (sm)^{0.75} L_c^{-1.71}$ with sm in kilograms and the characteristic length L_c in metres, capped by mass conservation [32], and the remaining fraction $1 - s$ stays in the intact population, counted from its new orbit as above; $s = 1$ is the catastrophic breakup of the object. The intact population is counted in objects, so a crossing removes s of an object from it; an object that keeps most of its mass would in fact remain a target, so for intermediate s this understates later crossings. Because the exponent is below one, repeated small strips produce more fragments in total than one complete breakup of the same mass; a variant shares the complete-breakup yield in proportion to s instead (Supplementary Note 6). How the sheet’s momentum divides is unknown, so two cases are computed: shared with the whole object, so that stripped material and remainder move together with $\mathbf{v}_{cm}$ (default), or given to the stripped material alone,

$Q = m_d/(sm)$, so that the remainder keeps its orbit; the second applies only while the stripped mass is at least the disc mass, because below that the object as a whole must push the disc out. Because s has not been measured, it is both sampled log-uniformly from 10^{-4} to 1 and scanned over 0, 0.01%, 0.03%, 0.1%, 1%, 3%, 10%, 30% and 100%.

Compute modules and satellite bodies

An impact on a dense element of mass M_e (a 100 t module, or a satellite body in the fleet) is catastrophic if its specific energy $\frac{1}{2}mv^2/M_e$ is at least 40 J/g [32,44]; the element then breaks up according to the standard model with mass $M_e + m$. Below this threshold the impact excavates crater ejecta of 10–100 times the impactor mass. Products are counted as above. Breakups enter the population balance at their expected rate, so the lethal population of a design with modules is an expectation over event histories; the results also give three further quantities: the probability of at least one event in 15 years, treating events as a Poisson process whose expected number is the event rate integrated over the heavy populations along the event-free trajectory; the lethal population if no event occurs; and the population added by one event.

Population dynamics and avoidance

For installed power G the populations evolve as $d\mathbf{N}/dt = \mathbf{S} + \mathbf{A}(G)\mathbf{N}$, where $\mathbf{A}$ contains the losses of each compartment, the loss of impactors and the products of every surface scaled by $k_j G$; the system is integrated for 15 years. Avoidance multiplies the rate at which a population reaches a surface by $(1 - \epsilon c)$, with screening efficiency ϵ and catalogue completeness c . Intact objects and every object able to destroy a compute module (tens of kilograms or more) are taken as catalogued ($c = 1$); smaller trackable debris has c of 0.50–0.95, bracketed by the ratio of catalogued objects to the MASTER population in each shell (Supplementary Note 1). When the structure and the modules both screen an object, the screenings use the same catalogue orbit and fail together, so the larger efficiency applies rather than their product. Fragments made by the structure are treated as catalogued at once. The designs (Table 1) differ in radiator orientation, in whether they carry compute modules and in avoidance: none; the whole structure screening intact objects only; the whole structure screening every catalogued object; and, with modules, the structure screening intact objects and the modules every catalogued object. The default efficiency is 0.99, with 0.90, 0.95, 0.97, 0.98, 0.995 and 0.999 as variants. The fleet has 4,400 satellites per gigawatt, each of 1–3 t with a body cross-section of 5–20 m², avoiding catalogued objects; it spreads the 88,000 satellites of the Starcloud application [2] over 20 GW, an assumption of this paper.

The cost of avoidance is estimated for conjunction-screening thresholds of 10^{-4} and 10^{-5} [2,47] (Supplementary Note 5). A Sun-pointing array in a dawn–dusk orbit lies close to its own orbital plane, so an object strikes it if the point where it crosses that plane lies within the array, a square of side 4 km at 5 GW. Objects meet the structure at a horizontal angle ϕ of 128–134°, set by the median impact speed: an error in an object’s position along its own track moves the crossing point along track one to one, an error across its track by $\tan(\phi/2) = 2.0$ –2.4, and a radial error radially. The structure manoeuvres when the predicted crossing point lies within κ standard deviations of the array, with $\kappa = 3.7$ or 4.3 the number of standard deviations at which a one-sided Gaussian tail equals the threshold. Isotropic position uncertainties σ_p of 100 m to 3 km are considered. Each manoeuvre is a tangential burn made one orbit before the conjunction, which moves the structure, and with it the array within its plane, along track until the crossing point is clear, and an equal burn after it that stops the drift, $\Delta v \approx \Delta x n/(6\pi)$ per burn with n the mean motion. Compute modules are compact, so their miss has to be made in the plane normal to the relative velocity, which an along-track

displacement reaches only as $\Delta x \cos(\phi/2)$. Propellant follows for a structural mass of 8,900 t per gigawatt (1,600 t of array, 4,800 t of radiator and 2,500 t of modules) and a specific impulse of 2,000 s, together with the thrust needed to deliver the largest burn within a quarter of an orbit and the electric power of thrusters with an efficiency of 0.6. Radiators facing radially account for 0.1–1.2% of the intact-object crossings and are not screened by this rule.

Monte Carlo and sensitivity cases

Twenty-three parameters describing fragmentation and flake lethality, area-to-mass ratios and masses, the scale from radar cross-section to area, catalogue completeness, module cross-section, crater ejecta, expansion speeds, the stripped fraction and the fleet are sampled independently by simple random sampling (Supplementary Table 1); the same 1,000 draws (seed 7) are used for all altitudes, thresholds and designs. The threshold s^* is the stripped fraction at which the median lethal population after 15 years at 20 GW equals today's, interpolated linearly in logs and the logarithm of the population, with $s = 0$ placed at 3×10^{-5} . Results are reported as medians and, where the sign of the effect is in question, as the share of draws in which a population exceeds today's; 5th–95th percentiles are given in the Supplementary Tables. Parameters are ranked by Spearman correlation with the logarithm of the lethal population. Modelling choices that the Monte Carlo cannot sample are tested on the first 150 draws (Supplementary Note 6; Supplementary Tables 10 and 11). They cover the mechanism (no momentum exchange), incidence (normal, or from the MASTER oriented-surface factors), area-to-mass ratios (without rescaling, or from the standard model) and the in-shell time (an effective-altitude approximation). Others change product counting (without calibration, with one or six compartments per bin, with steady-state weights, or with the residence time of the population joined), the stripping yield (linear in s), the screening efficiency, the array areal density (1–3 kg/m²) and the module mass (30 t). Two further variants change the fragment yield and radial mixing. In the first, every breakup makes 3.5 times the lethal fragments of the standard model, the excess found in tests on a modern satellite [33], alone and with the screening efficiencies above. In the second, only the share of today's objects whose perigee and apogee bracket the altitude band of the structures ($h_0 \pm 2$ km or ± 25 km), taken from the catalogue, can be struck, at a correspondingly higher rate, while the rest stays at today's number.

Use of generative AI

Claude (Anthropic; Claude Opus and Claude Sonnet models, 2026) was used to write and check code, to suggest and test modelling approaches, to retrieve and check literature and to draft and edit text from the author's analyses. The author directed the work, decided on the model and its assumptions, formulated and approved every scientific claim, checked the bibliographic record of every reference and, where the original document was accessible, the content cited from it, checked every number in the text against the model outputs, and takes full responsibility for the content. Figures were plotted from the model outputs by scripts; no image-generation tool was used.

Data availability

The derived input tables and all model outputs are available at Zenodo under a CC BY 4.0 licence [48]. Debris fluxes were generated with ESA's MASTER-8 software [36], available to registered users of ESA's Space Debris User Portal, and catalogue data were obtained from Space-Track.org [45], which requires an account. Raw MASTER outputs and catalogue records are not redistributed; the checksums of the catalogue files are provided, and the derived tables can be regenerated with the scripts provided.

Code availability

The code that reproduces every result and figure, including the shell model, the avoidance cost model and the sensitivity cases, is available in the same Zenodo record under the MIT licence [48].

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Author contributions

J.J. conceived the study, developed the model and code with the assistance described in Methods, performed the analysis and wrote the manuscript.

Competing interests

The author declares no competing interests.

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Supplementary Information

The Supplementary Notes and Tables below are cited in the main text by number; their citations use the reference list above.

Supplementary Note 1. Catalogue composition, area-to-mass calibration and completeness

The trackable population in each shell is split into intact objects and debris using the public catalogue (Space-Track.org general perturbations data of October 2026) [45]. Near-circular objects (eccentricity ≤ 0.02) whose semi-major axis lies within the 100 km shell are selected, active satellites are removed by cross-matching with a public list of active satellites, and the remainder is grouped by object type (rocket body, payload, debris, unknown) and radar cross-section class (small, medium, large). Rocket bodies and defunct satellites form the intact population I; debris and objects of unknown type form the trackable debris population D. The intact share of the trackable population is 0.30, 0.18, 0.10 and 0.38 at 550, 650, 850 and 1,000 km.

Area-to-mass ratios for debris come from the catalogue's ballistic coefficient. With B^* the drag term of the general perturbations element set, the ballistic coefficient is $B = 12.741621 B^*$ (m^2/kg times drag coefficient), and the area-to-mass ratio follows by dividing by a drag coefficient of 2.2. Ratios obtained this way are systematically low at the altitudes considered: the median rocket body in each shell yields 0.0003–0.001 m^2/kg , a factor of 3–40 below the 0.003–0.012 m^2/kg expected for upper stages. All ratios in a shell are therefore rescaled by the factor that brings the median rocket body to the sampled intact-object value. After this calibration, the median area-to-mass ratio of trackable debris is 0.035–0.079 m^2/kg for an intact-object value of 0.006 m^2/kg (0.018–0.16 m^2/kg over the sampled range), consistent with the median of the NASA standard breakup model for fragments of 10–40 cm [32]. Without calibration, most debris would appear compact, would not fragment on the thin surfaces and would lose much less speed in crossing them. The effect of the calibration on the results is tested in Supplementary Note 6.

Each catalogued object is assigned a physical area by radar cross-section class (0.03, 0.3 and 3 m^2 for small, medium and large) times a scale factor varied from 0.5 to 2 (Supplementary Table 1). Debris mass follows from area and calibrated area-to-mass ratio. Intact-object masses are sampled within 3–30 kg, 30–300 kg and 300–9,000 kg for the three classes.

Catalogue completeness for debris too small to destroy a compute module is bracketed by comparing the number of near-circular, non-operational catalogued objects in each shell with the population of non-maneuvrable objects of 10 cm or larger in the same shell in MASTER-8 (ESA's Meteoroid and Space Debris Terrestrial Environment Reference model): 0.51 at 550 km, 0.90 at 650 km, 0.92 at 850 km and 0.63 at 1,000 km. These ratios are lower bounds, because catalogued objects on eccentric orbits that cross the shell are not counted, and completeness is sampled from 0.50 to 0.95. Intact objects and all objects massive enough to destroy a module (tens of kilograms or more) are taken as catalogued.

Supplementary Note 2. Lethality thresholds and population definitions

Trackability is defined by size (characteristic length or flake side of at least 10 cm), consistent with the population of non-maneuvrable objects of 10 cm or larger in MASTER-8 that sets the initial trackable population. Lethality is defined by mass, because the damage done by an impactor depends on its mass and

velocity rather than its shape. The main threshold, 1.47 g, is the mass of a 1 cm object in MASTER's diameter–density relation (density 2,800 kg/m³ below 1.62 cm); MASTER's population of objects of 1 cm and larger therefore defines the initial lethal population consistently. The alternative threshold, 0.108 g, is the mass of an object with a characteristic length of 1 cm in the standard breakup model and is close to the impactor mass of about 100 mg at which impacts on satellite components have been found to end missions [44]. Using one consistent mass threshold for products and for the initial population avoids an inconsistency of about a factor of 13 between size-based definitions in the two models.

Lethal objects present today and those created by the structure share one area-to-mass ratio. It is sampled between that of a compact aluminium sphere of 1.5 cm (0.036 m²/kg) and the median of the standard breakup model over the lethal size range, weighted by the model's size distribution, and it sets both their residence time and their momentum exchange with a sheet. The first end corresponds to compact objects, the second to fragments.

Supplementary Note 3. Fragmentation on thin surfaces

Whether a debris fragment or a lethal object that crosses a thin surface breaks up, and into what, is set by the ratio of areal densities, and the disc it punches out breaks into flakes (Methods). Intact objects follow a separate treatment. The parameters below are sampled as listed in Supplementary Table 1.

Fragmentation threshold. For an impactor of mass m and cross-section A crossing a sheet of areal density σ at incidence angle Θ , the decisive quantity is the ratio of areal densities $Q_a = \sigma_\Theta (A/m)$, where $\sigma_\Theta = \sigma/\cos\Theta$ is the sheet mass crossed per unit of the impactor's cross-section. The impactor breaks up if

$$Q_a \geq Q_{th} = q_{th} \cdot 1.5 \left(\frac{1.436}{v} \right)^3,$$

with v the impact speed in km/s and q_{th} a scale factor sampled log-uniformly from 0.5 to 2. The form follows the onset of projectile fragmentation in Piekutowski's tests [30]. At the median impact speed of 13.6 km/s the threshold is about 0.0018 for $q_{th} = 1$. Trackable debris fragments with the calibrated median area-to-mass ratios of Supplementary Note 1 have Q_a of about 0.02–0.04 on a 0.5 kg/m² array at normal incidence, and a compact aluminium sphere of 1.5 cm about 0.018, so typical fragments and lethal objects break up. An impactor below the threshold does not fragment; it continues with the centre-of-mass velocity of impactor and disc and returns to its own population, counted as described in Supplementary Note 4.

Largest remnant. Above the threshold, the largest remnant has diameter $f_1 d$, with d the impactor diameter and

$$f_1 = 0.037 Q_a^{-q} \left(\frac{v}{6.7} \right)^{-2.24\nu},$$

clipped to the interval 0.07–1. The exponent q is sampled from 0.6 to 1.1. The velocity factor applies above 6.7 km/s only, and its exponent ν , sampled from 0 to 1, spans the range from a remnant size that no longer depends on speed to one that keeps decreasing with it. The remnant has mass $f_1^3 m$. A remnant of 10 cm or larger stays in a trackable population, a smaller one with a mass of at least m_L joins the lethal population L , and lighter remnants are not followed.

Size distribution of the other fragments. The rest of the impactor mass, $(1 - f_1^3) m$, is distributed over characteristic lengths x between x_{min} and $x_{max} = \min(f_1/2, c_x) d$, with a cumulative number

$N(> x) \propto x^{-b}$. The slope b is sampled from 1.7 to 3.2, the largest-fragment fraction c_x from 0.05 to 0.3 and x_{min} from 10^{-6} to 10^{-4} m. Each length is converted to a mass with the mass–size relation of the standard breakup model [32], and the distribution is normalised so that the fragment masses add up to the mass distributed. Fragments of 10 cm or larger join the new trackable population R ; smaller fragments with a mass of at least m_L join L . All fragments move with the centre-of-mass velocity plus an isotropic expansion speed of 100–1,500 m/s and are counted by their time in the shell (Supplementary Note 4).

Hole and flakes. The hole has diameter $D_h = \lambda_h d$, with λ_h sampled from 1 to 2, and the punched-out disc has mass $m_d = \sigma_\Theta \pi D_h^2 / 4$ (Methods). The disc breaks into square flakes of the sheet’s thickness, with sides ℓ between $10 x_{min}$ and $c_f D_h$ and a cumulative number $N(> \ell) \propto \ell^{-b_f}$; c_f is sampled from 0.1 to 0.5 and b_f from 1.7 to 3.2. A flake of side ℓ has mass $\sigma \ell^2$ and area-to-mass ratio $1/(2\sigma)$, which sets its residence time and its time in the shell. Flakes with sides of 10 cm or more join R . Smaller flakes with a mass of at least m_L join L with a lethality efficiency ζ of 0.3–1, which allows for a thin flake being less damaging than a compact object of the same mass. On a 0.5 kg/m² array a flake reaches the main lethal mass of 1.47 g at a side of about 5.4 cm and the alternative of 0.108 g at about 1.5 cm. Under the lower threshold many more flakes therefore count as lethal, which weakens the net removal without stripping to 0.52–0.95 times today’s population, against 0.26–0.84 at 1.47 g (Supplementary Table 6).

Intact objects. The relations above are not applied to rocket bodies and defunct satellites, for which no data on thin-sheet impacts exist. Their whole cross-section, m times the intact-object area-to-mass ratio, passes through the sheet, and the disc removed breaks into flakes as above with largest side $c_f d$. A crossing strips a fraction s of the object’s mass, scaled by $\sigma_\Theta / (0.5 \text{ kg/m}^2)$ and capped at 1. The stripped mass breaks up according to the standard model, $N(> L_c) = 0.1 (sm)^{0.75} L_c^{-1.71}$, capped by mass conservation [32], and expands at 50–500 m/s about the centre of mass. Because the exponent 0.75 is below one, $1/s$ crossings that each strip a fraction s produce $s^{-0.25}$ times as many fragments as one complete breakup of the same mass; a variant that shares the complete-breakup yield in proportion to s is given in Supplementary Note 6.

Validity. The threshold and remnant relations were obtained on bumpers that are thicker, relative to the projectile, than a 0.5 kg/m² array is relative to a decimetre fragment, so their use here is an extrapolation. It enters the uncertainty through q_{th} , q and ν . Of these, the remnant exponent q is among the five parameters most correlated with the lethal population in most of the monolithic designs, with Spearman coefficients of -0.11 to -0.38 , and ν in one case (Supplementary Table 9). Numerical simulations of spheres of about 1 cm crossing the micrometre membranes of solar power satellites find little damage to the projectile [10], so fragmentation on the thinnest surfaces may be weaker than assumed. Impact tests on a flexible amorphous-silicon array 0.25 mm thick produced holes about as large as the projectile, which broke into pieces smaller than 1 mm after crossing [49]. This supports the lower end of the sampled hole diameter, $\lambda_h = 1$, and suggests that the median of 1.5 overstates the disc mass, and with it the momentum exchange, somewhat. A projectile that does not fragment still shares momentum with the disc and is slowed in the same way, and the removal comes from that slowdown rather than from breakup below the lethal mass (Supplementary Note 6), so weaker fragmentation would change it less than the disc mass does.

Supplementary Note 4. Momentum exchange, product orbits and the counting of products

When an object crosses a thin sheet, the material it removes from the sheet is accelerated to roughly the object’s velocity, and momentum conservation fixes the velocity of the common centre of mass (Methods). At incidence angle Θ the object crosses $1/\cos\Theta$ times the sheet mass per unit of its own cross-section;

impacts are averaged over the flux-weighted distribution $p(\cos\Theta) = 2\cos\Theta$ on a plate struck by an isotropic flux with a six-point Gauss–Legendre quadrature, which gives the exact mean of $1/\cos\Theta$, 2. For trackable debris fragments the ratio Q of crossed sheet mass to impactor mass at normal incidence is 0.003–0.46, the centre of mass loses hundreds of metres per second, and the new orbit would reach a median of 2,200–3,700 km below the crossing altitude, that is, it would intersect the atmosphere; for 90–100% of the fragments the new perigee lies below 200 km. A lethal object of 1 cm, an aluminium sphere of 1.47 g, loses 1,120–1,190 m/s. These crossing statistics (Fig. 1 of the main text) are evaluated on a 0.5 kg/m² array at the median hole diameter of 1.5 d (1 d for intact objects) and the median impact speed, averaged over incidence angles. For intact objects $Q = 0.0015$ –0.006 at normal incidence on a 0.5 kg/m² array (area-to-mass ratios of 0.003–0.012 m²/kg), the slowdown averaged over incidence angles is 36–145 m/s and the perigee falls by 130–530 km. On a 3 kg/m² along-track radiator the same objects lose 210–770 m/s and their perigee falls by 690–2,300 km (data file `crossing_dv.csv`, columns `*_3kg`).

Each product leaves the impact point with the centre-of-mass velocity plus an expansion velocity $\mathbf{u}$, sampled over 48 directions. For each direction the perigee and apogee follow from the full velocity vector $\mathbf{v}$ at the impact radius r : the specific energy $|\mathbf{v}|^2/2 - \mu/r$ gives the semi-major axis a , the specific angular momentum $|\mathbf{r} \times \mathbf{v}|$ gives the eccentricity e , and the perigee and apogee radii are $a(1 \mp e)$. Unbound products and products whose perigee lies below 180 km are not counted.

Sheet material ejected backwards from the impact carries momentum opposite to the impactor’s motion and therefore reduces the slowdown of the forward cloud. The centre-of-mass slowdown computed here is accordingly an upper bound on the slowdown of what continues forward. For thin sheets struck by compact projectiles the backward ejecta are a small fraction of the crossed sheet mass, and the reduction is correspondingly small; the sensitivity case without momentum exchange, which removes the slowdown entirely, bounds its effect (Supplementary Note 6).

How the sheet’s momentum divides between the material stripped from an intact object and the remainder is unknown, and two cases are computed. In the default case the stripped material and the remainder move together with the centre of mass of object and disc. In the alternative the disc shares its momentum with the stripped material alone, with $Q = m_d/(sm)$, so that the stripped material is slowed strongly while the remainder keeps its orbit. The alternative applies only while the stripped mass is at least the disc mass; below that the object as a whole must push the disc out, and the default case is used. Both masses scale with the sheet mass crossed, so the condition is the same on every surface and at every incidence: $s \geq (0.5 \text{ kg/m}^2)(A/m)$, and the two cases coincide for stripped fractions below 0.15–0.6% (area-to-mass ratios of 0.003–0.012 m²/kg). The alternative raises the threshold s^* , because more of the stripped mass leaves the shell (Supplementary Table 6). The two cases do not bound the true division: wall material splashed back from the facing wall would be accelerated in the opposite sense and stay in orbit longer than in either case (Supplementary Note 8).

