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THE ECONOMICS OF ORBITAL MASS: HOW DEPOTS CAN WORK IN LEO AND WHERE TO PUT THEM

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1. Introduction

1.1 Why Now?

Humanity stands at the threshold of a new era in space development. For decades since the launch of Sputnik, space was solely the domain of a dozen or so nation-states operating dozens to hundreds of satellites. Now, our civilization is launching thousands of satellites into low-Earth orbit (LEO) at a furious rate, and increasingly, commercial interests are exceeding governmental deployments. This growth trend is often credited to lowered launch costs, but just as much credit is realistically due to the voracious demand for the information enabled by satellite infrastructure. The commercial *infosat* sector—made up of communications, weather sats, global positioning sats (GPS), and private-sector Earth observation (EO) satellites—is providing a pillar of services upon which our society is coming to rely, touching nearly every industry every day.

Most of this commercial infrastructure growth is in LEO. That means there is now a region of near-Earth space where multiple customers exist, such that the space industry is no longer a governmental monopsony there. The implication is that a space-to-space commercial marketplace is now possible from the demand side, but it still lacks a supply chain to materially support it.

The other repercussion of this satellite growth rate is a mounting congestion concern in LEO. This paper addresses both issues in discussing how orbital depots can feasibly act as a nexus both for mass consolidation (flow of materials) and for commerce (flow of money).

1.2 Defining "Depot"

On Earth there are supply depots ("warehouses"), fuel depots, and transportation depots. Often these are collocated with each other near the production of the goods that fill and run through them. Terrestrial depots serve to consolidate and stage inventory for distribution, providing strategic buffers on demand. Proximity to production is sometimes balanced with geographically centralizing to the distribution network. Terrestrial manufacturing facility siting is largely based on workforce considerations.

An orbital depot will need to go beyond this terrestrial model to add various levels of manufacturing to the depot logistics hub, but will require a "lights-out factory" autonomy approach. Sourcing space grade materials for producing space hardware in space can most easily be done from old space hardware in space—provided the technology to do all of that in an orbital environment can be developed. The traditional mindset on space resource utilization aims to solve the problem via asteroid exploitation, but many of the required steps are similar in recycling defunct satellite hardware back into operational satellite hardware as shown in Table 1. It can also be argued that developing and vetting those process technologies in LEO is substantially easier than jumping straight to demonstrating on an asteroid or even the Moon.

Table 1. Comparison of Space Resource Utilization

Asteroid/Lunar Space Resource Utilization[1]	LEO Resource Utilization by Sat Recycling
1. Prospecting	
2. Mining	1. Capture
3. Transport	2. Transport
4. Refining	3. Sortation
5. Feedstock production	4. Feedstock production
6. Component manufacturing	5. Component manufacturing
7. Subassembly manufacturing	6. Subassembly manufacturing
8. Product assembly	7. Product assembly

What if some of the production steps can be done on Earth? While various efforts have proposed manufacturing products in space for Earth using feedstocks from the already existing terrestrial supply chain (requiring both up and down mass), this business model is constrained to end products that must be extremely expensive by mass: biopharma and exotic materials (e.g., ZBLAN). Another industry accustomed to paying over $10,000 per kg is the satellite hardware industry, but at the moment they are only willing to pay for deploying a whole, functional satellite, which requires the entire supply chain. No single one of these levels can work commercially without the others as suppliers and customers, so this must either be coordinated as an ecosystem, or a single entity with very deep pockets must vertically integrate *all* the roles. Even the most vertically integrated manufacturers in the world cannot manufacture satellites from raw materials.

Whether that supply chain is one entity or many, the functions must support the entire stack of processes needed to produce space hardware from raw materials. Those raw materials are already in orbit as debris and old satellite hardware, but they must be consolidated to a depot to supply the raw materials.

1.3 Why in LEO?

The LEO domain covers orbits up to 2000 km in altitude and is characterized by:

- lower latency (i.e., less time for signals to travel)
- lower launch cost (due to less fuel required and higher rate of first stage recovery)
- relatively benign radiation environment (compared to deeper space)

These characteristics make LEO the orbital real estate of choice for the infosat sector. Also, the inherently shorter orbital periods (faster speeds of satellites relative to Earth surface), mean that to have persistent communication coverage with any particular area of Earth's surface, a constellation of satellites is required, since (whether for direct communication or for observation) information transfer requires line of sight. A single LEO satellite would only be in surface range for minutes at a time. In accordance with Wright's Law

[1] Various presentations by C. Dreyer, Colorado School of Mines, Space Resources Institute, this one accessed 2025 from https://www.youtube.com/live/r_9kCWE2D1g

affording smaller satellites, more and more can be launched and deployed with each launch. Ridesharing on rockets allows this to be done across more launches and a variety of orbits in LEO. At the same time, this improved accessibility has not reduced but rather increased demand for satellite deployments in fulfillment of Jevon's Paradox.