In-shell time. The time a product spends in the shell, $T_{in}(h_p, h_a; B)$, is obtained by integrating the orbit-averaged decay of semi-major axis a and eccentricity e under a tangential drag acceleration $-\rho Bv^2/2$,

$$\frac{da}{dt} = -\left\langle \frac{a^2 \rho B v^3}{\mu} \right\rangle, \quad \frac{de}{dt} = -\langle \rho B v (e + \cos\vartheta) \rangle,$$

with μ the gravitational parameter of the Earth, ϑ the true anomaly and $\langle \cdot \rangle$ the average over the mean anomaly (128 eccentric-anomaly nodes), and accumulating the exact fraction of each orbit spent inside the

shell until the perigee falls below 180 km or the apogee falls below the shell. Each step limits the change of perigee and apogee radius to 1 km plus 2% of their distance from the shell. The density profile $\rho(h) = 1/(B\sqrt{\pi a} \, dt_d/dh)$ is inferred from the circular decay times $t_d(h, B)$ to 180 km of the residence table (NRLMSIS 2.0 under a solar cycle, Methods), so that circular orbits reproduce the table; where t_d exceeds 1,000 years the profile for $B = 0.33 \text{ m}^2/\text{kg}$ is used, and above 2,000 km $\log \rho$ is extrapolated linearly. For a fixed profile all times scale as $1/B$, so $T_{in}(h_p, h_a; B)/T_{in}(h_0, h_0; B)$ depends on B only through the profile; it is tabulated at six values of B per altitude and interpolated in $\log B$, perigee offset and apogee offset. A product with ballistic coefficient B_p then has in-shell time $T = [T_{in}(h_p, h_a; B_p)/T_{in}(h_0, h_0; B_p)] \tau(B_p)$, where $\tau(B_p)$ is the tabulated residence time of a circular object with B_p ; flakes of sheet have $B_p = 2.2/(2\sigma)$, other products the ballistic coefficient of the population they join. The circular in-shell times of the integration are 0.61–1.20 times the tabulated residence times, because the static profile cannot reproduce the phase average of the solar cycle for objects whose decay time is comparable to the cycle; only the ratio of in-shell times is therefore taken from the integration (data file `inshell_weight_check.csv`).

Counting of products. The number of objects of a population in the shell is a spatial density times the shell volume, so a product counts, right after it is made, as f_0 , the fraction of its new orbit spent inside the shell, rather than as one object. Each population has, besides the compartment of today's objects (decay rate $1/\tau_g$), 13 product bins with representative times T_b about a factor of 3 apart from 0.1 to 30,000 years. A product is shared between the two bins whose T_b bracket its duration $T_f = T/f_0$. Bins with T_b of 1–300 years hold their count in a chain of three compartments, each emptying at $3/T_b$, so that the count survives for about T_b and then falls, closer to a product that leaves the shell after a fixed time than a single compartment emptying at $1/T_b$; shorter and longer bins are single compartments, because their products either leave within a few years or barely decay within 15 years. Every compartment of a population is struck like the population itself, and its products are counted in turn. Remnants that return to their own population, including the remainder $1 - s$ of a stripped intact object, are counted from their new orbits in the same way. The lethal population added by a compute-module breakup is the sum of f_0 over the lethal fragments of the event; Supplementary Table 5 and Fig. 4b of the main text give the shell's lethal population immediately after the event, one plus this increment relative to today.

A count held at f_0 misses one effect. Drag lowers the apogee of an eccentric product faster than its perigee, so an orbit that reaches high above the shell is drawn towards it and the fraction of the orbit spent in the shell grows with time. Each product's count is therefore calibrated: the drag integration records the in-shell time accumulated within the first 15 years, $q_{15}T$, and the product's bin weights are scaled so that the object-years it contributes within 15 years equal $q_{15}T$. The table is interpolated in $\log q_{15}$; against direct integration of 960 random products at the four shells (`q15_check.py`), the interpolated value lies within 0.79–1.21 of the integrated one in 99% of cases, with a median of 1.00.

The counting was checked against the drag integration for 180 products typical of stripped material and flakes, at shell centres of 550, 650, 850 and 1,000 km, with perigees 10–70 km below the shell centre, apogees 100–1,650 km above it and ballistic coefficients of 0.033, 0.11 and 1.1 m^2/kg (`counting_check.py`). The quantity compared is the population at year 15 of products made from year 0 at a rate $p(t)$, $\int_0^{15} p(15 - t') \chi(t') dt'$, with $\chi(t')$ the in-shell fraction at age t' . For constant production the calibrated counting reproduces the integration exactly. Without calibration, the counting gives 0.96–1.00 of it for durations below 3 years, 0.71–0.95 for 3–10 years, 0.47–0.70 for 10–30 years, 0.60–0.93 for 30–100 years and 0.88–1.00 above. When production falls with an e-folding time of 7 years, a factor of 8.5 over the

15 years, as for intact objects destroyed by complete breakup at 20 GW without avoidance, the calibrated counting gives 1.03–1.31, 1.22–1.49, 0.81–1.47, 0.85–1.01 and 0.98–1.01 of the integration in the same ranges of duration, and the uncalibrated counting 1.03–1.47, 0.90–1.54, 0.37–1.05, 0.49–0.90 and 0.84–1.00. The calibrated counting is therefore exact where production is steady, which holds for small stripped fractions and with avoidance, where few intact objects are lost, and tends to overstate products of durations of 3–30 years where production falls steeply, chiefly for complete breakup without avoidance. One or six compartments per bin instead of three change these ranges by up to 0.2 (Supplementary Note 6).

The steady-state weighting, computed as a variant, adds each product to its population with weight T/τ_g and lets it decay with that population. It gives the same object-years but distributes them differently in time. It understates short-lived products made in the last years before the 15-year horizon, which it spreads over τ_g , and it counts a long-lived eccentric product, whose apogee lies above the shell, with its full weight T/τ_g from the start, which overstates it by up to an order of magnitude when f_0 is small. When intact objects are stripped strongly, long-lived eccentric products dominate, and the steady weights give 1.7–2.4 times the lethal population of the calibrated counts for complete breakup (Supplementary Note 6).

A simpler approximation takes the in-shell time as the decay time of a circular orbit at an effective altitude $h_{eff} = h_p + (h_a - h_p)/4$ multiplied by the in-shell fraction of the orbit. Compared with the integration, it understates the in-shell time of products thrown 300 km above the shell centre by a factor of 3.6–5.7 and overstates that of products whose perigee falls 30–100 km below it by a factor of 1.1–1.9. Because fragments stripped from intact objects are thrown both ways, the approximation understates the lethal population for complete breakup by a factor of 1.8–2.3 (Supplementary Note 6).

Products that leave the shell downwards pass through lower shells before re-entering. With an expansion speed of 300 m/s about the centre of mass, 1–8% of the products of trackable debris fragments have perigees between 250 km and the bottom of the shell and stay in orbit for months or longer; the others re-enter within days to weeks. Intact objects that cross a 0.5 kg/m² array, or what remains of them, lose 36–145 m/s: averaged over their area-to-mass ratios of 0.003–0.012 m²/kg and the incidence angles, 3–22% of them have a new perigee below 180 km and re-enter, and 78–97% a perigee between 180 km and the bottom of the shell, from which they cross the shells below on every orbit until drag lowers their apogee (`crossing_fate.py`). Along-track radiators of 3 kg/m² send 75–100% of them into re-entry. This hazard in lower shells, from fragments and from slowed intact objects, is not included in the shell multiples reported in the main text; with avoidance few intact objects cross and it is correspondingly small.

Supplementary Note 5. Cost of avoidance

The cost of avoidance (main text, Fig. 3b) follows from a screening rule, the size of each manoeuvre and the mass to be moved; Supplementary Table 7 gives the full results. All figures refer to a 5 GW monolith, with propellant expressed per gigawatt per year.

Screening rule. The position error of a screened object is taken as an isotropic Gaussian with standard deviation σ_p , from 100 m, typical of special-perturbations orbits, to 3 km, typical of public two-line elements of poorly tracked objects. A manoeuvre is made whenever the predicted collision probability exceeds a screening threshold P_{thr} of 10^{-4} or 10^{-5} [2,47]. Objects meet the structure on near-circular orbits at its altitude, at a horizontal angle $\phi = 2\arcsin(v_{rel}/2v_c)$, which is 128–134° for the median impact speeds of

13.5–13.6 km/s; their velocity relative to the structure makes an angle of $90^\circ - \phi/2$ with its along-track direction.

Whole structure. A Sun-pointing array in a dawn–dusk Sun-synchronous orbit lies close to its own orbital plane, so an object strikes it if the point where it crosses that plane lies within the array, a square of side $L_a = 4$ km at 5 GW spanning the along-track and radial directions. An error δ in the object's position along its own track moves the crossing point along track by δ ; an error across its track moves it along track by $\delta \tan(\phi/2)$, 2.0–2.4 times as much; a radial error moves it radially. With isotropic errors the crossing point therefore has standard deviations $\sigma_x = \sigma_p \sqrt{1 + \tan^2(\phi/2)}$ along track and $\sigma_z = \sigma_p$ radially. A manoeuvre is made when the predicted crossing point lies within the box $|x| < a_x = L_a/2 + \kappa \sigma_x$, $|z| < a_z = L_a/2 + \kappa \sigma_z$, where $\kappa = 3.7$ or 4.3 is the number of standard deviations at which the one-sided tail of a Gaussian equals 10^{-4} or 10^{-5} . The number of manoeuvres per year is the flux of screened objects through the array plane over this box, $F \eta_{arr} 4a_x a_z$, with η_{arr} the MASTER flux factor of the array (both faces). Moving the structure along its track moves the array within its plane, so a predicted crossing point at x is cleared by a displacement $a_x - |x|$: $a_x/2$ on average, which sets the propellant, and a_x at most, which sets the thrust and power. Radiators facing radially lie parallel to the local horizontal and are crossed only by objects with a vertical velocity component; they account for 0.1–1.2% of the intact-object crossings and are not screened by this rule; the screening efficiencies of the main text refer to all intact-object crossings, including these, so radial radiators must be screened as well where the efficiency required exceeds what the array rule alone achieves. The rule of a disc about the structure's centre, with radius $R_e + \kappa \sigma_p$, $R_e = 3.5$ km the half-diagonal of a square holding every surface, and a displacement equal to that radius, is listed in Supplementary Table 7 for comparison; it costs several times more at position uncertainties of hundreds of metres and about as much at 3 km.

Compute modules. A target of cross-section A_t that is small compared with σ_p has a collision probability $P_c(r) \approx A_t/(2\pi\sigma_p^2) \exp(-r^2/2\sigma_p^2)$ at miss distance r in the encounter plane, normal to the relative velocity. A manoeuvre is therefore needed for miss distances below r_{thr} , with

$$r_{thr}^2 = 2\sigma_p^2 \ln \frac{A_t}{2\pi\sigma_p^2 P_{thr}},$$

and the fraction of collisions that screening removes is $\varepsilon = 1 - 2\pi\sigma_p^2 P_{thr}/A_t$; if $A_t < 2\pi\sigma_p^2 P_{thr}$, no conjunction reaches the threshold and $\varepsilon = 0$. Modules of 30–250 m² each, a wider range than the 30–100 m² of the population model so as to bound the cost, and position uncertainties of 50–200 m are considered, with the 25 modules of each gigawatt either dispersed, as 25 separate targets, or clustered, as one target per gigawatt with 25 times the module cross-section. Encounters follow from the MASTER flux Φ_{10} of non-manoeuverable objects of 10 cm or larger, an upper bound for the objects able to destroy a module, which are all catalogued (Supplementary Note 1). The number of manoeuvres per year is $\Phi_{10} \pi r_{thr}^2$ per target. An along-track displacement Δx moves a compact target by $\Delta x \cos(\phi/2)$ in the encounter plane, so a miss of r_{thr} plus the size of the target, $\sqrt{A_t}$, needs $\Delta x = (r_{thr} + \sqrt{A_t})/\cos(\phi/2)$, 2.3–2.6 times the miss.

Manoeuvre size. A tangential burn Δv on a circular orbit with mean motion n raises the semi-major axis by $2\Delta v/n$ and lengthens the period, so after one orbit the structure lags its unperturbed position by

$$\Delta x \approx \frac{6\pi \Delta v}{n}, \quad \Delta v \approx \frac{\Delta x n}{6\pi}.$$

The burn is made one orbit before the conjunction, which leaves 96–105 minutes of drift at 550–1,000 km. A second burn of the same size after the conjunction stops the drift, so each manoeuvre costs $2\Delta v$. Because the modules are attached to the structure, the whole structure moves in both cases.

Propellant, thrust and power. The structure has a mass of 8,900 t per gigawatt: 1,600 t of array (3.2 km² at 0.5 kg/m²), 4,800 t of radiator (1.6 km² at 3 kg/m²) and 2,500 t of compute modules (25 of 100 t), or 44,500 t for 5 GW. With a specific impulse I_{sp} of 2,000 s, the propellant per gigawatt per year is this mass times the number of manoeuvres per year of the 5 GW structure and $2\Delta v/(g_0 I_{sp})$. The thrust needed to deliver the largest burn within a quarter of an orbit is $F_T = M\Delta v/(P_{orb}/4)$, with M the mass of the 5 GW structure and P_{orb} the orbital period. The electric power of thrusters with an efficiency η_t of 0.6 is $P = F_T g_0 I_{sp}/(2\eta_t)$.

Limits of the estimate. The array is taken as flat and lying in the orbital plane; a tilt out of that plane, or radiators and modules extending across track, would enlarge the region to be cleared. Delivering a burn over a quarter of an orbit with low thrust costs about 10% more Δv than an impulsive burn. Conjunctions are treated one at a time, without combining manoeuvres or allowing for late updates of the orbit. The figures are therefore order-of-magnitude estimates.

Avoiding intact objects. A 5 GW structure is crossed by about 10–23 intact objects per year without avoidance. With position uncertainties of 100–300 m, screening requires 17–98 manoeuvres per year of 0.16–0.29 m/s each, 1.2–12 t of propellant per gigawatt per year, a thrust of 4–9 kN and an electric power of 70–145 MW, 1.4–2.9% of the structure’s output. With 1 km the propellant rises to 42–143 t per gigawatt per year and the power to 280–350 MW. With 3 km it reaches 670–2,460 t per gigawatt per year, 8–28% of the structural mass every year, with a thrust of 46–57 kN and a power of 740–920 MW, 15–18% of the output. The cost is highest at 1,000 km, where intact objects make up the largest share of the trackable population (Supplementary Note 1). The disc rule gives 13–54 t per gigawatt per year at 100–300 m and 716–2,220 t at 3 km.

Selective and non-selective avoidance. Avoiding every catalogued object, as conjunction screening for a spacecraft would, multiplies the number of encounters to be screened by the inverse of the intact share of the trackable population: 3.4 at 550 km, 5.7 at 650 km, 10.5 at 850 km and 2.6 at 1,000 km. The screening box and the size of each manoeuvre are unchanged, so the number of manoeuvres and the propellant grow by the same factors, 2.6–10, largest at 850 km, where debris fragments are most numerous relative to intact objects. The structure is then crossed by 53–103 catalogued objects per year without avoidance, and position uncertainties of 100–300 m require 90–430 manoeuvres per year and 7–55 t of propellant per gigawatt per year. At 3 km the propellant reaches 3,400–10,600 t per gigawatt per year, 39–119% of the structural mass every year, and exceeds that mass at 850 km. In the population model the two choices give nearly the same lethal population: 0.41–1.18 times today’s for complete breakup when only intact objects are avoided and 0.40–1.12 when every catalogued object is, and 0.18–0.82 against 0.17–0.80 without stripping (Supplementary Table 6). They differ in the trackable population. Without stripping it falls to 0.30–0.77 of today’s with selective avoidance, but only to 0.68–0.92 when every catalogued object is avoided, because the debris fragments that the structure would otherwise remove are then avoided as well (main text, Fig. 3a); for complete breakup it is 0.51–1.6 and 1.1–2.8 times today’s in the two cases (data file `strip_scan.csv`, column `trk_20GW`).

Module avoidance. Clustered modules screening every object able to destroy them need 3–154 manoeuvres per year of 5–24 cm/s each and at most 16 t of propellant per gigawatt per year (13 t for the 30–100 m²

modules of the population model), with a thrust below 3.6 kN and a power below 60 MW. Dispersed modules need 37–2,270 manoeuvres per year and up to 170 t per gigawatt per year, because each of the 25 modules per gigawatt is screened separately. The residual collision probability implies screening efficiencies of 0.97 to above 0.9999 for the clustered layout at position uncertainties of 50–200 m. The efficiency falls steeply as the uncertainty grows, because a target small compared with σ_p rarely reaches the threshold. For clustered modules with the 750–2,500 m² per gigawatt of the population model, ϵ is 0.97–0.99 at 200 m and $P_{thr} = 10^{-4}$, but only 0.16–0.75 at 1 km, or 0.92–0.97 at 1 km with $P_{thr} = 10^{-5}$. For dispersed modules of 30–100 m², ϵ is already 0.16–0.75 at 200 m and 10^{-4} ; at 1 km no conjunction reaches 10^{-4} , and ϵ is at most 0.37 at 10^{-5} . The module-breakup probability of about 1% within 15 years with module avoidance (main text) therefore requires orbits known to about 100–200 m for every object able to destroy a module, of about 45 kg or more, and not only for the intact objects screened by the whole structure.

Supplementary Note 6. Robustness to modelling choices

The Monte Carlo analysis samples 23 parameters, but several modelling choices cannot be sampled and are tested instead as 32 variants, each changing one choice of the base case or, for the combinations of fragment yield and screening efficiency, two. Each variant is run on the first 150 of the 1,000 draws and compared with the base case for the same draws (Supplementary Tables 10 and 11). In these draws the base case gives a lethal population after 15 years at 20 GW of 0.25–0.84 times today's for a structure of thin surfaces without stripping, 2.7–13 for complete breakup of intact objects, and 0.40–1.1 for complete breakup with the whole structure avoiding intact objects at an efficiency of 0.99. Unless stated otherwise, the figures below are medians over the 150 draws and ranges over the four altitudes, and a factor relative to the base case is the ratio of the two medians.

Mechanism of removal. Without momentum exchange the impactor and the disc keep the impactor's orbit, and the structure acts only by breaking objects into pieces. Without stripping the lethal population is then 1.0–1.5 times today's (1.30, 1.14, 1.05 and 1.50 at 550, 650, 850 and 1,000 km, against 0.84, 0.61, 0.31 and 0.25 with it), and exceeds today's in 53–71% of the draws. Breaking lethal objects into pieces below the lethal mass therefore does not by itself remove debris: the breakup of trackable fragments and the flakes of the sheet add lethal objects that, without the slowdown, stay in the shell. The removal comes from the slowdown of the centre of mass. For complete breakup of intact objects the lethal population rises to 5.2–23 times today's, 1.7–1.9 times the base case, because stripped material is no longer slowed.

Incidence angle. Restricting every impact to normal incidence leaves the result without stripping unchanged and raises the result for complete breakup by 15–24%, to 3.1–15, and with whole-structure avoidance to 0.43–1.2. The base case uses the incidence distribution of an isotropic flux on a plate for every surface, for which the mean of $1/\cos\Theta$ is exactly 2.0. Taking instead one effective incidence per surface from the MASTER oriented-surface factors, $1/\cos\Theta = 1/\eta_j$ capped at 10 (about 2.0–2.5 for the arrays, about 1.2 for along-track radiators and the cap for radial radiators, which are struck at grazing incidence), also leaves the result without stripping unchanged. For complete breakup it gives 2.4–11 times today's, 0.86–0.95 times the base case, and with avoidance 0.38–1.1; for a stripped fraction of 1% it gives 0.53–1.6 against 0.57–1.8. Neither choice changes the direction of any result.

Area-to-mass ratio of debris. Using the catalogue's ballistic coefficients without the rescaling of Supplementary Note 1 raises the result without stripping at 850 and 1,000 km, to 0.40 and 0.49 against 0.31 and 0.25, and the result for complete breakup by up to 17%; with whole-structure avoidance complete

breakup then gives 1.1 times today's at 1,000 km. The median of the standard breakup model changes the lethal population by at most 9% at the four stripped fractions tested, and lowers the share of draws in which the population exceeds today's without stripping from 20% to 5% at 550 km.

Counting of products. The base case counts each product by the fraction of its orbit spent in the shell, calibrated to the object-years of the drag integration within 15 years (Supplementary Note 4). Holding the count at the initial fraction f_0 without calibration gives 0.21–0.83 times today's without stripping and 1.8–8.0 for complete breakup, 0.5–0.8 times the base case, and with whole-structure avoidance 0.37–1.0; the expected lethal population of the monolith whose modules do not avoid catalogued objects then exceeds today's only at 550 km. One or six compartments per bin instead of three change the result by less than 5%. The steady product weights of Supplementary Note 4 raise the result without stripping slightly, to 0.21–0.86, and the share of draws above today's to 9–30%. For complete breakup they give 6.5–27 times today's, 1.7–2.4 times the base case, and with whole-structure avoidance 0.58–1.5, so that the avoiding structure would exceed today's population at 550 and 1,000 km and equal it at 650 km. The lethal population after one module breakup becomes 7–55 times today's in object-year equivalents, against 2.3–8.6 times for the fragments placed in the shell (Supplementary Table 11). The steady weights count long-lived eccentric products in full from the moment they are made, and the uncalibrated counts only with the share of their initial orbit spent in the shell; the drag integration lies between the two.

In-shell time. Replacing the orbit-averaged drag integration with the decay time of a circular orbit at the effective altitude $h_{eff} = h_p + (h_a - h_p)/4$ (Supplementary Note 4) leaves the result without stripping almost unchanged, 0.22–0.83. For complete breakup it gives 1.4–7.1 times today's, a factor of 1.8–2.3 below the integration, and with avoidance 0.35–0.98. The approximation understates the in-shell time of fragments thrown above the shell centre more than it overstates that of fragments thrown below it, and would hide part of the growth that stripping causes.

Residence time of products. Counting every product with the residence time of the population it joins, instead of its own, raises the result without stripping to 0.39–0.90, most at 1,000 km (0.58 against 0.25). Flakes of sheet have area-to-mass ratios of the order of 1 m²/kg and decay faster than the lethal objects they join, so this choice overweights them. For complete breakup the change is at most 6%.

Momentum of stripped material. Giving the sheet's momentum to the stripped material alone is the second case of the main analysis (main text, Fig. 2; Supplementary Table 6). In the 150 draws, a stripped fraction of 1% gives 0.19–0.82 times today's in this case against 0.57–1.8 in the default, and a stripped fraction of 10% 1.1–6.2 against 1.5–7.1. The two cases coincide without stripping, for complete breakup and, because the alternative needs the stripped mass to be at least the disc mass, for stripped fractions below 0.15–0.6% (Supplementary Note 4).

Stripping yield. Sharing the complete-breakup yield in proportion to the stripped fraction, $N(> L_c) = s \cdot 0.1 m^{0.75} L_c^{-1.71}$, instead of a standard-model breakup of the stripped mass, lowers the lethal population for partial stripping: 0.41–1.0 times today's against 0.57–1.8 for $s = 1\%$, and 1.1–4.8 against 1.5–7.1 for $s = 10\%$. Interpolated between the four stripped fractions tested, the threshold s^* rises to 0.39%, 2.3%, 8.0% and 1.3% at 550, 650, 850 and 1,000 km, two to twenty times the base case on the same grid, most at 550 km. Without stripping and for complete breakup the two coincide.

Fragment yield. Hypervelocity tests on a modern satellite collected more than 295,000 fragments of 2 mm and larger, about 3.5 times the 85,000 that the standard breakup model predicts [33]. In this variant every

standard-model breakup, of stripped material, of compute modules and of satellite bodies, makes 3.5 times as many lethal untrackable fragments, capped by the mass available. Without stripping nothing changes. For complete breakup the lethal population rises to 8.8–44 times today's, 3.2–3.4 times the base case, and for a stripped fraction of 1% to 1.2–5.5 against 0.57–1.8. On the grid of the four stripped fractions, s^* falls to 0.007%, 0.04%, 0.5% and 0.04% at 550, 650, 850 and 1,000 km, three to twenty-seven times below the base case on the same grid. With the whole structure avoiding intact objects at an efficiency of 0.99, complete breakup gives 1.9, 1.2, 0.67 and 2.0 times today's, so that the avoiding structure is a net source at every altitude except 850 km; a stripped fraction of 10% gives 0.39–1.1 and exceeds today's only at 550 km. The efficiencies at which the median returns to today's population under this yield are given below. In the monolith with modules, the probability of a module breakup is unchanged, but one breakup raises the lethal population to 5.6–28 times today's instead of 2.3–8.6 times (Supplementary Table 11), and without avoidance the expected lethal population without stripping is 1.2–3.8 times today's against 0.59–1.5.

Screening efficiency. The main results use a screening efficiency of 0.99. For complete breakup with whole-structure avoidance of intact objects and the standard fragment yield, the median lethal population is 1.2–4.7 times today's at an efficiency of 0.90, 0.79–2.7 at 0.95, 0.61–1.7 at 0.97, 0.51–1.5 at 0.98, 0.40–1.1 at 0.99, 0.36–0.97 at 0.995 and 0.25–0.85 at 0.999; the share of draws above today's falls from 61–100% at 0.90 to 1–71% at 0.99 and 0–21% at 0.999. With the fragment yield multiplied by 3.5 it is 3.2–15 at 0.90, 0.67–2.0 at 0.99 and 0.33–0.92 at 0.999. Interpolating linearly in $\log(1 - \varepsilon)$ and the logarithm of the population, the median equals today's population at efficiencies of 0.994 at 550 km, 0.977 at 650 km, 0.926 at 850 km and 0.985 at 1,000 km with the standard yield, and 0.999, 0.994, 0.981 and 0.996 with the higher yield (main text, Table 2 and Fig. 3c). For a stripped fraction of 10% the required efficiencies are 0.976 at 550 km and 0.94 at 1,000 km, and 0.90 or less at 650 and 850 km, with the standard yield, and 0.994, 0.973, 0.919 and 0.984 with the higher yield. For the monolith with both layers of avoidance, the structure screening intact objects and the modules screening every catalogued object, the probability of at least one module breakup within 15 years is 2.9–6.6% at 0.95 and 0.06–0.14% at 0.999, against 0.60–1.4% in the base case (Supplementary Table 11). The benefit of avoidance thus depends, to first order, on the efficiency achieved, and the efficiency required differs by altitude and by fragment yield.

Areal density of the array. Raising the array from 0.5 kg/m² to 1, 2 and 3 kg/m² slows intact objects more and removes more of what is stripped from them. For complete breakup without avoidance, the lethal population falls from 2.7–13 times today's to 2.1–9.8, 1.2–6.1 and 0.82–3.9, a reduction by a factor of 3.1–4.0 at 3 kg/m². At 3 kg/m² the median falls below today's only at 850 km, where 36% of the draws still exceed it. With avoidance, complete breakup gives 0.37–1.0, 0.33–0.93 and 0.30–0.87. Without stripping the denser arrays remove slightly less, 0.29–0.87 over the three areal densities against 0.25–0.84, with the largest change at 1,000 km. The array mass per gigawatt rises from 1,600 t to 3,200–9,600 t.

Module mass. Compute modules of 30 t instead of 100 t, at the same mass per gigawatt and with the total cross-section scaled for modules of equal density, are broken up more often but with smaller consequences. Without avoidance the probability of at least one breakup within 15 years rises from 32–65% to 54–84%, and the lethal population immediately after one breakup falls from 2.3–8.6 to 1.5–4.1 times today's. With both layers of avoidance the probability is 1.1–2.3% against 0.60–1.4% (Supplementary Table 11). Designs without modules are unaffected.

Radial mixing. The base case takes the shell as fully mixed: every member of a population meets the structure at the shell-mean rate. The opposite end is a shell without radial mixing, in which only today's

objects whose perigee and apogee bracket the altitude band occupied by the structures can be struck, at a correspondingly higher rate, while the rest stays at today's number; products, made at the structure, are struck at the shell-mean rate. For a band of ± 2 km about the shell centre, the accessible share in the catalogue is 0.39–0.68 for intact objects and 0.51–0.77 for debris fragments, which is also applied to lethal objects; for ± 25 km it is 0.70–0.97 and 0.84–0.95 (data file `radial_access.csv`). With ± 2 km, the result without stripping is 0.86, 0.68, 0.42 and 0.37 times today's at 550, 650, 850 and 1,000 km, so that the removal at 650–1,000 km falls by about a sixth, and complete breakup gives 1.6–8.0 times today's, 0.43–0.62 times the base case, because only the accessible intact objects can be struck and they are depleted. With whole-structure avoidance complete breakup gives 0.52–1.2, below today's at 650–1,000 km and above it at 550 km, as in the base case. Without avoidance the probability of a module breakup falls to 18–55%, and with both layers of avoidance it is 0.58–1.4%. With ± 25 km the results without stripping and with avoidance change by at most 16%, and complete breakup without avoidance falls by up to 29%. Real orbits lie between full mixing and no mixing, and neither end changes the direction of any result.

Other choices compared with the sampled spread. Apart from switching off the momentum exchange, counting products with the residence time of the population they join, using catalogue area-to-mass ratios without rescaling and restricting crossings to objects within ± 2 km of the structures' altitude, no variant moves the median without stripping by more than 0.06 times today's population, which is small compared with the spread over draws; at 1,000 km, for example, the 5th–95th percentile range over the 1,000 draws is 0.14–1.1 (Supplementary Table 6). The variants that matter act through the fragments shed by intact objects: the fragment yield, the counting of products, the stripping yield, the division of momentum, the screening efficiency and the areal density of the crossed surfaces. Of these, only the higher fragment yield, the steady product weights and screening efficiencies below the required values turn the avoiding structure into a net source at 650 or 1,000 km; switching off the momentum exchange does so as well, and unrescaled area-to-mass ratios bring it to about today's population at 1,000 km.

Installed power of 5 GW. At 5 GW, the scale of the Starcloud white paper [1], the removal is weaker because fewer objects cross the smaller structure within the same 15 years. Without stripping the median lethal population after 15 years is 0.68–0.96 times today's and exceeds it in 6–31% of the draws, against 0.26–0.84 and 1–22% at 20 GW; for complete breakup it is 4.6–21 times today's (1,000 draws; data file `strip_scan.csv`, column `L_5GW`).

Spread of the threshold over draws. The threshold s^* of the main text is taken from the median curve over draws, interpolated linearly in logs and the logarithm of the lethal population between the nine scanned values, with $s = 0$ placed at 3×10^{-5} (Methods). Interpolating the population itself linearly gives slightly lower thresholds, 0.12%, 1.0%, 3.2% and 0.18% at 550, 650, 850 and 1,000 km, against 0.13%, 1.0%, 3.3% and 0.24%. Computing it separately for each draw, as the stripped fraction at which that draw's lethal population equals today's, gives medians of 0.13%, 1.0%, 3.3% and 0.25%, nearly the same as the thresholds of the median curve. The 5th percentiles are zero at 550 and 1,000 km, where 22% and 7% of the draws exceed today's population already without stripping, and 0.04% and 0.15% at 650 and 850 km. The 95th percentiles are 1.3%, 9.3% and 2.8% at 550, 650 and 1,000 km, while at 850 km 5% of the draws stay below today's even for complete breakup. Across draws and the two momentum cases, the threshold thus ranges from zero to about ten per cent, and to tens of per cent at 850 km.

Supplementary Note 7. Millimetre-scale ejecta chain between opposite dawn–dusk planes

Dawn–dusk Sun-synchronous orbits come in two planes, with local times of the ascending node near 06:00 and 18:00, inclined to each other by about 164° . Structures in the two planes at the same altitude meet at relative velocities of about 15 km/s. Ejecta from impacts on brittle surfaces such as glass cover sheets and optical solar reflectors leave the parent structure slowly, stay close to its orbit and strike their parent at low relative velocity, but can strike structures in the opposite plane at full speed and produce more ejecta of similar size. This feedback forms a chain between the two planes.

The chain is represented by a generation matrix over 24 size bins from 10 μm to 3 mm. An impact of a particle of diameter d_p ejects 45 times the projectile mass at 6.8 km/s, scaled with impact velocity to the power 2.266 and limited by the film mass within a disc 6–13 projectile diameters across centred on the impact point. Ninety per cent of the ejected mass leaves as 10–20 equal spall fragments of the film thickness and 10% as a cone of smaller particles with a power-law size distribution. Impacts arrive at zenith angles of $67\text{--}89^\circ$ on Sun-pointing arrays, so the generation matrix is averaged over this range under two laws for the angular dependence: the ejected mass scaled by the square of the cosine of the zenith angle, as in MASTER, or by the normal velocity component. The probability that an ejected particle strikes the opposite plane before it decays is the encounter rate between two circular orbits multiplied by the particle's residence time near the shell altitude, using area-to-mass ratios for spall flakes and compact particles. With installed power split equally between the two planes, the chain becomes self-sustaining at a total power of $2/\Lambda_1$, where Λ_1 is the spectral radius of the generation matrix per gigawatt.

The chain is self-sustaining above 4.7–51 GW at 850 km and 1.5–16 GW at 1,000 km, with medians of 15–18 and 4.8–5.7 GW for the two angular laws, which differ by about 20% (Supplementary Table 8). At 550 and 650 km, ejecta decay quickly enough that a chain would need tens to hundreds of gigawatts. Glass along-track radiators, which see impacts close to normal incidence, would make the chain self-sustaining at 2–4 GW at 850 km and about 1 GW at 1,000 km (Supplementary Table 8). The chain does not arise if all structures at an altitude share one dawn–dusk plane or if radiators face radially. These conditions are inexpensive to meet at the design stage, and the chain rests on ejecta laws calibrated for thick targets, so it is a secondary hazard.

Supplementary Note 8. Modelling choices and their direction of bias

- **Fixed sources.** Each population has a constant source equal to today's steady-state loss rate, so the multiples describe the change attributable to the structure against today's environment, not a forecast of the environment.
- **Radial and orbital mixing.** Products are assumed to spread through the 100 km shell, and every member of a population meets the structure at the shell-mean rate. In the catalogue, only 39–68% of intact objects and 51–77% of debris fragments have perigees and apogees that bracket a band of ± 2 km about the shell centre. If only these can be struck, the removal without stripping at 650–1,000 km falls by about a sixth and the lethal population for complete breakup by two-fifths to three-fifths, without changing the direction of any result (Supplementary Note 6); full mixing thus overstates both the removal and the harm. Encounter rates also depend on inclination and local time of the ascending node, so when the structure clears a large share of a population (39–74% of the lethal population at 650–1,000 km without stripping) mixing overstates the removal of debris that rarely meets the

structure. Fragments also remain concentrated near their parent's orbit for weeks to months, which raises the local hazard to the structure and to neighbours in the same plane.

- **Hazard moved to lower shells.** Crossings lower the perigee of intact objects by 130–530 km on a 0.5 kg/m² array, and 78–97% of them keep a perigee above 180 km (Supplementary Note 4). These objects stay in orbit at lower altitudes, where they are not followed, so the decrease of the intact population in the shell partly reflects a transfer of collision risk to lower shells rather than removal. The same holds for the 1–8% of the products of debris fragments that remain in orbit below the shell (Supplementary Note 4). Both add to the hazard below the structure, for a structure at 850 or 1,000 km including the heavily used shells near 550 km.
- **Operating period.** The multiples describe the shell after 15 years of operation. When the structure stops operating its removal ends, while the fragments it has made remain for their residence times, and a structure that fails without disposal becomes a target that cannot avoid anything, as in the designs without avoidance, for as long as it stays in orbit. The 15-year multiples therefore overstate the lasting benefit of an avoiding structure.
- **Supercritical draws.** With the stripped fraction sampled, the structure without avoidance makes the population matrix supercritical at 20 GW or less in 12% of the draws at 850 and 1,000 km and 2% at 650 km, with critical powers as low as about 1.0 and 0.42 GW at 850 and 1,000 km (Supplementary Table 4). In these draws the lethal population keeps growing after the 15 years reported. With the whole structure avoiding intact objects no draw is supercritical below about 40 GW.
- **Composition of small objects.** MASTER's population of objects of 1 cm and larger includes sodium–potassium droplets and multilayer-insulation fragments, which may fall below the 1.47 g lethal mass. Their removal by the structure is counted as removal of lethal objects.
- **Stripped fraction and its momentum.** The mass lost by an intact object per crossing is unknown and is treated as a parameter from 0 to 1, with the stripped mass breaking up like a standard-model breakup of that mass. Melting or vaporisation of wall material, or containment of fragments inside the object, would make the standard model overestimate the lethal fragments; a more extensive breakup of a damaged object on later crossings would lower the threshold s^* . The two momentum cases computed (Supplementary Note 4) are scenarios, not bounds. In a third case, material splashed back from the wall facing the sheet is driven away from the sheet, which in the Earth frame adds to its velocity relative to the structure: it gains speed, raises its apogee and stays in orbit longer than in either case computed. If a significant share of the stripped mass leaves this way, s^* would be lower than in both.
- **Centre-of-mass slowdown.** The slowdown is computed from momentum sharing with the punched-out disc and is an upper bound on that of the forward cloud (Supplementary Note 4); a hole smaller than assumed, as impact tests on flexible arrays suggest [49], would decrease it.
- **Fragmentation relations.** The fragmentation threshold and remnant size come from tests on bumpers thicker, relative to the projectile, than a 0.5 kg/m² array; numerical simulations of spheres of about 1 cm crossing micrometre membranes find little damage to the projectile [10] (Supplementary Note 3). Projectiles that do not fragment still share momentum with the disc and are slowed in the same way, which is where the removal comes from: without momentum exchange the lethal population without stripping would be 1.0–1.5 times today's (Supplementary Note 6).
- **Incidence angle.** Every surface is struck with the incidence distribution of an isotropic flux on a plate, independent of its orientation, for which the mean of $1/\cos\Theta$ is 2.0. The MASTER oriented-surface factors imply 2.0–2.5 for the arrays and grazing impacts on radial radiators; the variant that uses them lowers the lethal population for complete breakup by 5–14% and leaves the result without stripping unchanged, and normal incidence raises it by 15–24% (Supplementary Note 6).

- **Counting of products.** Products are counted by the fraction of their orbit spent in the shell, calibrated so that each contributes the object-years of the drag integration within 15 years. This is exact for steady production. Where production falls steeply, as for complete breakup without avoidance, it overstates products whose duration in the shell is 3–30 years by up to about 50% (Supplementary Note 4); counting products at their initial fraction without calibration, which understates them, is given as a variant (Supplementary Note 6).
- **New fragments are catalogued at once.** Fragments made by the structure are treated as catalogued for avoidance as soon as they are produced. In practice cataloguing a new fragment takes weeks, during which fragments stay close to the orbit of their parent and may meet the structure again near the same node. This favours the avoidance of every catalogued object and the module avoidance; intact objects, which the whole structure screens selectively, remain catalogued after a crossing.
- **Screening efficiency.** Screening efficiency is fixed at 0.99 in the main results, and layered screenings are not multiplied because they share catalogue orbits. Results for 0.90–0.999, with the standard and a higher fragment yield, are given in Supplementary Note 6 and Supplementary Tables 10 and 11. The efficiency achievable for the modules depends steeply on the position uncertainty of the screened orbits (Supplementary Note 5).
- **Avoidance geometry.** The array is taken as flat and lying in the structure’s orbital plane, so that an along-track manoeuvre moves it within that plane; a tilt out of that plane, or parts extending across track, would enlarge the region to be cleared. Radiators facing radially, which account for 0.1–1.2% of the intact-object crossings, are not screened by this rule. Screening against a disc about the structure’s centre, as for a compact spacecraft, gives several times the propellant at position uncertainties of hundreds of metres and is listed for comparison (Supplementary Note 5).
- **Breakup and flux models.** Breakups follow the NASA standard breakup model, derived from tests on spacecraft of earlier decades; tests on a modern satellite are being used to revise it [50] and produced about 3.5 times the fragments of 2 mm and larger that the model predicts [33]. With the lethal fragments of every breakup multiplied by 3.5, complete breakup gives 3.2–3.4 times the lethal population of the standard model, s^* falls three- to twenty-sevenfold and the screening efficiency required for complete breakup rises to 0.981–0.999 (Supplementary Note 6); the standard model is therefore the optimistic choice. Fluxes come from MASTER-8; NASA’s ORDEM, used in US regulatory filings, gives different fluxes of small debris [43].
- **Structural failure.** The model removes discs of sheet at each crossing but does not follow tearing of the membrane beyond the hole, the failure of a main truss struck by an intact object, or the release of larger pieces of the structure itself; numerical simulations of debris striking solar-array substrates indicate that the array itself can release lethal fragments [51]. Each would add fragments not counted here.
- **Active satellites.** Active satellites are not part of the populations crossing the structure. At 650–1,000 km they add little to the large objects that would strike it, but at 550 km a 5 GW structure would be struck by 369–666 objects of 1 m or larger per year, almost all of them active satellites, against about 16 non-operational ones (Supplementary Table 2). If 99% of these encounters were avoided, by the structure or by the satellites, about 3.5–6.5 crossings by active satellites would remain each year, a quarter to a half of the 16 crossings by intact objects without avoidance and more than an order of magnitude above the 0.16 that remain with selective avoidance at an efficiency of 0.99. Each would be an additional intact-object crossing, so the results at 550 km, already the least favourable, are optimistic unless the structure’s operator and the satellite operators coordinate their manoeuvres.

- **Module and fleet design.** Module mass (100 t), number (25 per GW) and cross-section are illustrative values informed by the Starcloud white paper [1]; a case with 30 t modules is given in Supplementary Note 6 and Supplementary Table 11. Satellite count, mass and cross-section in the fleet comparison are assumptions of this paper for a constellation of 88,000 satellites delivering about 20 GW.

Supplementary Tables

Supplementary Table 1. Monte Carlo parameters. The same 1,000 draws (seed 7, simple random sampling) are used for all altitudes, thresholds and designs.

Parameter	Distribution	Range	Meaning
slope	uniform	1.7–3.2	Slope b of the size distribution of projectile fragments, $N(>x) \propto x^{-b}$
flake_slope	uniform	1.7–3.2	Slope of the size distribution of sheet flakes
cap	uniform	0.05–0.3	Largest projectile fragment as a fraction of projectile diameter
vexp	uniform	0–1	Exponent v of the velocity scaling of the remnant size above 6.7 km/s
qth	log-uniform	0.5–2	Scale factor q_th on the fragmentation threshold
q_exp	uniform	0.6–1.1	Exponent q of the remnant-size relation
hole	uniform	1–2	Hole diameter as a multiple of projectile diameter
flake_cap	uniform	0.1–0.5	Largest flake side as a fraction of hole diameter
phi	uniform	0.3–1	Lethality efficiency of flakes above the lethal mass
am_rb	log-uniform	0.003–0.012	Area-to-mass ratio of intact objects (m ² /kg)
xmin	log-uniform	10 ⁻⁶ –10 ⁻⁴	Smallest fragment characteristic length (m)
complete	uniform	0.5–0.95	Catalogue completeness for debris smaller than module-destroying objects
A_cont	log-uniform	750–2,500	Compute-module cross-section per GW (m ²)
ej_ratio	log-uniform	10–100	Crater ejecta mass as a multiple of impactor mass
racs_scale	log-uniform	0.5–2	Scale from catalogue radar cross-section class to area
u_mass	uniform	0–1	Position of intact-object mass within its size class (log scale)
strip	log-uniform	10 ⁻⁴ –1	Stripped fraction s: mass fraction stripped from an intact object per normal-incidence crossing of a 0.5 kg/m ² sheet
u_frag	log-uniform	100–1,500	Expansion speed of fragments from fragmenting debris (m/s)
u_int	log-uniform	50–500	Expansion speed of products stripped from intact objects (m/s)
u_cat	log-uniform	50–500	Expansion speed of products of a module or satellite breakup (m/s)
m_sat	log-uniform	1,000–3,000	Satellite mass in the fleet comparison (kg)
a_sat	log-uniform	5–20	Satellite body cross-section in the fleet comparison (m ²)
lfrag	uniform	0–1	Area-to-mass ratio of lethal objects, log-interpolated from a compact 1.5 cm sphere (0) to the SBM fragment median (1)

Supplementary Table 2. Exposure. Left: impacts per year on a 5 GW structure by objects larger than the stated size (all man-made objects; ranges span radial and along-track radiators). Right: catalogued debris fragments, intact objects and lethal untrackable objects (≥ 1.47 g) crossing 1 GW of array per year, and the share of the crossing mass carried by intact objects.