LEO orbits have many intersections. There are a near infinite number of possible LEO orbits, but each one precludes all other orbits that *might* conjunct with it (a conjunction is an intersection of orbits where two objects occupy the same space at the same time). How one defines "might" dictates the number of practically supportable orbits in LEO. The exclusion zone for a satellite is somewhat loosely acknowledged as a 5-20 km radius. This lays the framework for overcrowding and practical limits to growth, setting the stage and impetus for the "land grab" in LEO already underway.

This is potentially exacerbated by the de facto grant of right-of-way to the satellite first in orbit (right of transit), and despite the Outer Space Treaty, sovereign ownership in perpetuity for hardware placed in orbit (mineral rights). These two aspects amount to orbital real estate ownership, staked by orbital mass.

2. Sustainability in LEO

The drivers discussed in the previous section converge to cause the growth we now see in LEO. Figure 1 charts this growth[2] since the turn of the 21st century and where it is extrapolated to go. Note the logarithmic vertical axis. Since NASA's Donald Kessler posited the potential of a catastrophic collision cascade,[3] much has been discussed as to what the carrying capacity of satellites actually is in LEO. Bongers and Torres recently arrived at a rough estimate of 72,000 satellites with their model[4]. This methodology is based on probabilistic mechanisms and is not deterministic—meaning that that number does not guarantee catastrophe, nor does falling short of that number guarantee against a catastrophe. Using a shell methodology[5], with a 10 km exclusion in chain spacing and 50 km between shells, puts an upper bound of ~240,000 satellites in LEO, assuming circular orbits and slotting coordination that does not currently exist for U.S. regulation, much less at the international level. Satellite slotting is currently very ad hoc, with many highly elliptical orbits (HEO) crossing several shells, substantially lowering the carrying capacity. The current growth rate will likely achieve the lower BT bound before the end of the decade. The cumulative

[2] *Satellite Registry Database,* Union of Concerned Scientists, retrieved 2025 from https://www.ucsusa.org/resources/satellite-database

[3] D. Kessler & B. Palais, *Collision Frequ*ency of Artificial Satellites: The Creation of a Debris Belt, Journal of Geophysical Research (Updated 2024), Retrieved 2025 from https://web.archive.org/web/20110515132446/http://webpages.charter.net/dkessler/files/Collision%20Frequency.pdf

[4] A. Bongers & J. Torres, *Orbital debris and the market for satellite*s, Ecological Economics (2023), retrieved 2025 from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4254744

[5] M. Lifson, et al. *Low-Earth-Orbit Packing: Implications for Orbit Design and Polic*y, Journal of Spacecraft and Rockets, March–April 2025, retrieved 2025 from https://doi.org/10.2514/1.A35913

mass of material in LEO in 2024 is estimated to be over 13,500 metric tons[6], 430 tons of which are contributed by the International Space Station (ISS).