Altitude (km)	≥ 1 mm	≥ 1 cm	≥ 10 cm	≥ 1 m	Debris fragments	Intact objects	Lethal objects	Intact mass share
550	17,445–29,378	736–1,303	408–739	369–666	7.5	3.2	62	96%
650	28,136–50,352	960–1,768	71–137	12–23	10.1	2.2	162	97%
850	70,488–135,370	1,688–3,403	109–220	31–65	18.5	1.9	318	93%
1,000	77,387–153,706	1,063–2,009	61–120	31–65	7.3	4.5	182	98%

Supplementary Table 3. Shell populations today (medians over draws), residence times, the share of the trackable population crossing 1 GW of array per year, and the centre-of-mass slowdown of catalogued debris fragments and 1 cm lethal objects crossing the array at the median impact speed.

Altitude (km)	N_I	N_D	N_L (1.47 g)	τ_I (yr)	τ_D (yr)	τ_R (yr)	τ_L (yr)	Array crossing (% per GW per year)	Debris perigee drop, median (km)	Debris with perigee <200 km	Lethal-object slowdown (m/s)
550	30 0	709	5,884	9.62	2.76	1.11	1.45	1.06	2,240	100%	1120
650	24 6	1,14 6	18,260	38.8	4.43	3.7	4.56	0.88	3,693	100%	1147
850	25 1	2,39 0	41,073	349	45.5	19.6	27.2	0.77	3,127	93%	1195
1,000	59 1	961	24,112	966	165	57.3	77.9	0.76	2,464	90%	1163

Supplementary Table 4. Populations after 15 years relative to today for every design, with the stripped fraction s sampled log-uniformly from 10^{-4} to 1 (median, 5th–95th percentile). Because these distributions depend on the assumed range of s , the main text reports results against fixed s (Supplementary Table 6). $G^* \leq 20$ GW: share of draws whose critical scale, the smallest installed power at which the largest real eigenvalue of the population matrix becomes positive, is at most 20 GW.

Design	Lethal threshold	Altitude (km)	Intact, 20 GW	Debris, 20 GW	Trackable, 20 GW	Lethal, 5 GW	Lethal, 20 GW	$G^* \leq 20$ GW	G^* min (GW)
Monolith, thin surfaces, radial radiators	1.47 g	550	0.38	0.63	1.06 (0.57– 9.21)	1.66 (0.96– 14.3)	1.7 (0.78– 14.4)	0%	—
Monolith, thin surfaces, radial radiators	1.47 g	650	0.27	0.56	1.32 (0.56– 10.8)	1.24 (0.84– 8.36)	1.04 (0.54– 7.77)	2%	14.9
Monolith, thin surfaces, radial radiators	1.47 g	850	0.3	0.19	1.24 (0.27– 10.5)	1 (0.66–5.9)	0.69 (0.24– 5.77)	12%	1.01
Monolith, thin surfaces, radial radiators	1.47 g	1,000	0.36	0.15	5.59 (0.48– 58.7)	1.99 (0.68– 27.6)	2.16 (0.26– 30.4)	12%	0.42
Monolith, thin surfaces, along- track radiators	1.47 g	550	0.23	0.49	0.75 (0.4–5.27)	1.68 (0.91– 12.5)	1.31 (0.65– 8.23)	0%	—
Monolith, thin surfaces, along- track radiators	1.47 g	650	0.1	0.4	0.63 (0.35–3.3)	1.2 (0.72– 7.34)	0.62 (0.36– 2.41)	0%	—
Monolith, thin surfaces, along- track radiators	1.47 g	850	0.04	0.072	0.27 (0.083– 1.75)	0.81 (0.45– 4.71)	0.23 (0.092– 1.08)	0%	—
Monolith, thin surfaces, along- track radiators	1.47 g	1,000	0.047	0.032	1.21 (0.093– 10.6)	2.31 (0.5– 26)	0.66 (0.083– 6.17)	0%	—
Monolith, structure avoids intact objects	1.47 g	550	0.99	0.63	0.8 (0.69–1.06)	0.97 (0.9– 1.71)	0.87 (0.69– 1.94)	0%	—
Monolith, structure avoids intact objects	1.47 g	650	0.98	0.56	0.71 (0.58– 1.03)	0.88 (0.78– 1.15)	0.63 (0.47– 1.03)	0%	1,486
Monolith, structure avoids intact objects	1.47 g	850	0.99	0.19	0.33 (0.25– 0.58)	0.69 (0.62– 1.02)	0.3 (0.19– 0.62)	0%	101
Monolith, structure avoids intact objects	1.47 g	1,000	0.99	0.15	0.59 (0.48– 1.85)	0.66 (0.6– 1.17)	0.24 (0.15– 0.99)	0%	41.9
Monolith, structure avoids every catalogued object	1.47 g	550	0.99	0.87	0.96 (0.85– 1.33)	0.96 (0.9– 1.27)	0.85 (0.68– 1.39)	0%	—
Monolith, structure avoids every catalogued object	1.47 g	650	0.98	0.82	0.93 (0.79– 1.48)	0.86 (0.78– 0.99)	0.61 (0.46– 0.86)	0%	1,486
Monolith, structure avoids every catalogued object	1.47 g	850	0.99	0.59	0.75 (0.52–1.2)	0.68 (0.62– 0.81)	0.29 (0.18– 0.52)	0%	101
Monolith, structure avoids every catalogued object	1.47 g	1,000	0.99	0.57	0.94 (0.68– 3.25)	0.64 (0.59– 0.98)	0.23 (0.15– 0.91)	0%	41.9

Design	Lethal threshold	Altitude (km)	Intact, 20 GW	Debris, 20 GW	Trackable, 20 GW	Lethal, 5 GW	Lethal, 20 GW	G* ≤ 20 GW	G* min (GW)
Monolith with compute modules, no avoidance	1.47 g	550	0.38	0.63	1.58 (0.91–9.49)	2.35 (1.33–14.7)	2.63 (1.31–15.5)	0%	—
Monolith with compute modules, no avoidance	1.47 g	650	0.26	0.56	2.1 (0.94–11.5)	1.74 (1.09–8.65)	1.7 (0.83–8.45)	2%	14.9
Monolith with compute modules, no avoidance	1.47 g	850	0.3	0.19	2.02 (0.55–11.5)	1.38 (0.82–6.22)	1.16 (0.42–6.43)	12%	1.01
Monolith with compute modules, no avoidance	1.47 g	1,000	0.36	0.15	9.01 (1.77–60.7)	3.53 (1.23–28.2)	4.31 (0.9–31.9)	12%	0.42
Monolith with modules, structure and modules avoid	1.47 g	550	0.99	0.63	0.81 (0.7–1.08)	0.98 (0.92–1.74)	0.88 (0.72–1.97)	0%	—
Monolith with modules, structure and modules avoid	1.47 g	650	0.98	0.56	0.72 (0.6–1.04)	0.88 (0.79–1.15)	0.64 (0.48–1.06)	0%	1,490
Monolith with modules, structure and modules avoid	1.47 g	850	0.99	0.19	0.34 (0.26–0.59)	0.7 (0.62–1.04)	0.31 (0.2–0.63)	0%	101
Monolith with modules, structure and modules avoid	1.47 g	1,000	0.99	0.15	0.64 (0.5–1.89)	0.67 (0.61–1.19)	0.27 (0.17–1)	0%	42
Fleet of separate satellites	1.47 g	550	0.99	0.86	1.96 (1.31–3.62)	1.46 (1.07–2.55)	1.93 (1.08–4.57)	0%	105
Fleet of separate satellites	1.47 g	650	0.98	0.82	3.78 (1.78–12.1)	1.36 (0.97–2.6)	1.74 (0.84–6.16)	3%	9.34
Fleet of separate satellites	1.47 g	850	0.99	0.58	4.14 (1.51–23.4)	1.2 (0.77–3.12)	1.36 (0.46–9.29)	15%	2.45
Fleet of separate satellites	1.47 g	1,000	0.99	0.56	4.76 (1.68–27)	1.17 (0.72–2.95)	1.4 (0.39–9.73)	28%	0.94
Monolith, thin surfaces, radial radiators	0.108 g	550	0.38	0.63	1.06 (0.57–9.21)	1.62 (0.98–12.3)	1.79 (0.86–13.2)	0%	—
Monolith, thin surfaces, radial radiators	0.108 g	650	0.27	0.56	1.32 (0.56–10.8)	1.45 (0.9–10.4)	1.36 (0.63–9.93)	2%	14.9
Monolith, thin surfaces, radial radiators	0.108 g	850	0.3	0.19	1.24 (0.27–10.5)	1.41 (0.73–8.33)	1.15 (0.34–8.69)	12%	1.01
Monolith, thin surfaces, radial radiators	0.108 g	1,000	0.36	0.15	5.59 (0.48–58.7)	3.07 (0.8–38.7)	3.67 (0.42–41.8)	12%	0.42
Monolith, thin surfaces, along-track radiators	0.108 g	550	0.23	0.49	0.75 (0.4–5.27)	1.78 (0.96–11.9)	1.54 (0.75–7.88)	0%	—
Monolith, thin surfaces, along-track radiators	0.108 g	650	0.1	0.4	0.63 (0.35–3.3)	1.56 (0.81–9.31)	0.88 (0.44–3.35)	0%	—
Monolith, thin surfaces, along-track radiators	0.108 g	850	0.04	0.072	0.27 (0.083–1.75)	1.29 (0.54–7.01)	0.4 (0.13–1.8)	0%	—
Monolith, thin surfaces, along-track radiators	0.108 g	1,000	0.047	0.032	1.21 (0.093–10.6)	4.1 (0.71–35.2)	1.19 (0.15–9.05)	0%	—
Monolith, structure avoids intact objects	0.108 g	550	0.99	0.63	0.8 (0.69–1.06)	1 (0.92–1.93)	0.95 (0.72–2.35)	0%	—
Monolith, structure avoids intact objects	0.108 g	650	0.98	0.56	0.71 (0.58–1.03)	0.94 (0.8–1.41)	0.76 (0.5–1.42)	0%	1,486
Monolith, structure avoids intact objects	0.108 g	850	0.99	0.19	0.33 (0.25–0.58)	0.78 (0.64–1.44)	0.43 (0.21–1.1)	0%	101
Monolith, structure avoids intact objects	0.108 g	1,000	0.99	0.15	0.59 (0.48–1.85)	0.74 (0.61–1.56)	0.36 (0.17–1.51)	0%	41.9
Monolith, structure avoids every catalogued object	0.108 g	550	0.99	0.87	0.96 (0.85–1.33)	0.98 (0.91–1.31)	0.92 (0.71–1.53)	0%	—
Monolith, structure avoids every catalogued object	0.108 g	650	0.98	0.82	0.93 (0.79–1.48)	0.92 (0.8–1.11)	0.72 (0.49–1.08)	0%	1,486
Monolith, structure avoids every catalogued object	0.108 g	850	0.99	0.59	0.75 (0.52–1.2)	0.75 (0.63–1.01)	0.41 (0.21–0.84)	0%	101
Monolith, structure avoids every catalogued object	0.108 g	1,000	0.99	0.57	0.94 (0.68–3.25)	0.71 (0.6–1.21)	0.34 (0.17–1.31)	0%	41.9

Design	Lethal threshold	Altitude (km)	Intact, 20 GW	Debris, 20 GW	Trackable, 20 GW	Lethal, 5 GW	Lethal, 20 GW	G* ≤ 20 GW	G* min (GW)
Monolith with compute modules, no avoidance	0.108 g	550	0.38	0.63	1.58 (0.91–9.49)	2.2 (1.24–13)	2.56 (1.3–13.9)	0%	—
Monolith with compute modules, no avoidance	0.108 g	650	0.26	0.56	2.1 (0.94–11.5)	2.02 (1.17–10.9)	2.09 (1–10.5)	2%	14.9
Monolith with compute modules, no avoidance	0.108 g	850	0.3	0.19	2.02 (0.55–11.5)	1.93 (0.99–8.83)	1.86 (0.63–9.57)	12%	1.01
Monolith with compute modules, no avoidance	0.108 g	1,000	0.36	0.15	9.01 (1.77–60.7)	4.99 (1.6–40.3)	6.51 (1.39–44.3)	12%	0.42
Monolith with modules, structure and modules avoid	0.108 g	550	0.99	0.63	0.81 (0.7–1.08)	1.01 (0.93–1.98)	0.97 (0.76–2.37)	0%	—
Monolith with modules, structure and modules avoid	0.108 g	650	0.98	0.56	0.72 (0.6–1.04)	0.94 (0.82–1.46)	0.78 (0.53–1.46)	0%	1,490
Monolith with modules, structure and modules avoid	0.108 g	850	0.99	0.19	0.34 (0.26–0.59)	0.79 (0.65–1.48)	0.44 (0.23–1.13)	0%	101
Monolith with modules, structure and modules avoid	0.108 g	1,000	0.99	0.15	0.64 (0.5–1.89)	0.76 (0.63–1.59)	0.4 (0.2–1.55)	0%	42
Fleet of separate satellites	0.108 g	550	0.99	0.86	1.96 (1.31–3.62)	1.42 (1.07–2.66)	1.89 (1.12–5.05)	0%	5.78
Fleet of separate satellites	0.108 g	650	0.98	0.82	3.78 (1.78–12.1)	1.57 (1.05–3.47)	2.26 (1.02–11.9)	5%	0.73
Fleet of separate satellites	0.108 g	850	0.99	0.58	4.14 (1.51–23.4)	1.65 (0.89–4.91)	2.33 (0.69–23.2)	19%	0.35
Fleet of separate satellites	0.108 g	1,000	0.99	0.56	4.76 (1.68–27)	1.49 (0.81–4.27)	2.13 (0.56–20.2)	30%	0.3

Supplementary Table 5. Breakups of compute modules (monolith) or satellite bodies (fleet) over 15 years at 20 GW: expected number of events, probability of at least one (median, 5th–95th percentile), lethal population of the shell immediately after one event relative to today, and lethal population after 15 years if no event occurs. The population after one event is one plus the number of lethal fragments that the event places in the shell, relative to today’s lethal population; each fragment counts as the fraction of its new orbit spent in the shell, and fragments whose perigee falls below 180 km are not counted (as in Fig. 3b of the main text). The stripped fraction s is sampled log-uniformly from 10^{-4} to 1, as in Supplementary Table 4; for $s = 0$ the lethal population with and without module breakups is given in Table 2 of the main text.

Design	Altitude (km)	Expected events	P(≥1)	Lethal after one event	No event: lethal
Monolith with compute modules, no avoidance	550	0.51	39.73% (23.65%–59.69%)	×10.6 (×4.6–24.0)	1.74
Monolith with compute modules, no avoidance	650	0.36	30.54% (16.88%–53.77%)	×4.4 (×2.2–8.4)	1.06
Monolith with compute modules, no avoidance	850	0.5	39.44% (19.86%–69.94%)	×2.7 (×1.6–4.2)	0.69
Monolith with compute modules, no avoidance	1,000	0.97	62.19% (38.00%–88.92%)	×3.8 (×2.0–6.4)	2.2
Monolith with modules, structure and modules avoid	550	0.0084	0.84% (0.47%–1.48%)	×10.6 (×4.6–24.1)	0.87
Monolith with modules, structure and modules avoid	650	0.0061	0.61% (0.35%–1.06%)	×4.4 (×2.2–8.4)	0.63
Monolith with modules, structure and modules avoid	850	0.0072	0.72% (0.40%–1.29%)	×2.7 (×1.6–4.2)	0.3
Monolith with modules, structure and modules avoid	1,000	0.014	1.41% (0.82%–2.40%)	×3.8 (×2.0–6.4)	0.24
Fleet of separate satellites	550	10.5	100.00% (96.23%–100.00%)	×1.5 (×1.2–2.3)	0.86
Fleet of separate satellites	650	12.5	100.00% (97.70%–100.00%)	×1.2 (×1.1–1.4)	0.63

Design	Altitude (km)	Expected events	P(≥ 1)	Lethal after one event	No event: lethal
Fleet of separate satellites	850	26.2	100.00% (99.98%–100.00%)	$\times 1.1$ ($\times 1.0$ – 1.2)	0.3
Fleet of separate satellites	1,000	11.6	100.00% (97.85%–100.00%)	$\times 1.1$ ($\times 1.0$ – 1.3)	0.23

Supplementary Table 6. Lethal population after 15 years at 20 GW relative to today against the stripped fraction s : median (5th–95th percentile over the other parameters; share of draws above today’s population). The momentum column states whether the sheet’s momentum is shared with the whole object or given to the stripped material alone. Avoiding designs screen at an efficiency of 0.99; designs with compute modules count module breakups at their expected rate.

Design	Momentum	Lethal threshold	Altitude (km)	$s = 0\%$	$s = 0.01\%$	$s = 0.03\%$	$s = 0.1\%$	$s = 1\%$	$s = 3\%$	$s = 10\%$	$s = 30\%$	$s = 100\%$
Monolith, thin surfaces, radial radiators	whole object	1.47 g	550	0.84 (0.67–1.84; 22%)	0.85 (0.7–1.86; 23%)	0.88 (0.73–1.89; 26%)	0.95 (0.76–1.98; 41%)	1.48 (0.96–3.2; 90%)	2.18 (1.17–5.78; 99%)	3.91 (1.66–12.3; 100%)	7.22 (2.6–24.5; 100%)	11 (3.89–38.2; 100%)
Monolith, thin surfaces, radial radiators	whole object	1.47 g	650	0.61 (0.46–0.92; 4%)	0.62 (0.47–0.93; 4%)	0.64 (0.49–0.97; 5%)	0.69 (0.51–1.16; 9%)	0.99 (0.64–2.47; 49%)	1.4 (0.75–4.68; 75%)	2.38 (1.02–9.19; 96%)	3.86 (1.51–13.5; 100%)	5.04 (1.98–15.8; 100%)
Monolith, thin surfaces, radial radiators	whole object	1.47 g	850	0.31 (0.18–0.63; 1%)	0.32 (0.2–0.67; 1%)	0.34 (0.21–0.71; 2%)	0.37 (0.22–0.86; 3%)	0.62 (0.31–2.26; 23%)	0.96 (0.4–4.23; 49%)	1.74 (0.58–8.14; 76%)	2.73 (0.85–10.7; 91%)	3.07 (0.95–10.7; 94%)
Monolith, thin surfaces, radial radiators	whole object	1.47 g	1,000	0.26 (0.14–1.1; 6%)	0.34 (0.17–1.32; 10%)	0.44 (0.2–1.63; 14%)	0.64 (0.25–2.44; 29%)	2.04 (0.56–10; 80%)	4.13 (1.04–20.8; 95%)	8.78 (2.02–42.7; 100%)	14.2 (3.28–57.6; 100%)	15.1 (3.59–59.1; 100%)
Monolith, thin surfaces, radial radiators	stripped spray	1.47 g	550	0.84 (0.67–1.84; 22%)	0.85 (0.7–1.86; 23%)	0.88 (0.73–1.89; 26%)	0.95 (0.76–1.98; 41%)	0.82 (0.67–1.82; 21%)	0.89 (0.68–2.77; 41%)	2.36 (0.82–11.9; 86%)	7.04 (2.01–31.7; 100%)	11 (3.89–38.2; 100%)
Monolith, thin surfaces, radial radiators	stripped spray	1.47 g	650	0.61 (0.46–0.92; 4%)	0.62 (0.47–0.93; 4%)	0.64 (0.49–0.97; 5%)	0.69 (0.51–1.16; 9%)	0.6 (0.45–1.04; 6%)	0.74 (0.48–20.3; 33%)	2.41 (0.69–24.2; 86%)	5.35 (1.6–24.2; 100%)	5.04 (1.98–15.8; 100%)
Monolith, thin surfaces, radial radiators	stripped spray	1.47 g	850	0.31 (0.18–0.63; 1%)	0.32 (0.2–0.67; 1%)	0.34 (0.21–0.71; 2%)	0.37 (0.22–0.86; 3%)	0.27 (0.18–0.58; 1%)	0.33 (0.19–1.6; 10%)	1.25 (0.32–10.7; 58%)	3.41 (1.03–16.8; 96%)	3.07 (0.95–10.7; 94%)
Monolith, thin surfaces, radial radiators	stripped spray	1.47 g	1,000	0.26 (0.14–1.1; 6%)	0.34 (0.17–1.32; 10%)	0.44 (0.2–1.63; 14%)	0.64 (0.25–2.44; 29%)	0.19 (0.14–1.25; 6%)	1.01 (0.16–11.2; 50%)	7.55 (1.61–56.5; 99%)	18.4 (4.62–86.7; 100%)	15.1 (3.59–59.1; 100%)
Monolith, thin surfaces, along-track radiators	whole object	1.47 g	550	0.75 (0.54–1.54; 18%)	0.76 (0.56–1.55; 19%)	0.77 (0.58–1.56; 21%)	0.82 (0.6–1.63; 26%)	1.14 (0.75–2.34; 64%)	1.59 (0.91–3.88; 88%)	2.63 (1.23–7.69; 99%)	4.06 (1.71–12.6; 100%)	5.68 (2.32–17.9; 100%)
Monolith, thin surfaces, along-track radiators	whole object	1.47 g	650	0.45 (0.3–0.65; 0%)	0.45 (0.31–0.66; 0%)	0.46 (0.32–0.67; 1%)	0.47 (0.33–0.7; 1%)	0.58 (0.39–1.05; 6%)	0.72 (0.45–1.65; 25%)	1.02 (0.57–2.78; 52%)	1.35 (0.7–3.57; 71%)	1.62 (0.8–4.29; 80%)
Monolith, thin surfaces, along-track radiators	whole object	1.47 g	850	0.14 (0.07–0.26; 0%)	0.15 (0.073–0.27; 0%)	0.15 (0.075–0.28; 0%)	0.16 (0.08–0.32; 0%)	0.22 (0.1–0.66; 2%)	0.28 (0.13–1.15; 7%)	0.42 (0.17–1.82; 14%)	0.51 (0.22–1.73; 18%)	0.51 (0.23–1.43; 17%)

Design	Momentum	Lethal threshold	Altitude (km)	s = 0%	s = 0.01%	s = 0.03%	s = 0.1%	s = 1%	s = 3%	s = 10%	s = 30%	s = 100%
Monolith, thin surfaces, along-track radiators	whole object	1.47 g	1,000	0.11 (0.041–0.66; 2%)	0.13 (0.049–0.77; 3%)	0.15 (0.057–0.87; 4%)	0.21 (0.074–1.18; 7%)	0.58 (0.16–4.04; 30%)	1.07 (0.27–7.56; 53%)	1.96 (0.47–10.6; 76%)	2.37 (0.64–9.5; 84%)	2.27 (0.63–8.11; 82%)
Monolith, structure avoids intact objects	whole object	1.47 g	550	0.82 (0.66–1.81; 20%)	0.82 (0.66–1.81; 20%)	0.82 (0.67–1.81; 20%)	0.82 (0.67–1.81; 20%)	0.83 (0.69–1.84; 21%)	0.85 (0.71–1.86; 22%)	0.9 (0.74–1.92; 30%)	1.02 (0.8–2.08; 53%)	1.18 (0.86–2.36; 72%)
Monolith, structure avoids intact objects	whole object	1.47 g	650	0.59 (0.45–0.9; 4%)	0.59 (0.45–0.9; 4%)	0.59 (0.45–0.9; 4%)	0.6 (0.45–0.9; 4%)	0.6 (0.46–0.9; 4%)	0.61 (0.47–0.92; 4%)	0.65 (0.5–0.97; 4%)	0.71 (0.54–1.09; 8%)	0.8 (0.58–1.33; 21%)
Monolith, structure avoids intact objects	whole object	1.47 g	850	0.27 (0.18–0.54; 0%)	0.27 (0.18–0.54; 0%)	0.27 (0.18–0.54; 0%)	0.27 (0.18–0.54; 0%)	0.28 (0.18–0.55; 0%)	0.29 (0.19–0.57; 1%)	0.31 (0.2–0.61; 1%)	0.36 (0.22–0.68; 1%)	0.41 (0.24–0.83; 2%)
Monolith, structure avoids intact objects	whole object	1.47 g	1,000	0.18 (0.14–0.43; 0%)	0.18 (0.14–0.43; 0%)	0.18 (0.14–0.43; 0%)	0.18 (0.14–0.43; 0%)	0.22 (0.15–0.47; 0%)	0.25 (0.17–0.57; 1%)	0.35 (0.2–0.87; 2%)	0.54 (0.25–1.56; 19%)	0.8 (0.31–2.61; 38%)
Monolith, structure avoids intact objects	stripped spray	1.47 g	550	0.82 (0.66–1.81; 20%)	0.82 (0.66–1.81; 20%)	0.82 (0.67–1.81; 20%)	0.82 (0.67–1.81; 20%)	0.82 (0.66–1.81; 20%)	0.82 (0.67–1.81; 20%)	0.83 (0.69–1.83; 21%)	0.94 (0.75–1.99; 39%)	1.18 (0.86–2.36; 72%)
Monolith, structure avoids intact objects	stripped spray	1.47 g	650	0.59 (0.45–0.9; 4%)	0.59 (0.45–0.9; 4%)	0.59 (0.45–0.9; 4%)	0.6 (0.45–0.9; 4%)	0.59 (0.45–0.9; 4%)	0.59 (0.45–0.92; 4%)	0.61 (0.46–0.92; 4%)	0.67 (0.51–1.03; 5%)	0.8 (0.58–1.33; 21%)
Monolith, structure avoids intact objects	stripped spray	1.47 g	850	0.27 (0.18–0.54; 0%)	0.27 (0.18–0.54; 0%)	0.27 (0.18–0.54; 0%)	0.27 (0.18–0.54; 0%)	0.27 (0.18–0.54; 0%)	0.27 (0.18–0.54; 0%)	0.28 (0.18–0.54; 0%)	0.33 (0.21–0.63; 1%)	0.41 (0.24–0.83; 2%)
Monolith, structure avoids intact objects	stripped spray	1.47 g	1,000	0.18 (0.14–0.43; 0%)	0.18 (0.14–0.43; 0%)	0.18 (0.14–0.43; 0%)	0.18 (0.14–0.43; 0%)	0.17 (0.13–0.42; 0%)	0.18 (0.14–0.43; 0%)	0.23 (0.16–0.5; 0%)	0.45 (0.23–1.21; 9%)	0.8 (0.31–2.61; 38%)
Monolith, structure avoids every catalogued object	whole object	1.47 g	550	0.8 (0.66–1.15; 9%)	0.8 (0.66–1.15; 9%)	0.8 (0.66–1.15; 10%)	0.8 (0.67–1.15; 10%)	0.81 (0.68–1.17; 10%)	0.83 (0.7–1.19; 11%)	0.88 (0.73–1.26; 21%)	0.98 (0.79–1.53; 46%)	1.12 (0.85–1.92; 68%)
Monolith, structure avoids every catalogued object	whole object	1.47 g	650	0.57 (0.45–0.73; 1%)	0.57 (0.45–0.73; 1%)	0.57 (0.45–0.73; 1%)	0.58 (0.45–0.73; 1%)	0.58 (0.45–0.74; 1%)	0.6 (0.47–0.75; 1%)	0.64 (0.49–0.8; 1%)	0.7 (0.52–0.96; 3%)	0.77 (0.56–1.22; 16%)
Monolith, structure avoids every catalogued object	whole object	1.47 g	850	0.26 (0.18–0.44; 0%)	0.26 (0.18–0.44; 0%)	0.26 (0.18–0.44; 0%)	0.26 (0.18–0.44; 0%)	0.26 (0.18–0.44; 0%)	0.28 (0.19–0.45; 0%)	0.3 (0.2–0.48; 0%)	0.35 (0.22–0.58; 0%)	0.4 (0.24–0.76; 1%)
Monolith, structure avoids every catalogued object	whole object	1.47 g	1,000	0.17 (0.13–0.33; 0%)	0.17 (0.14–0.33; 0%)	0.17 (0.14–0.34; 0%)	0.18 (0.14–0.34; 0%)	0.21 (0.15–0.39; 0%)	0.25 (0.17–0.5; 0%)	0.34 (0.2–0.81; 2%)	0.53 (0.25–1.52; 18%)	0.77 (0.31–2.55; 37%)
Monolith with compute modules, no avoidance	whole object	1.47 g	550	1.64 (1.16–3.09; 100%)	1.66 (1.18–3.12; 100%)	1.69 (1.2–3.15; 100%)	1.77 (1.23–3.28; 100%)	2.29 (1.41–4.47; 100%)	3.01 (1.64–6.99; 100%)	4.74 (2.17–13.2; 100%)	8.04 (3.16–25.2; 100%)	11.8 (4.46–39.3; 100%)

Design	Momentum	Lethal threshold	Altitude (km)	s = 0%	s = 0.01%	s = 0.03%	s = 0.1%	s = 1%	s = 3%	s = 10%	s = 30%	s = 100%
Monolith with compute modules, no avoidance	whole object	1.47 g	650	1.04 (0.72–2.11; 56%)	1.05 (0.73–2.15; 58%)	1.07 (0.74–2.2; 60%)	1.12 (0.77–2.36; 66%)	1.46 (0.88–3.7; 86%)	1.92 (1.01–5.68; 95%)	2.87 (1.31–10.1; 100%)	4.25 (1.8–14.2; 100%)	5.32 (2.2–16; 100%)
Monolith with compute modules, no avoidance	whole object	1.47 g	850	0.63 (0.34–1.72; 21%)	0.65 (0.35–1.77; 22%)	0.66 (0.36–1.84; 23%)	0.7 (0.38–1.97; 26%)	0.98 (0.46–3.31; 49%)	1.33 (0.56–4.91; 66%)	2.06 (0.76–8.67; 86%)	3.04 (1.04–11.1; 96%)	3.29 (1.13–10.9; 98%)
Monolith with compute modules, no avoidance	whole object	1.47 g	1,000	1.62 (0.57–5.58; 76%)	1.71 (0.6–5.79; 79%)	1.79 (0.64–6.31; 82%)	2.05 (0.73–7.23; 88%)	3.57 (1.2–13.7; 98%)	5.69 (1.78–23.3; 100%)	10.2 (2.85–44; 100%)	15.3 (4.09–58.9; 100%)	15.9 (4.18–60.5; 100%)
Monolith with modules, structure and modules avoid	whole object	1.47 g	550	0.84 (0.69–1.84; 22%)	0.84 (0.69–1.84; 22%)	0.84 (0.69–1.84; 22%)	0.84 (0.69–1.84; 22%)	0.85 (0.72–1.85; 22%)	0.87 (0.73–1.88; 23%)	0.92 (0.76–1.97; 34%)	1.04 (0.82–2.12; 57%)	1.2 (0.87–2.38; 75%)
Monolith with modules, structure and modules avoid	whole object	1.47 g	650	0.61 (0.46–0.91; 4%)	0.61 (0.46–0.91; 4%)	0.61 (0.46–0.91; 4%)	0.61 (0.46–0.91; 4%)	0.61 (0.47–0.92; 4%)	0.63 (0.49–0.94; 4%)	0.66 (0.51–0.99; 5%)	0.72 (0.55–1.11; 9%)	0.81 (0.58–1.34; 23%)
Monolith with modules, structure and modules avoid	whole object	1.47 g	850	0.28 (0.18–0.55; 1%)	0.28 (0.18–0.55; 1%)	0.28 (0.19–0.55; 1%)	0.28 (0.19–0.55; 1%)	0.28 (0.19–0.56; 1%)	0.29 (0.2–0.58; 1%)	0.32 (0.21–0.62; 1%)	0.37 (0.23–0.68; 1%)	0.42 (0.25–0.83; 2%)
Monolith with modules, structure and modules avoid	whole object	1.47 g	1,000	0.2 (0.15–0.45; 0%)	0.2 (0.15–0.45; 0%)	0.21 (0.16–0.46; 0%)	0.21 (0.16–0.46; 0%)	0.24 (0.17–0.52; 0%)	0.28 (0.19–0.6; 1%)	0.38 (0.22–0.9; 3%)	0.56 (0.28–1.59; 20%)	0.83 (0.33–2.64; 40%)
Monolith, thin surfaces, radial radiators	whole object	0.108 g	550	0.95 (0.71–2.29; 42%)	0.97 (0.75–2.29; 44%)	0.99 (0.77–2.32; 48%)	1.06 (0.81–2.45; 61%)	1.5 (0.99–3.51; 94%)	2.1 (1.16–5.87; 99%)	3.53 (1.51–12.2; 100%)	6.1 (2.21–23.5; 100%)	9.2 (3.15–36.6; 100%)
Monolith, thin surfaces, radial radiators	whole object	0.108 g	650	0.77 (0.49–1.43; 19%)	0.79 (0.53–1.46; 21%)	0.81 (0.55–1.53; 24%)	0.86 (0.58–1.71; 31%)	1.21 (0.75–3.29; 69%)	1.72 (0.89–5.93; 89%)	2.89 (1.2–11.2; 99%)	4.72 (1.69–17.2; 100%)	5.76 (2.14–21.2; 100%)
Monolith, thin surfaces, radial radiators	whole object	0.108 g	850	0.52 (0.23–1.56; 16%)	0.54 (0.25–1.6; 17%)	0.55 (0.26–1.66; 19%)	0.62 (0.28–1.86; 22%)	1.02 (0.42–3.67; 51%)	1.53 (0.55–6.63; 71%)	2.71 (0.83–12.4; 90%)	4.13 (1.26–15.8; 98%)	4.43 (1.44–15.2; 99%)
Monolith, thin surfaces, radial radiators	whole object	0.108 g	1,000	0.7 (0.18–4.48; 36%)	0.8 (0.22–4.77; 41%)	0.95 (0.27–5; 47%)	1.23 (0.36–6.02; 60%)	3.18 (0.83–15; 91%)	5.88 (1.45–29.8; 99%)	11.6 (2.88–57.6; 100%)	18.8 (4.45–79.9; 100%)	20.2 (4.87–80.1; 100%)
Monolith, thin surfaces, along-track radiators	whole object	0.108 g	550	0.95 (0.6–2.14; 42%)	0.96 (0.62–2.15; 43%)	0.97 (0.64–2.18; 45%)	0.99 (0.67–2.21; 49%)	1.28 (0.82–2.92; 78%)	1.66 (0.97–4.43; 93%)	2.58 (1.23–8.08; 99%)	3.78 (1.63–12.7; 100%)	5.24 (2.11–18.1; 100%)
Monolith, thin surfaces, along-track radiators	whole object	0.108 g	650	0.64 (0.35–1.12; 9%)	0.64 (0.36–1.13; 9%)	0.65 (0.38–1.14; 10%)	0.66 (0.39–1.19; 12%)	0.79 (0.46–1.59; 27%)	0.96 (0.56–2.37; 46%)	1.33 (0.72–3.79; 71%)	1.74 (0.88–4.96; 88%)	2.02 (1.02–5.87; 96%)
Monolith, thin surfaces, along-track radiators	whole object	0.108 g	850	0.26 (0.096–0.64; 1%)	0.27 (0.099–0.67; 1%)	0.27 (0.1–0.69; 2%)	0.28 (0.11–0.75; 2%)	0.36 (0.14–1.21; 8%)	0.45 (0.18–1.84; 15%)	0.65 (0.25–2.67; 29%)	0.79 (0.31–2.63; 38%)	0.78 (0.34–2.17; 37%)

Design	Momentum	Lethal threshold	Altitude (km)	s = 0%	s = 0.01%	s = 0.03%	s = 0.1%	s = 1%	s = 3%	s = 10%	s = 30%	s = 100%
Monolith, thin surfaces, along-track radiators	whole object	0.108 g	1,000	0.33 (0.067–2.61; 18%)	0.36 (0.081–2.74; 19%)	0.39 (0.095–2.89; 20%)	0.46 (0.12–3.26; 24%)	0.99 (0.25–6.57; 50%)	1.64 (0.4–10.8; 66%)	2.77 (0.7–14.8; 86%)	3.29 (0.89–13.1; 92%)	3.09 (0.87–11; 92%)
Monolith, structure avoids intact objects	whole object	0.108 g	550	0.91 (0.69–2.21; 29%)	0.91 (0.69–2.21; 29%)	0.91 (0.69–2.21; 29%)	0.91 (0.69–2.22; 29%)	0.92 (0.71–2.23; 29%)	0.93 (0.74–2.25; 31%)	0.97 (0.78–2.31; 42%)	1.07 (0.84–2.44; 64%)	1.2 (0.9–2.67; 81%)
Monolith, structure avoids intact objects	whole object	0.108 g	650	0.71 (0.47–1.31; 12%)	0.71 (0.47–1.31; 12%)	0.71 (0.47–1.31; 12%)	0.71 (0.47–1.32; 12%)	0.72 (0.48–1.32; 12%)	0.74 (0.51–1.33; 14%)	0.78 (0.55–1.35; 15%)	0.85 (0.6–1.46; 25%)	0.96 (0.66–1.78; 44%)
Monolith, structure avoids intact objects	whole object	0.108 g	850	0.39 (0.19–0.99; 5%)	0.39 (0.19–0.99; 5%)	0.39 (0.19–0.99; 5%)	0.39 (0.2–0.99; 5%)	0.4 (0.2–1.01; 5%)	0.41 (0.22–1.02; 5%)	0.45 (0.24–1.05; 6%)	0.51 (0.27–1.14; 7%)	0.59 (0.3–1.32; 13%)
Monolith, structure avoids intact objects	whole object	0.108 g	1,000	0.26 (0.15–0.75; 2%)	0.26 (0.15–0.76; 3%)	0.26 (0.15–0.76; 3%)	0.27 (0.15–0.77; 3%)	0.31 (0.17–0.83; 3%)	0.36 (0.2–0.92; 4%)	0.5 (0.24–1.27; 12%)	0.75 (0.32–2.21; 32%)	1.09 (0.42–3.57; 55%)
Monolith, structure avoids every catalogued object	whole object	0.108 g	550	0.88 (0.68–1.34; 18%)	0.88 (0.68–1.34; 18%)	0.88 (0.68–1.34; 18%)	0.88 (0.68–1.34; 18%)	0.89 (0.7–1.35; 19%)	0.91 (0.72–1.35; 21%)	0.95 (0.77–1.43; 33%)	1.03 (0.83–1.64; 57%)	1.14 (0.89–1.99; 77%)
Monolith, structure avoids every catalogued object	whole object	0.108 g	650	0.67 (0.46–0.93; 4%)	0.67 (0.46–0.93; 4%)	0.67 (0.46–0.93; 4%)	0.67 (0.47–0.93; 4%)	0.68 (0.48–0.94; 4%)	0.7 (0.5–0.96; 4%)	0.75 (0.53–1.01; 5%)	0.82 (0.59–1.17; 15%)	0.91 (0.64–1.49; 36%)
Monolith, structure avoids every catalogued object	whole object	0.108 g	850	0.36 (0.19–0.74; 2%)	0.36 (0.19–0.74; 2%)	0.37 (0.19–0.75; 2%)	0.37 (0.19–0.75; 2%)	0.38 (0.2–0.76; 2%)	0.39 (0.21–0.77; 2%)	0.43 (0.23–0.82; 2%)	0.49 (0.26–0.92; 4%)	0.57 (0.29–1.14; 9%)
Monolith, structure avoids every catalogued object	whole object	0.108 g	1,000	0.24 (0.15–0.58; 1%)	0.24 (0.15–0.58; 1%)	0.24 (0.15–0.58; 1%)	0.25 (0.15–0.59; 1%)	0.3 (0.17–0.66; 1%)	0.35 (0.19–0.76; 2%)	0.48 (0.24–1.15; 9%)	0.72 (0.32–2.12; 30%)	1.06 (0.41–3.51; 54%)
Monolith with compute modules, no avoidance	whole object	0.108 g	550	1.68 (1.18–3.42; 100%)	1.7 (1.19–3.46; 100%)	1.73 (1.2–3.52; 100%)	1.79 (1.23–3.65; 100%)	2.21 (1.34–4.7; 100%)	2.84 (1.5–7.09; 100%)	4.25 (1.85–13.2; 100%)	6.88 (2.56–24.7; 100%)	9.9 (3.51–37.6; 100%)
Monolith with compute modules, no avoidance	whole object	0.108 g	650	1.31 (0.88–2.83; 84%)	1.33 (0.9–2.9; 85%)	1.35 (0.91–2.99; 86%)	1.4 (0.95–3.24; 89%)	1.76 (1.05–4.99; 97%)	2.32 (1.19–7.49; 99%)	3.47 (1.48–12.9; 100%)	5.14 (1.96–18.3; 100%)	6.19 (2.35–22; 100%)
Monolith with compute modules, no avoidance	whole object	0.108 g	850	1.07 (0.49–3.05; 55%)	1.09 (0.5–3.12; 56%)	1.11 (0.51–3.25; 58%)	1.17 (0.54–3.44; 62%)	1.58 (0.67–5.42; 78%)	2.1 (0.82–8.02; 89%)	3.23 (1.12–13.3; 97%)	4.6 (1.52–16.8; 100%)	4.79 (1.75–15.7; 100%)
Monolith with compute modules, no avoidance	whole object	0.108 g	1,000	2.74 (0.9–10.2; 92%)	2.81 (0.95–10.4; 94%)	2.93 (1.02–10.6; 95%)	3.27 (1.1–11.9; 96%)	5.34 (1.72–20.9; 100%)	7.99 (2.44–33.8; 100%)	13.9 (3.98–60.9; 100%)	20.3 (5.49–81.2; 100%)	21.2 (5.77–81.1; 100%)
Monolith with modules, structure and modules avoid	whole object	0.108 g	550	0.93 (0.72–2.27; 30%)	0.93 (0.72–2.27; 30%)	0.93 (0.72–2.27; 30%)	0.93 (0.72–2.27; 30%)	0.94 (0.74–2.28; 32%)	0.95 (0.77–2.29; 35%)	0.99 (0.81–2.35; 46%)	1.09 (0.86–2.51; 70%)	1.23 (0.92–2.71; 84%)

Design	Momentum	Lethal threshold	Altitude (km)	s = 0%	s = 0.01%	s = 0.03%	s = 0.1%	s = 1%	s = 3%	s = 10%	s = 30%	s = 100%
Monolith with modules, structure and modules avoid	whole object	0.108 g	650	0.73 (0.49–1.35; 13%)	0.73 (0.49–1.35; 13%)	0.73 (0.49–1.35; 13%)	0.73 (0.5–1.35; 13%)	0.74 (0.51–1.36; 14%)	0.76 (0.53–1.38; 15%)	0.8 (0.57–1.43; 17%)	0.87 (0.62–1.5; 28%)	0.98 (0.67–1.8; 46%)
Monolith with modules, structure and modules avoid	whole object	0.108 g	850	0.4 (0.2–1.05; 5%)	0.4 (0.21–1.05; 5%)	0.4 (0.21–1.05; 5%)	0.41 (0.21–1.06; 5%)	0.41 (0.22–1.07; 6%)	0.42 (0.23–1.07; 6%)	0.46 (0.25–1.1; 6%)	0.53 (0.28–1.17; 8%)	0.61 (0.31–1.36; 14%)
Monolith with modules, structure and modules avoid	whole object	0.108 g	1,000	0.29 (0.18–0.8; 3%)	0.3 (0.18–0.8; 3%)	0.3 (0.18–0.81; 3%)	0.3 (0.19–0.82; 3%)	0.35 (0.21–0.87; 4%)	0.4 (0.23–0.98; 4%)	0.53 (0.28–1.32; 14%)	0.78 (0.36–2.28; 34%)	1.14 (0.45–3.61; 58%)

Supplementary Table 7. Cost of avoidance for a 5 GW monolith (structural mass 8,900 t per GW, specific impulse 2,000 s, start and stop burns). Ranges span screening thresholds of 10^{-4} and 10^{-5} and, for the modules, cross-sections of 30–250 m² each. Crossings: objects of the screened class that would cross the structure each year without avoidance; for every catalogued object, all non-maneuvrable objects of 10 cm or larger are taken as catalogued, an upper bound. Screening efficiency: fraction of collisions removed by the screening rule, given for the modules, which are small compared with the position uncertainty (Supplementary Note 5). Whole structure: manoeuvre when the predicted point where the object crosses the array plane lies within the screening box (default), or, for comparison, when it passes within a disc about the structure’s centre whose radius is the half-diagonal of a square holding every surface plus the screening margin. Δv per manoeuvre: mean over the predicted crossing points; thrust: the largest burn delivered within a quarter orbit; power: electric thrusters with an efficiency of 0.6. Module displacements include the projection onto the encounter plane.