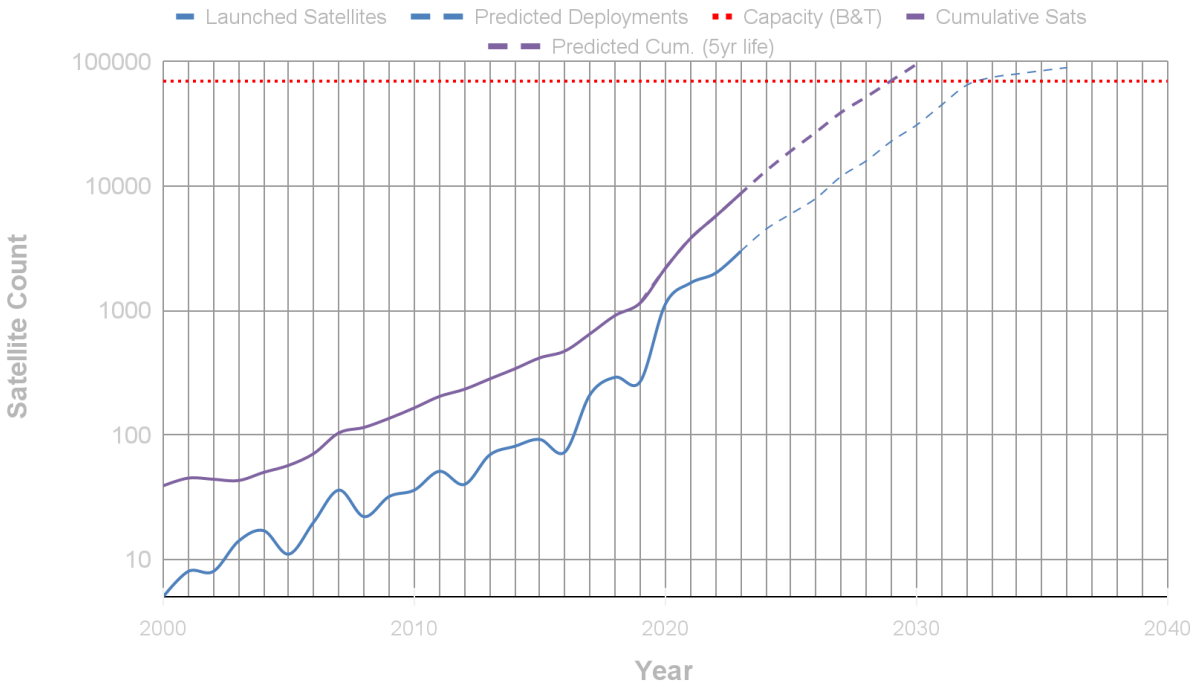

Figure 1. Growth of satellites in LEO over time.

This chart does not include incidental objects that have fallen off during various launches, or debris created by fragmentation of satellites such as the debris fields created by the 2021 Russian (Kosmos 1408) anti-satellite test or the 2009 Iridium 33-Kosmos 2251 collision. A large percentage of this unregistered debris (i.e., not tracked by the UCS database) lies in the 800-1200 km altitude range.

This spectacular growth has caused both excitement and concern even beyond the space industry, prompting new investments and the (now eclipsed) ORBITS Act in the U.S. Congress[7].

While geostationary Earth orbit (GEO) has an associated graveyard orbit much farther out, the current solution for orbit clearance in nearby LEO is to deorbit objects. Regardless of orbital parameters in LEO, this means getting the lowest point of the orbit (i.e., perigee) to encounter the Earth's upper atmosphere sufficient to further slow the object. *Nominally* this causes the debris to burn up in the atmosphere, such that whatever remains doesn't (literally) impact any human concerns. The current norm for mission life in

[6] ESA. *Space Environment Statistics,* Space Debris User Portal (updated 2025), accessed 2025 from https://sdup.esoc.esa.int/discosweb/statistics/.

[7] *Cantwell, Hickenlooper Bill to Clean Up Space Junk Passes Senate Unanimously*, US Senate Press Release (2023), accessed 2025 from https://www.commerce.senate.gov/2023/11/cantwell-hickenlooper-bill-to-clean-up-space-junk-passes-senate-unanimously

LEO is five years, and there is FCC guidance loosely mandating disposal of satellites within five years of the end of mission. In the optimum case of 100% deorbit then, the cumulative (purple) line in Figure 1 is made to resemble the annual launch line (blue) with a 5-year lag. This is the best-case scenario.

Leaving dead satellites and space debris in place is not viable, and deorbiting only slightly delays the overcrowding problem without addressing the problem of orbital mass demand. While there are clear strategic reasons to desire a proliferated and distributed constellation architecture (beyond the orbital land grab imperative), it's also clear that this approach has sustainability limits that even deorbiting cannot solve. Sustainability is a concern both from the congestion perspective, and from the perspective of launch supply capacity to meet demand.

3. Mass Criticality

There are four main reasons that orbital mass must, and presumably will, continue to increase:

1. Orbital Real Estate: As mentioned, effective ownership of an orbit is staked by mass. Thus, because the number of satellites in LEO has limits, satellite sizes can be expected to increase to leverage consolidation in existing orbital claims.
2. Capability: Capabilities require orbital infrastructure. While technology allows more functionality with less mass, everything useful, including software and information, requires hardware. Hardware means mass. In the case of satellites, functionality is tied directly to power, which in LEO is almost exclusively photovoltaic (PV) solar. Currently PV masses about 1 kg/kW.
3. Mobility: Our current understanding of physics precludes reactionless propulsion[8], so the tyranny of the rocket equation dictates that mass must be expended for mobility. Every orbit has an associated velocity that balances centripetal acceleration with Earth's gravity (see Equation 1). To change orbits, a change in velocity, "delta Vee" (Δv), is required to move at a cost of some of the mass being moved.
4. Resilience: More mass is also more momentum, which in LEO means less orbital decay due to atmospheric drag. Shielding for satellites also requires more mass, as does design redundancy.