Altitude (km)	Avoidance	Position uncertainty (m)	Crossings per year	Screening efficiency	Manoeuvres per year	Δv per manoeuvre (cm/s)	Propellant (t per GW per year)	Thrust (kN)	Power (MW)
550	Modules, clustered	50–200	—	0.97 to >0.9999	3–65	5.4–23.0	0.079–6.8	0.83–3.6	14–58
550	Modules, dispersed	50–200	—	0.16–0.9994	37–963	3.3–16.5	0.55–72	0.51–2.6	8.3–42
550	Whole structure vs intact objects, crossing point on the array plane	100	16	—	27–29	16.5–17.3	2.0–2.3	5.1–5.4	84–88
550	Whole structure vs intact objects, crossing point on the array plane	300	16	—	56–65	26.3–28.7	6.7–8.4	8.2–8.9	130–150
550	Whole structure vs intact objects, crossing point on the array plane	1,000	16	—	236–295	60.6–68.5	65–92	19–21	310–350
550	Whole structure vs intact objects, crossing point on the array plane	3,000	16	—	1,420–1,858	158.4–182.2	1,000–1,500	49–57	800–920
550	Whole structure vs intact objects, envelope disc (upper bound)	100	16	—	92–94	44.5–45.2	19	6.9–7.0	110
550	Whole structure vs intact objects, envelope disc (upper bound)	300	16	—	130–141	53.1–55.2	31–35	8.2–8.6	130–140
550	Whole structure vs intact objects, envelope disc (upper bound)	1,000	16	—	320–376	83.2–90.2	120–150	13–14	210–230

Altitude (km)	Avoidance	Position uncertainty (m)	Crossings per year	Screening efficiency	Manoeuvres per year	Δv per manoeuvre (cm/s)	Propellant (t per GW per year)	Thrust (kN)	Power (MW)
550	Whole structure vs intact objects, envelope disc (upper bound)	3,000	16	—	1,321–1,668	169.2–190.1	1,000–1,400	26–29	430–480
550	Whole structure vs every catalogued object, crossing point on the array plane	100	53	—	90–97	16.5–17.3	6.7–7.6	5.1–5.4	84–88
550	Whole structure vs every catalogued object, crossing point on the array plane	300	53	—	188–217	26.3–28.7	22–28	8.2–8.9	130–150
550	Whole structure vs every catalogued object, crossing point on the array plane	1,000	53	—	794–993	60.6–68.5	220–310	19–21	310–350
550	Whole structure vs every catalogued object, crossing point on the array plane	3,000	53	—	4,774–6,246	158.4–182.2	3,400–5,200	49–57	800–920
550	Whole structure vs every catalogued object, envelope disc (upper bound)	100	53	—	308–318	44.5–45.2	62–65	6.9–7.0	110
550	Whole structure vs every catalogued object, envelope disc (upper bound)	300	53	—	438–473	53.1–55.2	110–120	8.2–8.6	130–140
550	Whole structure vs every catalogued object, envelope disc (upper bound)	1,000	53	—	1,075–1,262	83.2–90.2	410–520	13–14	210–230
550	Whole structure vs every catalogued object, envelope disc (upper bound)	3,000	53	—	4,442–5,608	169.2–190.1	3,400–4,800	26–29	430–480
650	Modules, clustered	50–200	—	0.97 to >0.9999	4–86	5.3–22.7	0.10–8.9	0.80–3.4	13–56
650	Modules, dispersed	50–200	—	0.16–0.9994	49–1,272	3.2–16.2	0.72–94	0.49–2.5	8.1–40
650	Whole structure vs intact objects, crossing point on the array plane	100	11	—	18–20	16.2–17.0	1.3–1.5	4.9–5.2	80–84
650	Whole structure vs intact objects, crossing point on the array plane	300	11	—	38–44	25.8–28.2	4.5–5.7	7.8–8.6	130–140
650	Whole structure vs intact objects, crossing point on the array plane	1,000	11	—	162–203	59.6–67.5	44–62	18–20	300–330
650	Whole structure vs intact objects, crossing point on the array plane	3,000	11	—	978–1,279	156.2–179.7	690–1,000	47–55	770–890
650	Whole structure vs intact objects, envelope disc (upper bound)	100	11	—	72–74	43.6–44.3	14–15	6.6–6.7	110
650	Whole structure vs intact objects, envelope disc (upper bound)	300	11	—	102–110	52.0–54.1	24–27	7.9–8.2	130

Altitude (km)	Avoidance	Position uncertainty (m)	Crossings per year	Screening efficiency	Manoeuvres per year	Δv per manoeuvre (cm/s)	Propellant (t per GW per year)	Thrust (kN)	Power (MW)
650	Whole structure vs intact objects, envelope disc (upper bound)	1,000	11	—	251–294	81.5–88.3	93–120	12–13	200– 220
650	Whole structure vs intact objects, envelope disc (upper bound)	3,000	11	—	1,036–1,307	165.6–186.0	780–1,100	25–28	410– 460
650	Whole structure vs every catalogued object, crossing point on the array plane	100	62	—	104–112	16.2–17.0	7.6–8.6	4.9–5.2	80–84
650	Whole structure vs every catalogued object, crossing point on the array plane	300	62	—	218–251	25.8–28.2	26–32	7.8–8.6	130– 140
650	Whole structure vs every catalogued object, crossing point on the array plane	1,000	62	—	920–1,150	59.6–67.5	250–350	18–20	300– 330
650	Whole structure vs every catalogued object, crossing point on the array plane	3,000	62	—	5,537–7,245	156.2–179.7	3,900–5,900	47–55	770– 890
650	Whole structure vs every catalogued object, envelope disc (upper bound)	100	62	—	406–419	43.6–44.3	80–84	6.6–6.7	110
650	Whole structure vs every catalogued object, envelope disc (upper bound)	300	62	—	578–625	52.0–54.1	140–150	7.9–8.2	130
650	Whole structure vs every catalogued object, envelope disc (upper bound)	1,000	62	—	1,419–1,667	81.5–88.3	520–670	12–13	200– 220
650	Whole structure vs every catalogued object, envelope disc (upper bound)	3,000	62	—	5,865–7,404	165.6–186.0	4,400–6,300	25–28	410– 460
850	Modules, clustered	50–200	—	0.97 to >0.9999	8–154	5.4–23.2	0.19–16	0.79– 3.4	13–55
850	Modules, dispersed	50–200	—	0.16–0.9994	87–2,267	3.3–16.6	1.3–170	0.48– 2.4	7.9–39
850	Whole structure vs intact objects, crossing point on the array plane	100	10	—	17–18	15.8–16.6	1.2–1.4	4.6–4.8	75–79
850	Whole structure vs intact objects, crossing point on the array plane	300	10	—	36–41	25.7–28.1	4.2–5.3	7.5–8.2	120– 130
850	Whole structure vs intact objects, crossing point on the array plane	1,000	10	—	153–191	60.3–68.3	42–59	18–20	290– 320
850	Whole structure vs intact objects, crossing point on the array plane	3,000	10	—	927–1,214	159.0–183.0	670–1,000	46–53	760– 870
850	Whole structure vs intact objects, envelope disc (upper bound)	100	10	—	69–71	41.8–42.4	13–14	6.1–6.2	99–100

Altitude (km)	Avoidance	Position uncertainty (m)	Crossings per year	Screening efficiency	Manoeuvres per year	Δv per manoeuvre (cm/s)	Propellant (t per GW per year)	Thrust (kN)	Power (MW)
850	Whole structure vs intact objects, envelope disc (upper bound)	300	10	—	98–106	49.9–51.8	22–25	7.3–7.5	120
850	Whole structure vs intact objects, envelope disc (upper bound)	1,000	10	—	240–282	78.1–84.6	85–110	11–12	190– 200
850	Whole structure vs intact objects, envelope disc (upper bound)	3,000	10	—	994–1,254	158.8–178.4	720–1,000	23–26	380– 420
850	Whole structure vs every catalogued object, crossing point on the array plane	100	103	—	176–189	15.8–16.6	13–14	4.6–4.8	75–79
850	Whole structure vs every catalogued object, crossing point on the array plane	300	103	—	375–433	25.7–28.1	44–55	7.5–8.2	120– 130
850	Whole structure vs every catalogued object, crossing point on the array plane	1,000	103	—	1,609–2,015	60.3–68.3	440–620	18–20	290– 320
850	Whole structure vs every catalogued object, crossing point on the array plane	3,000	103	—	9,756–12,772	159.0–183.0	7,000–11,000	46–53	760– 870
850	Whole structure vs every catalogued object, envelope disc (upper bound)	100	103	—	725–747	41.8–42.4	140	6.1–6.2	99–100
850	Whole structure vs every catalogued object, envelope disc (upper bound)	300	103	—	1,031–1,114	49.9–51.8	230–260	7.3–7.5	120
850	Whole structure vs every catalogued object, envelope disc (upper bound)	1,000	103	—	2,530–2,971	78.1–84.6	900–1,100	11–12	190– 200
850	Whole structure vs every catalogued object, envelope disc (upper bound)	3,000	103	—	10,455–13,199	158.8–178.4	7,500–11,000	23–26	380– 420
1,000	Modules, clustered	50–200	—	0.97 to >0.9999	4–87	5.5–23.6	0.11–9.3	0.78– 3.3	13–54
1,000	Modules, dispersed	50–200	—	0.16–0.9994	49–1,277	3.4–16.9	0.75–98	0.48– 2.4	7.8–39
1,000	Whole structure vs intact objects, crossing point on the array plane	100	23	—	39–42	15.6–16.4	2.8–3.1	4.4–4.6	72–76
1,000	Whole structure vs intact objects, crossing point on the array plane	300	23	—	84–98	25.6–28.1	9.8–12	7.2–7.9	120– 130
1,000	Whole structure vs intact objects, crossing point on the array plane	1,000	23	—	366–459	60.8–68.9	100–140	17–19	280– 320
1,000	Whole structure vs intact objects, crossing point on the array plane	3,000	23	—	2,231–2,921	161.1–185.5	1,600–2,500	45–52	740– 860

Altitude (km)	Avoidance	Position uncertainty (m)	Crossings per year	Screening efficiency	Manoeuvres per year	Δv per manoeuvre (cm/s)	Propellant (t per GW per year)	Thrust (kN)	Power (MW)
1,000	Whole structure vs intact objects, envelope disc (upper bound)	100	23	—	155–160	40.5–41.2	29–30	5.7–5.8	93–95
1,000	Whole structure vs intact objects, envelope disc (upper bound)	300	23	—	221–239	48.3–50.3	48–54	6.8–7.1	110–120
1,000	Whole structure vs intact objects, envelope disc (upper bound)	1,000	23	—	542–637	75.7–82.1	190–240	11–12	170–190
1,000	Whole structure vs intact objects, envelope disc (upper bound)	3,000	23	—	2,241–2,829	153.9–173.0	1,600–2,200	22–24	360–400
1,000	Whole structure vs every catalogued object, crossing point on the array plane	100	59	—	103–111	15.6–16.4	7.3–8.2	4.4–4.6	72–76
1,000	Whole structure vs every catalogued object, crossing point on the array plane	300	59	—	221–256	25.6–28.1	26–33	7.2–7.9	120–130
1,000	Whole structure vs every catalogued object, crossing point on the array plane	1,000	59	—	961–1,205	60.8–68.9	270–380	17–19	280–320
1,000	Whole structure vs every catalogued object, crossing point on the array plane	3,000	59	—	5,860–7,676	161.1–185.5	4,300–6,500	45–52	740–860
1,000	Whole structure vs every catalogued object, envelope disc (upper bound)	100	59	—	408–421	40.5–41.2	75–79	5.7–5.8	93–95
1,000	Whole structure vs every catalogued object, envelope disc (upper bound)	300	59	—	581–627	48.3–50.3	130–140	6.8–7.1	110–120
1,000	Whole structure vs every catalogued object, envelope disc (upper bound)	1,000	59	—	1,425–1,673	75.7–82.1	490–620	11–12	170–190
1,000	Whole structure vs every catalogued object, envelope disc (upper bound)	3,000	59	—	5,887–7,433	153.9–173.0	4,100–5,800	22–24	360–400

Supplementary Table 8. Millimetre-scale ejecta chain between structures in opposite dawn–dusk planes: critical total installed power G^* (split equally between the two planes).

Altitude (km)	Surface	Angular scaling	G^* range (GW)	G^* median (GW)
550	Arrays	$\cos^2\Theta$ scaling	51–450	170
550	Arrays	normal-velocity scaling	66–560	200
550	Glass radiators facing the flight direction	$\cos^2\Theta$ scaling	23 / 44	—
650	Arrays	$\cos^2\Theta$ scaling	15–130	48
650	Arrays	normal-velocity scaling	19–160	58
650	Glass radiators facing the flight direction	$\cos^2\Theta$ scaling	6.7 / 13	—
850	Arrays	$\cos^2\Theta$ scaling	4.7–41	15

Altitude (km)	Surface	Angular scaling	G* range (GW)	G* median (GW)
850	Arrays	normal-velocity scaling	6.1–51	18
850	Glass radiators facing the flight direction	$\cos^2\Theta$ scaling	2.1 / 4.0	—
1,000	Arrays	$\cos^2\Theta$ scaling	1.5–13	4.8
1,000	Arrays	normal-velocity scaling	1.9–16	5.7
1,000	Glass radiators facing the flight direction	$\cos^2\Theta$ scaling	0.66 / 1.3	—

Supplementary Table 9. Five parameters with the largest Spearman correlation with the logarithm of the lethal population after 15 years at 20 GW (threshold 1.47 g; 1,000 draws, stripped fraction sampled log-uniformly from 10^{-4} to 1; screening efficiency 0.99 for the avoiding designs).

Design	Altitude (km)	Parameters (Spearman ρ)
Monolith, thin surfaces, radial radiators	550	strip +0.86; u_mass +0.31; q_exp -0.16; u_int +0.13; slope -0.08
Monolith, thin surfaces, radial radiators	650	strip +0.85; u_mass +0.32; am_rb -0.24; q_exp -0.11; u_int +0.08
Monolith, thin surfaces, radial radiators	850	strip +0.80; u_mass +0.37; am_rb -0.27; q_exp -0.11; u_int -0.08
Monolith, thin surfaces, radial radiators	1,000	strip +0.84; u_mass +0.39; am_rb -0.23; u_int -0.13; flake_slope -0.08
Monolith, structure avoids intact objects	550	q_exp -0.38; slope -0.37; strip +0.37; lfrag +0.34; vexp +0.18
Monolith, structure avoids intact objects	650	lfrag +0.58; strip +0.34; slope -0.31; q_exp -0.27; u_mass +0.17
Monolith, structure avoids intact objects	850	lfrag +0.62; slope -0.30; strip +0.29; q_exp -0.29; u_mass +0.15
Monolith, structure avoids intact objects	1,000	strip +0.69; u_mass +0.27; q_exp -0.24; lfrag +0.22; slope -0.21
Monolith, structure avoids every catalogued object	550	strip +0.47; lfrag +0.43; q_exp -0.30; slope -0.26; u_mass +0.19
Monolith, structure avoids every catalogued object	650	lfrag +0.67; strip +0.39; q_exp -0.19; slope -0.18; u_mass +0.17
Monolith, structure avoids every catalogued object	850	lfrag +0.68; strip +0.33; q_exp -0.24; slope -0.23; u_mass +0.15
Monolith, structure avoids every catalogued object	1,000	strip +0.73; u_mass +0.27; lfrag +0.24; q_exp -0.20; slope -0.16
Monolith with modules, structure and modules avoid	550	slope -0.42; strip +0.37; q_exp -0.37; lfrag +0.32; u_mass +0.18
Monolith with modules, structure and modules avoid	650	lfrag +0.56; slope -0.35; strip +0.34; q_exp -0.27; u_mass +0.17
Monolith with modules, structure and modules avoid	850	lfrag +0.61; slope -0.33; strip +0.29; q_exp -0.28; u_mass +0.15
Monolith with modules, structure and modules avoid	1,000	strip +0.67; u_mass +0.27; q_exp -0.24; slope -0.24; lfrag +0.18
Fleet of separate satellites	550	complete -0.61; a_sat +0.52; lfrag -0.27; m_sat +0.24; u_cat -0.23
Fleet of separate satellites	650	complete -0.58; a_sat +0.50; u_cat -0.44; m_sat +0.18; am_rb -0.14
Fleet of separate satellites	850	u_cat -0.69; complete -0.45; a_sat +0.41; m_sat +0.19; am_rb -0.11
Fleet of separate satellites	1,000	u_cat -0.66; complete -0.41; a_sat +0.41; m_sat +0.18; strip +0.15

Supplementary Table 10. Sensitivity of the lethal population after 15 years at 20 GW (relative to today; threshold 1.47 g) to modelling choices that the Monte Carlo does not sample, for fixed stripped fractions s : median over the first 150 of the 1,000 draws (share of draws above today’s population). Each variant changes one choice of the base case (Supplementary Note 6). The screening-efficiency variants act only on the avoiding design, and the module variant leaves both designs, which carry no modules, unchanged; both are listed for completeness.

Variant	Design	Altitude (km)	$s = 0$	$s = 0.01$	$s = 0.1$	$s = 1$
Base case	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	1.45 (86%)	3.84 (100%)	10.4 (100%)
Base case	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	0.95 (45%)	2.28 (94%)	4.97 (100%)
Base case	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	0.57 (21%)	1.46 (73%)	2.71 (94%)
Base case	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	1.78 (77%)	7.1 (99%)	13 (100%)
Base case	Monolith, structure avoids intact objects	550	0.82 (17%)	0.83 (20%)	0.89 (26%)	1.13 (71%)

Variant	Design	Altitude (km)	s = 0	s = 0.01	s = 0.1	s = 1
Base case	Monolith, structure avoids intact objects	650	0.59 (4%)	0.61 (4%)	0.65 (4%)	0.78 (17%)
Base case	Monolith, structure avoids intact objects	850	0.27 (0%)	0.28 (0%)	0.31 (1%)	0.4 (1%)
Base case	Monolith, structure avoids intact objects	1,000	0.18 (0%)	0.22 (0%)	0.35 (1%)	0.75 (33%)
No momentum exchange	Monolith, thin surfaces, radial radiators	550	1.3 (71%)	5.46 (100%)	17.2 (100%)	18.1 (100%)
No momentum exchange	Monolith, thin surfaces, radial radiators	650	1.14 (58%)	5.38 (100%)	15.5 (100%)	8.53 (100%)
No momentum exchange	Monolith, thin surfaces, radial radiators	850	1.05 (53%)	4.01 (99%)	9.75 (100%)	5.18 (100%)
No momentum exchange	Monolith, thin surfaces, radial radiators	1,000	1.5 (63%)	14.1 (100%)	40.5 (100%)	22.7 (100%)
No momentum exchange	Monolith, structure avoids intact objects	550	1 (51%)	1.03 (53%)	1.26 (76%)	1.79 (96%)
No momentum exchange	Monolith, structure avoids intact objects	650	0.75 (33%)	0.77 (35%)	0.91 (41%)	1.25 (67%)
No momentum exchange	Monolith, structure avoids intact objects	850	0.58 (27%)	0.59 (27%)	0.66 (30%)	0.83 (42%)
No momentum exchange	Monolith, structure avoids intact objects	1,000	0.44 (21%)	0.51 (24%)	0.8 (40%)	1.53 (74%)
Normal incidence only	Monolith, thin surfaces, radial radiators	550	0.83 (17%)	1.4 (88%)	3.78 (100%)	12.9 (100%)
Normal incidence only	Monolith, thin surfaces, radial radiators	650	0.62 (4%)	0.99 (49%)	2.37 (96%)	5.8 (100%)
Normal incidence only	Monolith, thin surfaces, radial radiators	850	0.31 (0%)	0.63 (26%)	1.75 (77%)	3.12 (97%)
Normal incidence only	Monolith, thin surfaces, radial radiators	1,000	0.24 (6%)	1.88 (79%)	8.1 (99%)	15 (100%)
Normal incidence only	Monolith, structure avoids intact objects	550	0.82 (15%)	0.83 (17%)	0.88 (19%)	1.18 (77%)
Normal incidence only	Monolith, structure avoids intact objects	650	0.59 (4%)	0.6 (4%)	0.65 (4%)	0.82 (25%)
Normal incidence only	Monolith, structure avoids intact objects	850	0.27 (0%)	0.27 (0%)	0.31 (0%)	0.43 (1%)
Normal incidence only	Monolith, structure avoids intact objects	1,000	0.18 (0%)	0.21 (0%)	0.31 (0%)	0.79 (38%)
Incidence from the MASTER oriented-surface factors	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	1.49 (86%)	3.99 (100%)	9.89 (100%)
Incidence from the MASTER oriented-surface factors	Monolith, thin surfaces, radial radiators	650	0.61 (5%)	0.9 (37%)	2.21 (91%)	4.27 (99%)
Incidence from the MASTER oriented-surface factors	Monolith, thin surfaces, radial radiators	850	0.3 (1%)	0.53 (18%)	1.3 (64%)	2.36 (89%)
Incidence from the MASTER oriented-surface factors	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	1.63 (71%)	6.23 (99%)	11.3 (100%)
Incidence from the MASTER oriented-surface factors	Monolith, structure avoids intact objects	550	0.82 (19%)	0.83 (19%)	0.9 (29%)	1.1 (65%)
Incidence from the MASTER oriented-surface factors	Monolith, structure avoids intact objects	650	0.6 (5%)	0.61 (5%)	0.65 (5%)	0.75 (14%)
Incidence from the MASTER oriented-surface factors	Monolith, structure avoids intact objects	850	0.27 (0%)	0.28 (0%)	0.32 (0%)	0.38 (1%)
Incidence from the MASTER oriented-surface factors	Monolith, structure avoids intact objects	1,000	0.18 (0%)	0.22 (1%)	0.37 (4%)	0.66 (29%)
Catalogue area-to-mass, not rescaled	Monolith, thin surfaces, radial radiators	550	0.83 (16%)	1.44 (87%)	3.93 (100%)	10.4 (100%)

Variant	Design	Altitude (km)	s = 0	s = 0.01	s = 0.1	s = 1
Catalogue area-to-mass, not rescaled	Monolith, thin surfaces, radial radiators	650	0.62 (13%)	0.97 (49%)	2.4 (94%)	5.09 (100%)
Catalogue area-to-mass, not rescaled	Monolith, thin surfaces, radial radiators	850	0.4 (18%)	0.71 (36%)	1.82 (82%)	3.17 (94%)
Catalogue area-to-mass, not rescaled	Monolith, thin surfaces, radial radiators	1,000	0.49 (27%)	2.4 (84%)	8.77 (99%)	15 (100%)
Catalogue area-to-mass, not rescaled	Monolith, structure avoids intact objects	550	0.82 (15%)	0.83 (16%)	0.89 (23%)	1.13 (69%)
Catalogue area-to-mass, not rescaled	Monolith, structure avoids intact objects	650	0.61 (11%)	0.62 (13%)	0.66 (13%)	0.78 (24%)
Catalogue area-to-mass, not rescaled	Monolith, structure avoids intact objects	850	0.35 (17%)	0.36 (18%)	0.39 (18%)	0.5 (19%)
Catalogue area-to-mass, not rescaled	Monolith, structure avoids intact objects	1,000	0.29 (21%)	0.33 (21%)	0.55 (24%)	1.08 (57%)
Standard-model area-to-mass	Monolith, thin surfaces, radial radiators	550	0.82 (5%)	1.34 (85%)	3.74 (100%)	10.4 (100%)
Standard-model area-to-mass	Monolith, thin surfaces, radial radiators	650	0.6 (0%)	0.91 (41%)	2.24 (94%)	4.94 (100%)
Standard-model area-to-mass	Monolith, thin surfaces, radial radiators	850	0.29 (0%)	0.55 (19%)	1.45 (70%)	2.69 (94%)
Standard-model area-to-mass	Monolith, thin surfaces, radial radiators	1,000	0.23 (4%)	1.75 (74%)	7.1 (99%)	13 (100%)
Standard-model area-to-mass	Monolith, structure avoids intact objects	550	0.8 (3%)	0.82 (3%)	0.88 (13%)	1.09 (63%)
Standard-model area-to-mass	Monolith, structure avoids intact objects	650	0.59 (0%)	0.6 (0%)	0.64 (0%)	0.76 (11%)
Standard-model area-to-mass	Monolith, structure avoids intact objects	850	0.25 (0%)	0.26 (0%)	0.29 (0%)	0.38 (0%)
Standard-model area-to-mass	Monolith, structure avoids intact objects	1,000	0.17 (0%)	0.2 (0%)	0.32 (1%)	0.7 (30%)
Stripped material takes the momentum	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	0.82 (18%)	2.3 (83%)	10.4 (100%)
Stripped material takes the momentum	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	0.6 (5%)	2.19 (84%)	4.97 (100%)
Stripped material takes the momentum	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	0.27 (0%)	1.13 (53%)	2.71 (94%)
Stripped material takes the momentum	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	0.19 (3%)	6.15 (98%)	13 (100%)
Stripped material takes the momentum	Monolith, structure avoids intact objects	550	0.82 (17%)	0.82 (17%)	0.83 (19%)	1.13 (71%)
Stripped material takes the momentum	Monolith, structure avoids intact objects	650	0.59 (4%)	0.59 (4%)	0.61 (4%)	0.78 (17%)
Stripped material takes the momentum	Monolith, structure avoids intact objects	850	0.27 (0%)	0.27 (0%)	0.28 (0%)	0.4 (1%)
Stripped material takes the momentum	Monolith, structure avoids intact objects	1,000	0.18 (0%)	0.18 (0%)	0.23 (0%)	0.75 (33%)
Stripping yield linear in s	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	1.03 (57%)	2.88 (99%)	10.4 (100%)
Stripping yield linear in s	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	0.74 (18%)	1.72 (86%)	4.97 (100%)
Stripping yield linear in s	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	0.41 (7%)	1.1 (53%)	2.71 (94%)
Stripping yield linear in s	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	0.84 (41%)	4.79 (99%)	13 (100%)
Stripping yield linear in s	Monolith, structure avoids intact objects	550	0.82 (17%)	0.82 (18%)	0.86 (21%)	1.13 (71%)

Variant	Design	Altitude (km)	s = 0	s = 0.01	s = 0.1	s = 1
Stripping yield linear in s	Monolith, structure avoids intact objects	650	0.59 (4%)	0.6 (4%)	0.63 (4%)	0.78 (17%)
Stripping yield linear in s	Monolith, structure avoids intact objects	850	0.27 (0%)	0.27 (0%)	0.3 (0%)	0.4 (1%)
Stripping yield linear in s	Monolith, structure avoids intact objects	1,000	0.18 (0%)	0.2 (0%)	0.29 (0%)	0.75 (33%)
Steady product weights	Monolith, thin surfaces, radial radiators	550	0.86 (30%)	1.85 (93%)	6.21 (100%)	18.7 (100%)
Steady product weights	Monolith, thin surfaces, radial radiators	650	0.65 (16%)	1.09 (57%)	3.06 (96%)	8.32 (100%)
Steady product weights	Monolith, thin surfaces, radial radiators	850	0.31 (13%)	0.64 (29%)	2.05 (79%)	6.45 (97%)
Steady product weights	Monolith, thin surfaces, radial radiators	1,000	0.21 (9%)	1.83 (74%)	8.19 (98%)	26.7 (100%)
Steady product weights	Monolith, structure avoids intact objects	550	0.85 (28%)	0.87 (29%)	0.99 (48%)	1.49 (85%)
Steady product weights	Monolith, structure avoids intact objects	650	0.64 (15%)	0.66 (17%)	0.72 (21%)	1.03 (53%)
Steady product weights	Monolith, structure avoids intact objects	850	0.3 (13%)	0.31 (13%)	0.37 (13%)	0.58 (23%)
Steady product weights	Monolith, structure avoids intact objects	1,000	0.19 (9%)	0.25 (11%)	0.51 (21%)	1.43 (66%)
In-shell time from an effective altitude	Monolith, thin surfaces, radial radiators	550	0.83 (17%)	1.1 (71%)	2.34 (100%)	5.85 (100%)
In-shell time from an effective altitude	Monolith, thin surfaces, radial radiators	650	0.61 (1%)	0.74 (19%)	1.33 (73%)	2.14 (99%)
In-shell time from an effective altitude	Monolith, thin surfaces, radial radiators	850	0.29 (0%)	0.46 (15%)	1.1 (53%)	1.36 (69%)
In-shell time from an effective altitude	Monolith, thin surfaces, radial radiators	1,000	0.22 (5%)	1.46 (60%)	5.59 (97%)	7.06 (98%)
In-shell time from an effective altitude	Monolith, structure avoids intact objects	550	0.82 (17%)	0.83 (17%)	0.86 (17%)	0.98 (43%)
In-shell time from an effective altitude	Monolith, structure avoids intact objects	650	0.59 (1%)	0.59 (1%)	0.62 (1%)	0.68 (3%)
In-shell time from an effective altitude	Monolith, structure avoids intact objects	850	0.26 (0%)	0.27 (0%)	0.29 (0%)	0.35 (0%)
In-shell time from an effective altitude	Monolith, structure avoids intact objects	1,000	0.17 (0%)	0.2 (0%)	0.26 (0%)	0.48 (17%)
Products counted with the residence time of the population they join	Monolith, thin surfaces, radial radiators	550	0.9 (35%)	1.53 (89%)	4.03 (100%)	10.5 (100%)
Products counted with the residence time of the population they join	Monolith, thin surfaces, radial radiators	650	0.66 (9%)	0.98 (49%)	2.35 (94%)	5.12 (100%)
Products counted with the residence time of the population they join	Monolith, thin surfaces, radial radiators	850	0.39 (14%)	0.72 (30%)	1.68 (75%)	2.88 (95%)
Products counted with the residence time of the population they join	Monolith, thin surfaces, radial radiators	1,000	0.58 (42%)	2.73 (85%)	8.25 (99%)	13.7 (100%)
Products counted with the residence time of the population they join	Monolith, structure avoids intact objects	550	0.84 (19%)	0.85 (20%)	0.9 (31%)	1.17 (71%)
Products counted with the residence time of the population they join	Monolith, structure avoids intact objects	650	0.61 (4%)	0.62 (4%)	0.66 (4%)	0.78 (19%)
Products counted with the residence time of the population they join	Monolith, structure avoids intact objects	850	0.3 (0%)	0.31 (0%)	0.33 (1%)	0.42 (1%)
Products counted with the residence time of the population they join	Monolith, structure avoids intact objects	1,000	0.21 (0%)	0.24 (0%)	0.38 (3%)	0.76 (36%)
Screening efficiency 0.90	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	1.45 (86%)	3.84 (100%)	10.4 (100%)

Variant	Design	Altitude (km)	s = 0	s = 0.01	s = 0.1	s = 1
Screening efficiency 0.90	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	0.95 (45%)	2.28 (94%)	4.97 (100%)
Screening efficiency 0.90	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	0.57 (21%)	1.46 (73%)	2.71 (94%)
Screening efficiency 0.90	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	1.78 (77%)	7.1 (99%)	13 (100%)
Screening efficiency 0.90	Monolith, structure avoids intact objects	550	0.82 (17%)	0.94 (37%)	1.58 (94%)	3.4 (100%)
Screening efficiency 0.90	Monolith, structure avoids intact objects	650	0.6 (4%)	0.68 (5%)	0.99 (48%)	2 (95%)
Screening efficiency 0.90	Monolith, structure avoids intact objects	850	0.28 (0%)	0.35 (1%)	0.55 (12%)	1.2 (61%)
Screening efficiency 0.90	Monolith, structure avoids intact objects	1,000	0.2 (0%)	0.46 (11%)	1.52 (72%)	4.67 (99%)
Screening efficiency 0.95	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	1.45 (86%)	3.84 (100%)	10.4 (100%)
Screening efficiency 0.95	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	0.95 (45%)	2.28 (94%)	4.97 (100%)
Screening efficiency 0.95	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	0.57 (21%)	1.46 (73%)	2.71 (94%)
Screening efficiency 0.95	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	1.78 (77%)	7.1 (99%)	13 (100%)
Screening efficiency 0.95	Monolith, structure avoids intact objects	550	0.82 (17%)	0.88 (23%)	1.19 (75%)	2.29 (98%)
Screening efficiency 0.95	Monolith, structure avoids intact objects	650	0.6 (4%)	0.65 (4%)	0.81 (27%)	1.4 (77%)
Screening efficiency 0.95	Monolith, structure avoids intact objects	850	0.27 (0%)	0.31 (0%)	0.43 (2%)	0.79 (31%)
Screening efficiency 0.95	Monolith, structure avoids intact objects	1,000	0.19 (0%)	0.34 (0%)	0.88 (43%)	2.68 (95%)
Screening efficiency 0.97	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	1.45 (86%)	3.84 (100%)	10.4 (100%)
Screening efficiency 0.97	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	0.95 (45%)	2.28 (94%)	4.97 (100%)
Screening efficiency 0.97	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	0.57 (21%)	1.46 (73%)	2.71 (94%)
Screening efficiency 0.97	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	1.78 (77%)	7.1 (99%)	13 (100%)
Screening efficiency 0.97	Monolith, structure avoids intact objects	550	0.82 (17%)	0.85 (21%)	1.04 (57%)	1.73 (96%)
Screening efficiency 0.97	Monolith, structure avoids intact objects	650	0.59 (4%)	0.62 (4%)	0.74 (11%)	1.1 (57%)
Screening efficiency 0.97	Monolith, structure avoids intact objects	850	0.27 (0%)	0.3 (0%)	0.38 (1%)	0.61 (18%)
Screening efficiency 0.97	Monolith, structure avoids intact objects	1,000	0.19 (0%)	0.28 (0%)	0.62 (23%)	1.74 (77%)
Screening efficiency 0.98	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	1.45 (86%)	3.84 (100%)	10.4 (100%)
Screening efficiency 0.98	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	0.95 (45%)	2.28 (94%)	4.97 (100%)
Screening efficiency 0.98	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	0.57 (21%)	1.46 (73%)	2.71 (94%)
Screening efficiency 0.98	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	1.78 (77%)	7.1 (99%)	13 (100%)
Screening efficiency 0.98	Monolith, structure avoids intact objects	550	0.82 (17%)	0.84 (21%)	0.97 (41%)	1.47 (91%)

Variant	Design	Altitude (km)	s = 0	s = 0.01	s = 0.1	s = 1
Screening efficiency 0.98	Monolith, structure avoids intact objects	650	0.59 (4%)	0.61 (4%)	0.69 (5%)	0.94 (42%)
Screening efficiency 0.98	Monolith, structure avoids intact objects	850	0.27 (0%)	0.29 (0%)	0.36 (1%)	0.51 (8%)
Screening efficiency 0.98	Monolith, structure avoids intact objects	1,000	0.18 (0%)	0.25 (0%)	0.48 (12%)	1.26 (61%)
Screening efficiency 0.995	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	1.45 (86%)	3.84 (100%)	10.4 (100%)
Screening efficiency 0.995	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	0.95 (45%)	2.28 (94%)	4.97 (100%)
Screening efficiency 0.995	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	0.57 (21%)	1.46 (73%)	2.71 (94%)
Screening efficiency 0.995	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	1.78 (77%)	7.1 (99%)	13 (100%)
Screening efficiency 0.995	Monolith, structure avoids intact objects	550	0.82 (17%)	0.82 (18%)	0.85 (21%)	0.97 (43%)
Screening efficiency 0.995	Monolith, structure avoids intact objects	650	0.59 (4%)	0.6 (4%)	0.62 (4%)	0.69 (6%)
Screening efficiency 0.995	Monolith, structure avoids intact objects	850	0.27 (0%)	0.27 (0%)	0.29 (0%)	0.36 (1%)
Screening efficiency 0.995	Monolith, structure avoids intact objects	1,000	0.18 (0%)	0.2 (0%)	0.27 (0%)	0.48 (13%)
Screening efficiency 0.999	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	1.45 (86%)	3.84 (100%)	10.4 (100%)
Screening efficiency 0.999	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	0.95 (45%)	2.28 (94%)	4.97 (100%)
Screening efficiency 0.999	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	0.57 (21%)	1.46 (73%)	2.71 (94%)
Screening efficiency 0.999	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	1.78 (77%)	7.1 (99%)	13 (100%)
Screening efficiency 0.999	Monolith, structure avoids intact objects	550	0.82 (17%)	0.82 (17%)	0.83 (18%)	0.85 (21%)
Screening efficiency 0.999	Monolith, structure avoids intact objects	650	0.59 (4%)	0.59 (4%)	0.6 (4%)	0.61 (4%)
Screening efficiency 0.999	Monolith, structure avoids intact objects	850	0.27 (0%)	0.27 (0%)	0.27 (0%)	0.29 (0%)
Screening efficiency 0.999	Monolith, structure avoids intact objects	1,000	0.18 (0%)	0.18 (0%)	0.2 (0%)	0.25 (0%)
Compute modules of 30 t	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	1.45 (86%)	3.84 (100%)	10.4 (100%)
Compute modules of 30 t	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	0.95 (45%)	2.28 (94%)	4.97 (100%)
Compute modules of 30 t	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	0.57 (21%)	1.46 (73%)	2.71 (94%)
Compute modules of 30 t	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	1.78 (77%)	7.1 (99%)	13 (100%)
Compute modules of 30 t	Monolith, structure avoids intact objects	550	0.82 (17%)	0.83 (20%)	0.89 (26%)	1.13 (71%)
Compute modules of 30 t	Monolith, structure avoids intact objects	650	0.59 (4%)	0.61 (4%)	0.65 (4%)	0.78 (17%)
Compute modules of 30 t	Monolith, structure avoids intact objects	850	0.27 (0%)	0.28 (0%)	0.31 (1%)	0.4 (1%)
Compute modules of 30 t	Monolith, structure avoids intact objects	1,000	0.18 (0%)	0.22 (0%)	0.35 (1%)	0.75 (33%)
Array areal density 1 kg/m ²	Monolith, thin surfaces, radial radiators	550	0.86 (24%)	1.39 (81%)	3.66 (99%)	7.24 (100%)

Variant	Design	Altitude (km)	s = 0	s = 0.01	s = 0.1	s = 1
Array areal density 1 kg/m ²	Monolith, thin surfaces, radial radiators	650	0.62 (3%)	0.87 (35%)	1.98 (89%)	3.5 (98%)
Array areal density 1 kg/m ²	Monolith, thin surfaces, radial radiators	850	0.32 (1%)	0.5 (15%) (59%)	1.19 (88%)	2.06 (88%)
Array areal density 1 kg/m ²	Monolith, thin surfaces, radial radiators	1,000	0.29 (8%)	1.52 (67%)	5.61 (99%)	9.81 (100%)
Array areal density 1 kg/m ²	Monolith, structure avoids intact objects	550	0.83 (19%)	0.84 (21%)	0.9 (32%)	1.02 (53%)
Array areal density 1 kg/m ²	Monolith, structure avoids intact objects	650	0.61 (3%)	0.61 (3%)	0.65 (4%)	0.72 (10%)
Array areal density 1 kg/m ²	Monolith, structure avoids intact objects	850	0.27 (0%)	0.29 (0%)	0.32 (0%)	0.37 (0%)
Array areal density 1 kg/m ²	Monolith, structure avoids intact objects	1,000	0.19 (0%)	0.23 (0%)	0.38 (4%)	0.59 (23%)
Array areal density 2 kg/m ²	Monolith, thin surfaces, radial radiators	550	0.86 (27%)	1.23 (73%)	2.87 (97%)	3.92 (97%)
Array areal density 2 kg/m ²	Monolith, thin surfaces, radial radiators	650	0.62 (2%)	0.8 (23%)	1.6 (77%)	2.04 (86%)
Array areal density 2 kg/m ²	Monolith, thin surfaces, radial radiators	850	0.31 (0%)	0.43 (7%) (45%)	0.92 (45%)	1.24 (60%)
Array areal density 2 kg/m ²	Monolith, thin surfaces, radial radiators	1,000	0.3 (9%)	1.15 (57%)	4.32 (97%)	6.06 (100%)
Array areal density 2 kg/m ²	Monolith, structure avoids intact objects	550	0.84 (19%)	0.84 (20%)	0.88 (27%)	0.93 (33%)
Array areal density 2 kg/m ²	Monolith, structure avoids intact objects	650	0.61 (1%)	0.61 (1%)	0.64 (2%)	0.67 (3%)
Array areal density 2 kg/m ²	Monolith, structure avoids intact objects	850	0.28 (0%)	0.29 (0%)	0.31 (0%)	0.33 (0%)
Array areal density 2 kg/m ²	Monolith, structure avoids intact objects	1,000	0.19 (0%)	0.22 (0%)	0.37 (3%)	0.45 (7%)
Array areal density 3 kg/m ²	Monolith, thin surfaces, radial radiators	550	0.87 (26%)	1.16 (71%)	2.35 (89%)	2.6 (90%)
Array areal density 3 kg/m ²	Monolith, thin surfaces, radial radiators	650	0.63 (2%)	0.78 (21%)	1.45 (71%)	1.6 (74%)
Array areal density 3 kg/m ²	Monolith, thin surfaces, radial radiators	850	0.3 (0%)	0.38 (2%)	0.73 (31%)	0.82 (36%)
Array areal density 3 kg/m ²	Monolith, thin surfaces, radial radiators	1,000	0.3 (9%)	1 (49%) (95%)	3.37 (95%)	3.88 (95%)
Array areal density 3 kg/m ²	Monolith, structure avoids intact objects	550	0.84 (17%)	0.84 (18%)	0.87 (23%)	0.87 (27%)
Array areal density 3 kg/m ²	Monolith, structure avoids intact objects	650	0.61 (1%)	0.62 (1%)	0.64 (1%)	0.65 (1%)
Array areal density 3 kg/m ²	Monolith, structure avoids intact objects	850	0.28 (0%)	0.28 (0%)	0.3 (0%)	0.3 (0%)
Array areal density 3 kg/m ²	Monolith, structure avoids intact objects	1,000	0.19 (0%)	0.22 (0%)	0.33 (1%)	0.35 (3%)
Product counts not calibrated	Monolith, thin surfaces, radial radiators	550	0.83 (13%)	1.2 (76%) (100%)	2.84 (100%)	7.86 (100%)
Product counts not calibrated	Monolith, thin surfaces, radial radiators	650	0.59 (0%)	0.73 (7%) (71%)	1.27 (71%)	2.6 (100%)
Product counts not calibrated	Monolith, thin surfaces, radial radiators	850	0.27 (0%)	0.41 (1%) (41%)	0.83 (41%)	1.78 (82%)
Product counts not calibrated	Monolith, thin surfaces, radial radiators	1,000	0.21 (0%)	0.85 (42%)	3.5 (97%)	8.05 (100%)
Product counts not calibrated	Monolith, structure avoids intact objects	550	0.82 (11%)	0.83 (11%)	0.87 (17%)	1.02 (53%)

Variant	Design	Altitude (km)	s = 0	s = 0.01	s = 0.1	s = 1
Product counts not calibrated	Monolith, structure avoids intact objects	650	0.58 (0%)	0.58 (0%)	0.61 (0%)	0.69 (1%)
Product counts not calibrated	Monolith, structure avoids intact objects	850	0.26 (0%)	0.26 (0%)	0.29 (0%)	0.37 (0%)
Product counts not calibrated	Monolith, structure avoids intact objects	1,000	0.18 (0%)	0.2 (0%)	0.28 (0%)	0.53 (16%)
Calibrated counts, one compartment per bin	Monolith, thin surfaces, radial radiators	550	0.84 (19%)	1.44 (85%)	3.77 (100%)	10.2 (100%)
Calibrated counts, one compartment per bin	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	0.95 (46%)	2.37 (93%)	5.01 (100%)
Calibrated counts, one compartment per bin	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	0.58 (23%)	1.5 (73%)	2.71 (94%)
Calibrated counts, one compartment per bin	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	1.82 (77%)	7.24 (99%)	13 (100%)
Calibrated counts, one compartment per bin	Monolith, structure avoids intact objects	550	0.82 (17%)	0.83 (20%)	0.88 (25%)	1.13 (69%)
Calibrated counts, one compartment per bin	Monolith, structure avoids intact objects	650	0.6 (4%)	0.61 (4%)	0.65 (4%)	0.78 (19%)
Calibrated counts, one compartment per bin	Monolith, structure avoids intact objects	850	0.27 (0%)	0.28 (0%)	0.31 (1%)	0.41 (1%)
Calibrated counts, one compartment per bin	Monolith, structure avoids intact objects	1,000	0.18 (0%)	0.22 (0%)	0.35 (1%)	0.75 (35%)
Calibrated counts, six compartments per bin	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	1.45 (87%)	3.87 (100%)	10.5 (100%)
Calibrated counts, six compartments per bin	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	0.93 (45%)	2.26 (94%)	4.96 (100%)
Calibrated counts, six compartments per bin	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	0.57 (21%)	1.45 (72%)	2.71 (94%)
Calibrated counts, six compartments per bin	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	1.77 (77%)	7.07 (99%)	13 (100%)
Calibrated counts, six compartments per bin	Monolith, structure avoids intact objects	550	0.82 (17%)	0.83 (20%)	0.89 (26%)	1.14 (71%)
Calibrated counts, six compartments per bin	Monolith, structure avoids intact objects	650	0.59 (4%)	0.6 (4%)	0.65 (4%)	0.78 (17%)
Calibrated counts, six compartments per bin	Monolith, structure avoids intact objects	850	0.27 (0%)	0.28 (0%)	0.31 (1%)	0.4 (1%)
Calibrated counts, six compartments per bin	Monolith, structure avoids intact objects	1,000	0.18 (0%)	0.22 (0%)	0.35 (1%)	0.74 (33%)
Small-fragment yield of breakups $\times 3.5$	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	2.87 (99%)	11 (100%)	34 (100%)
Small-fragment yield of breakups $\times 3.5$	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	1.82 (87%)	6.53 (100%)	15.9 (100%)
Small-fragment yield of breakups $\times 3.5$	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	1.17 (56%)	4.44 (98%)	8.78 (100%)
Small-fragment yield of breakups $\times 3.5$	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	5.5 (99%)	24.3 (100%)	44.4 (100%)
Small-fragment yield of breakups $\times 3.5$	Monolith, structure avoids intact objects	550	0.82 (17%)	0.86 (21%)	1.09 (65%)	1.9 (97%)
Small-fragment yield of breakups $\times 3.5$	Monolith, structure avoids intact objects	650	0.59 (4%)	0.63 (4%)	0.76 (13%)	1.2 (67%)
Small-fragment yield of breakups $\times 3.5$	Monolith, structure avoids intact objects	850	0.27 (0%)	0.3 (0%)	0.39 (1%)	0.67 (22%)
Small-fragment yield of breakups $\times 3.5$	Monolith, structure avoids intact objects	1,000	0.18 (0%)	0.29 (0%)	0.7 (29%)	2.03 (85%)
Small-fragment yield $\times 3.5$, screening efficiency 0.9	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	2.87 (99%)	11 (100%)	34 (100%)

Variant	Design	Altitude (km)	s = 0	s = 0.01	s = 0.1	s = 1
Small-fragment yield ×3.5, screening efficiency 0.9	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	1.82 (87%)	6.53 (100%)	15.9 (100%)
Small-fragment yield ×3.5, screening efficiency 0.9	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	1.17 (56%)	4.44 (98%)	8.78 (100%)
Small-fragment yield ×3.5, screening efficiency 0.9	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	5.5 (99%)	24.3 (100%)	44.4 (100%)
Small-fragment yield ×3.5, screening efficiency 0.9	Monolith, structure avoids intact objects	550	0.82 (17%)	1.26 (77%)	3.08 (100%)	9.55 (100%)
Small-fragment yield ×3.5, screening efficiency 0.9	Monolith, structure avoids intact objects	650	0.6 (4%)	0.84 (31%)	1.95 (93%)	5.52 (100%)
Small-fragment yield ×3.5, screening efficiency 0.9	Monolith, structure avoids intact objects	850	0.28 (0%)	0.46 (3%)	1.12 (59%)	3.25 (97%)
Small-fragment yield ×3.5, screening efficiency 0.9	Monolith, structure avoids intact objects	1,000	0.2 (0%)	1.06 (52%)	4.77 (99%)	15.3 (100%)
Small-fragment yield ×3.5, screening efficiency 0.95	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	2.87 (99%)	11 (100%)	34 (100%)
Small-fragment yield ×3.5, screening efficiency 0.95	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	1.82 (87%)	6.53 (100%)	15.9 (100%)
Small-fragment yield ×3.5, screening efficiency 0.95	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	1.17 (56%)	4.44 (98%)	8.78 (100%)
Small-fragment yield ×3.5, screening efficiency 0.95	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	5.5 (99%)	24.3 (100%)	44.4 (100%)
Small-fragment yield ×3.5, screening efficiency 0.95	Monolith, structure avoids intact objects	550	0.82 (17%)	1.05 (59%)	2.08 (97%)	5.45 (100%)
Small-fragment yield ×3.5, screening efficiency 0.95	Monolith, structure avoids intact objects	650	0.6 (4%)	0.74 (11%)	1.3 (72%)	3.3 (98%)
Small-fragment yield ×3.5, screening efficiency 0.95	Monolith, structure avoids intact objects	850	0.27 (0%)	0.39 (1%)	0.76 (31%)	1.91 (87%)
Small-fragment yield ×3.5, screening efficiency 0.95	Monolith, structure avoids intact objects	1,000	0.19 (0%)	0.65 (24%)	2.57 (94%)	8.41 (100%)
Small-fragment yield ×3.5, screening efficiency 0.97	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	2.87 (99%)	11 (100%)	34 (100%)
Small-fragment yield ×3.5, screening efficiency 0.97	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	1.82 (87%)	6.53 (100%)	15.9 (100%)
Small-fragment yield ×3.5, screening efficiency 0.97	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	1.17 (56%)	4.44 (98%)	8.78 (100%)
Small-fragment yield ×3.5, screening efficiency 0.97	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	5.5 (99%)	24.3 (100%)	44.4 (100%)
Small-fragment yield ×3.5, screening efficiency 0.97	Monolith, structure avoids intact objects	550	0.82 (17%)	0.96 (39%)	1.64 (95%)	3.73 (100%)
Small-fragment yield ×3.5, screening efficiency 0.97	Monolith, structure avoids intact objects	650	0.59 (4%)	0.68 (5%)	1.04 (55%)	2.26 (96%)
Small-fragment yield ×3.5, screening efficiency 0.97	Monolith, structure avoids intact objects	850	0.27 (0%)	0.35 (1%)	0.57 (14%)	1.34 (67%)
Small-fragment yield ×3.5, screening efficiency 0.97	Monolith, structure avoids intact objects	1,000	0.19 (0%)	0.47 (11%)	1.65 (74%)	5.35 (99%)
Small-fragment yield ×3.5, screening efficiency 0.98	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	2.87 (99%)	11 (100%)	34 (100%)
Small-fragment yield ×3.5, screening efficiency 0.98	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	1.82 (87%)	6.53 (100%)	15.9 (100%)
Small-fragment yield ×3.5, screening efficiency 0.98	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	1.17 (56%)	4.44 (98%)	8.78 (100%)
Small-fragment yield ×3.5, screening efficiency 0.98	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	5.5 (99%)	24.3 (100%)	44.4 (100%)
Small-fragment yield ×3.5, screening efficiency 0.98	Monolith, structure avoids intact objects	550	0.82 (17%)	0.9 (30%)	1.39 (84%)	2.93 (99%)

Variant	Design	Altitude (km)	s = 0	s = 0.01	s = 0.1	s = 1
Small-fragment yield $\times 3.5$, screening efficiency 0.98	Monolith, structure avoids intact objects	650	0.59 (4%)	0.66 (4%)	0.89 (38%)	1.73 (91%)
Small-fragment yield $\times 3.5$, screening efficiency 0.98	Monolith, structure avoids intact objects	850	0.27 (0%)	0.32 (1%)	0.49 (5%)	1.02 (51%)
Small-fragment yield $\times 3.5$, screening efficiency 0.98	Monolith, structure avoids intact objects	1,000	0.18 (0%)	0.39 (3%)	1.16 (57%)	3.74 (97%)
Small-fragment yield $\times 3.5$, screening efficiency 0.995	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	2.87 (99%)	11 (100%)	34 (100%)
Small-fragment yield $\times 3.5$, screening efficiency 0.995	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	1.82 (87%)	6.53 (100%)	15.9 (100%)
Small-fragment yield $\times 3.5$, screening efficiency 0.995	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	1.17 (56%)	4.44 (98%)	8.78 (100%)
Small-fragment yield $\times 3.5$, screening efficiency 0.995	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	5.5 (99%)	24.3 (100%)	44.4 (100%)
Small-fragment yield $\times 3.5$, screening efficiency 0.995	Monolith, structure avoids intact objects	550	0.82 (17%)	0.84 (21%)	0.96 (39%)	1.39 (85%)
Small-fragment yield $\times 3.5$, screening efficiency 0.995	Monolith, structure avoids intact objects	650	0.59 (4%)	0.61 (4%)	0.68 (5%)	0.9 (37%)
Small-fragment yield $\times 3.5$, screening efficiency 0.995	Monolith, structure avoids intact objects	850	0.27 (0%)	0.28 (0%)	0.35 (1%)	0.48 (7%)
Small-fragment yield $\times 3.5$, screening efficiency 0.995	Monolith, structure avoids intact objects	1,000	0.18 (0%)	0.24 (0%)	0.45 (9%)	1.14 (58%)
Small-fragment yield $\times 3.5$, screening efficiency 0.999	Monolith, thin surfaces, radial radiators	550	0.84 (20%)	2.87 (99%)	11 (100%)	34 (100%)
Small-fragment yield $\times 3.5$, screening efficiency 0.999	Monolith, thin surfaces, radial radiators	650	0.61 (4%)	1.82 (87%)	6.53 (100%)	15.9 (100%)
Small-fragment yield $\times 3.5$, screening efficiency 0.999	Monolith, thin surfaces, radial radiators	850	0.31 (1%)	1.17 (56%)	4.44 (98%)	8.78 (100%)
Small-fragment yield $\times 3.5$, screening efficiency 0.999	Monolith, thin surfaces, radial radiators	1,000	0.25 (5%)	5.5 (99%)	24.3 (100%)	44.4 (100%)
Small-fragment yield $\times 3.5$, screening efficiency 0.999	Monolith, structure avoids intact objects	550	0.82 (17%)	0.82 (18%)	0.84 (21%)	0.92 (33%)
Small-fragment yield $\times 3.5$, screening efficiency 0.999	Monolith, structure avoids intact objects	650	0.59 (4%)	0.6 (4%)	0.61 (4%)	0.67 (4%)
Small-fragment yield $\times 3.5$, screening efficiency 0.999	Monolith, structure avoids intact objects	850	0.27 (0%)	0.27 (0%)	0.28 (0%)	0.33 (1%)
Small-fragment yield $\times 3.5$, screening efficiency 0.999	Monolith, structure avoids intact objects	1,000	0.18 (0%)	0.19 (0%)	0.25 (0%)	0.4 (6%)
No radial mixing, structures within ± 2 km	Monolith, thin surfaces, radial radiators	550	0.86 (17%)	1.21 (77%)	2.63 (100%)	6.37 (100%)
No radial mixing, structures within ± 2 km	Monolith, thin surfaces, radial radiators	650	0.68 (4%)	0.81 (19%)	1.32 (73%)	2.12 (97%)
No radial mixing, structures within ± 2 km	Monolith, thin surfaces, radial radiators	850	0.42 (0%)	0.58 (12%)	1.1 (55%)	1.63 (82%)
No radial mixing, structures within ± 2 km	Monolith, thin surfaces, radial radiators	1,000	0.37 (3%)	1.42 (68%)	5.23 (99%)	8.03 (100%)
No radial mixing, structures within ± 2 km	Monolith, structure avoids intact objects	550	0.85 (17%)	0.86 (18%)	0.92 (29%)	1.17 (76%)
No radial mixing, structures within ± 2 km	Monolith, structure avoids intact objects	650	0.67 (4%)	0.68 (4%)	0.72 (4%)	0.84 (26%)
No radial mixing, structures within ± 2 km	Monolith, structure avoids intact objects	850	0.39 (0%)	0.4 (0%)	0.44 (0%)	0.52 (1%)
No radial mixing, structures within ± 2 km	Monolith, structure avoids intact objects	1,000	0.32 (0%)	0.36 (0%)	0.48 (1%)	0.87 (41%)
No radial mixing, structures within ± 25 km	Monolith, thin surfaces, radial radiators	550	0.84 (19%)	1.38 (83%)	3.52 (100%)	9.21 (100%)

Variant	Design	Altitude (km)	s = 0	s = 0.01	s = 0.1	s = 1
No radial mixing, structures within ±25 km	Monolith, thin surfaces, radial radiators	650	0.63 (4%)	0.86 (33%)	1.82 (89%)	3.54 (99%)
No radial mixing, structures within ±25 km	Monolith, thin surfaces, radial radiators	850	0.33 (0%)	0.55 (17%)	1.28 (66%)	2.19 (93%)
No radial mixing, structures within ±25 km	Monolith, thin surfaces, radial radiators	1,000	0.27 (5%)	1.77 (77%)	6.94 (99%)	12.6 (100%)
No radial mixing, structures within ±25 km	Monolith, structure avoids intact objects	550	0.83 (17%)	0.84 (19%)	0.89 (27%)	1.14 (71%)
No radial mixing, structures within ±25 km	Monolith, structure avoids intact objects	650	0.62 (4%)	0.63 (4%)	0.67 (4%)	0.79 (20%)
No radial mixing, structures within ±25 km	Monolith, structure avoids intact objects	850	0.29 (0%)	0.3 (0%)	0.34 (0%)	0.43 (1%)
No radial mixing, structures within ±25 km	Monolith, structure avoids intact objects	1,000	0.21 (0%)	0.25 (0%)	0.38 (1%)	0.76 (35%)

Supplementary Table 11. Compute-module breakups over 15 years at 20 GW for the module, screening-efficiency, product-counting, fragment-yield and radial-mixing variants (s = 0; median over the first 150 draws): probability of at least one breakup and lethal population immediately after one breakup relative to today, counted as in Supplementary Table 5. Under steady product weights the second quantity counts each fragment with its in-shell time divided by the residence time of the lethal population, an object-year equivalent rather than the number placed in the shell, and is given only for comparison.

Variant	Design	Altitude (km)	P(≥1)	Lethal after one event
Base case	Monolith with compute modules, no avoidance	550	39.67%	×8.6
Base case	Monolith with compute modules, no avoidance	650	32.04%	×3.7
Base case	Monolith with compute modules, no avoidance	850	39.67%	×2.3
Base case	Monolith with compute modules, no avoidance	1,000	64.97%	×3.4
Base case	Monolith with modules, structure and modules avoid	550	0.81%	×8.6
Base case	Monolith with modules, structure and modules avoid	650	0.60%	×3.7
Base case	Monolith with modules, structure and modules avoid	850	0.68%	×2.3
Base case	Monolith with modules, structure and modules avoid	1,000	1.39%	×3.4
Compute modules of 30 t	Monolith with compute modules, no avoidance	550	65.66%	×4.1
Compute modules of 30 t	Monolith with compute modules, no avoidance	650	54.04%	×2.1
Compute modules of 30 t	Monolith with compute modules, no avoidance	850	69.41%	×1.5
Compute modules of 30 t	Monolith with compute modules, no avoidance	1,000	83.82%	×2.0
Compute modules of 30 t	Monolith with modules, structure and modules avoid	550	1.56%	×4.1
Compute modules of 30 t	Monolith with modules, structure and modules avoid	650	1.09%	×2.1
Compute modules of 30 t	Monolith with modules, structure and modules avoid	850	1.54%	×1.5
Compute modules of 30 t	Monolith with modules, structure and modules avoid	1,000	2.32%	×2.0
Screening efficiency 0.95	Monolith with compute modules, no avoidance	550	39.67%	×8.6
Screening efficiency 0.95	Monolith with compute modules, no avoidance	650	32.04%	×3.7
Screening efficiency 0.95	Monolith with compute modules, no avoidance	850	39.67%	×2.3
Screening efficiency 0.95	Monolith with compute modules, no avoidance	1,000	64.97%	×3.4
Screening efficiency 0.95	Monolith with modules, structure and modules avoid	550	3.89%	×8.6
Screening efficiency 0.95	Monolith with modules, structure and modules avoid	650	2.88%	×3.7
Screening efficiency 0.95	Monolith with modules, structure and modules avoid	850	3.32%	×2.3
Screening efficiency 0.95	Monolith with modules, structure and modules avoid	1,000	6.61%	×3.4
Screening efficiency 0.999	Monolith with compute modules, no avoidance	550	39.67%	×8.6
Screening efficiency 0.999	Monolith with compute modules, no avoidance	650	32.04%	×3.7
Screening efficiency 0.999	Monolith with compute modules, no avoidance	850	39.67%	×2.3
Screening efficiency 0.999	Monolith with compute modules, no avoidance	1,000	64.97%	×3.4

Variant	Design	Altitude (km)	P(≥ 1)	Lethal after one event
Screening efficiency 0.999	Monolith with modules, structure and modules avoid	550	0.08%	$\times 8.6$
Screening efficiency 0.999	Monolith with modules, structure and modules avoid	650	0.06%	$\times 3.7$
Screening efficiency 0.999	Monolith with modules, structure and modules avoid	850	0.07%	$\times 2.3$
Screening efficiency 0.999	Monolith with modules, structure and modules avoid	1,000	0.14%	$\times 3.4$
Steady product weights	Monolith with compute modules, no avoidance	550	38.10%	$\times 55.0$
Steady product weights	Monolith with compute modules, no avoidance	650	24.91%	$\times 22.9$
Steady product weights	Monolith with compute modules, no avoidance	850	30.99%	$\times 7.0$
Steady product weights	Monolith with compute modules, no avoidance	1,000	47.33%	$\times 10.4$
Steady product weights	Monolith with modules, structure and modules avoid	550	0.81%	$\times 55.0$
Steady product weights	Monolith with modules, structure and modules avoid	650	0.60%	$\times 22.9$
Steady product weights	Monolith with modules, structure and modules avoid	850	0.68%	$\times 7.0$
Steady product weights	Monolith with modules, structure and modules avoid	1,000	1.38%	$\times 10.4$
Product counts not calibrated	Monolith with compute modules, no avoidance	550	39.26%	$\times 8.6$
Product counts not calibrated	Monolith with compute modules, no avoidance	650	27.64%	$\times 3.7$
Product counts not calibrated	Monolith with compute modules, no avoidance	850	34.90%	$\times 2.3$
Product counts not calibrated	Monolith with compute modules, no avoidance	1,000	54.10%	$\times 3.4$
Product counts not calibrated	Monolith with modules, structure and modules avoid	550	0.81%	$\times 8.6$
Product counts not calibrated	Monolith with modules, structure and modules avoid	650	0.60%	$\times 3.7$
Product counts not calibrated	Monolith with modules, structure and modules avoid	850	0.68%	$\times 2.3$
Product counts not calibrated	Monolith with modules, structure and modules avoid	1,000	1.39%	$\times 3.4$
Small-fragment yield of breakups $\times 3.5$	Monolith with compute modules, no avoidance	550	39.67%	$\times 27.6$
Small-fragment yield of breakups $\times 3.5$	Monolith with compute modules, no avoidance	650	32.04%	$\times 10.3$
Small-fragment yield of breakups $\times 3.5$	Monolith with compute modules, no avoidance	850	39.67%	$\times 5.6$
Small-fragment yield of breakups $\times 3.5$	Monolith with compute modules, no avoidance	1,000	64.97%	$\times 9.3$
Small-fragment yield of breakups $\times 3.5$	Monolith with modules, structure and modules avoid	550	0.81%	$\times 27.6$
Small-fragment yield of breakups $\times 3.5$	Monolith with modules, structure and modules avoid	650	0.60%	$\times 10.3$
Small-fragment yield of breakups $\times 3.5$	Monolith with modules, structure and modules avoid	850	0.68%	$\times 5.6$
Small-fragment yield of breakups $\times 3.5$	Monolith with modules, structure and modules avoid	1,000	1.39%	$\times 9.4$
No radial mixing, structures within ± 2 km	Monolith with compute modules, no avoidance	550	28.77%	$\times 8.6$
No radial mixing, structures within ± 2 km	Monolith with compute modules, no avoidance	650	17.94%	$\times 3.7$
No radial mixing, structures within ± 2 km	Monolith with compute modules, no avoidance	850	30.49%	$\times 2.3$
No radial mixing, structures within ± 2 km	Monolith with compute modules, no avoidance	1,000	54.70%	$\times 3.4$
No radial mixing, structures within ± 2 km	Monolith with modules, structure and modules avoid	550	0.78%	$\times 8.6$
No radial mixing, structures within ± 2 km	Monolith with modules, structure and modules avoid	650	0.58%	$\times 3.7$
No radial mixing, structures within ± 2 km	Monolith with modules, structure and modules avoid	850	0.65%	$\times 2.3$
No radial mixing, structures within ± 2 km	Monolith with modules, structure and modules avoid	1,000	1.38%	$\times 3.4$