Because of these reasons, there is reason to consider keeping materials in orbit, provided we can utilize them as resources. Instead of a graveyard, what if we had a depot where debris could be consolidated and ultimately processed into new orbital infrastructure?

4. Deorbiting versus Delivering to a Depot

Every altitude has an associated orbital velocity according to Equation 1, where r is the radial distance from the center of the Earth, and μ is Earth's gravitational constant ($2.986 \times 10^{-11} m^3/s^2$):

[8] Solar sails are one "reactionless" mobility possibility in space, but not viably in LEO where solar winds are attenuated by Earth, its magnetic field, and Van Allen belts. Sails also necessarily occupy extremely large volumes that would exacerbate crowding issues in LEO and increase mission risk profiles for micrometeoroids and orbital debris (MMOD).

$$v = \sqrt{\frac{\mu}{r}} \tag{1}$$

To deorbit a satellite, one only needs to reduce the altitude sufficiently to allow atmospheric drag to complete the job, nominally burning up most of the satellite, depending on size. We have calculated the Δv for this in two different ways. For the most conservative of these, the Δv for deorbit is simply the change in orbital velocities for those altitudes:

$$\Delta v_{deorbit} = v_{sat} - v_{decay} \tag{2}$$

This accounts for high LEO orbits that require a higher degree of control during reentry. However, because for most sats, the atmosphere itself tends to circularize the orbit once the perigee reaches the decay altitude, no fuel is needed for recircularizing. Practically the Δv expenditure is only about half[9]:

$$\Delta v_{deorbit} = \frac{v_{sat} - v_{decay}}{2} \tag{3}$$

The decay altitude we use in our calculations corresponds to r_{sat} = 6428 km (~50 km altitude above surface, with a v_{decay}= 7.87 km/s).

Sending a satellite to an arbitrary orbital depot is more complicated. If there was a depot in orbit to which to deliver this notional satellite, we would need to consider also any inclination plane changes (Δi) as well as the altitude difference:

$$\Delta v_{depot} = \sqrt{v_{sat}^2 - 2 \cdot v_{sat} v_{depot} cos(\Delta i) + v_{depot}^2} \tag{4}$$

Note that Δi is the angular difference between the sat plane and the depot plane. Other orbital parameters could affect Δv, but can be eliminated by optimized burn timing (so long as minimizing fuel use supersedes other considerations like urgency). For the sake of simplicity, we are only looking at prograde circular orbits, and assume optimal (i.e., Hohmann) burns for depot transfers. We can also let $v_i = v_{depot} cos(\Delta i)$ to capture just the plane change to make the equation more concise. To see the simple breakeven then, we set the Δv alternatives equal and solve:

$$\Delta v_{deorbit} = \Delta v_{depot} \tag{5}$$

$$v_{sbh} = \frac{(4v_i - v_{decay}) \pm 2\sqrt{(4v_i^2 + v_{decay}^2) - (2v_i v_{decay} + 3v_{depot}^2)}}{3} \tag{6}$$

[9] The 1st burn of a Hohmann transfer includes a radical term that turns our breakeven algebra into a 4th degree polynomial. For altitudes in LEO (r < 7500km), the difference in Δv approximated by Equation 3 is within 10 m/s.

However, this simple breakeven paradigm is based on the orbital economics as seen from just the individual satellite's perspective. Often, an orbital transfer vehicle (OTV) may be used to transport a satellite or space debris, and the OTV must eventually be refueled at a depot. Also, increasingly, satellites in LEO are part of constellation architectures. For a constellation operator who desires to have continual operation, that satellite's end of mission isn't the end of business; a replacement must be deployed in order to maintain the services that provide revenue. So we must also consider the replacement cost in terms of Δv. On the deorbit side of the equation, this means adding the launch of the replacement satellite from Earth's surface ($\Delta v_{launch} \simeq 10\ km/s$); on the depot side, it means a trip from the depot to deploy the new satellite, plus a reverse trip to return the old one. These logistics are illustrated in Figure 2.

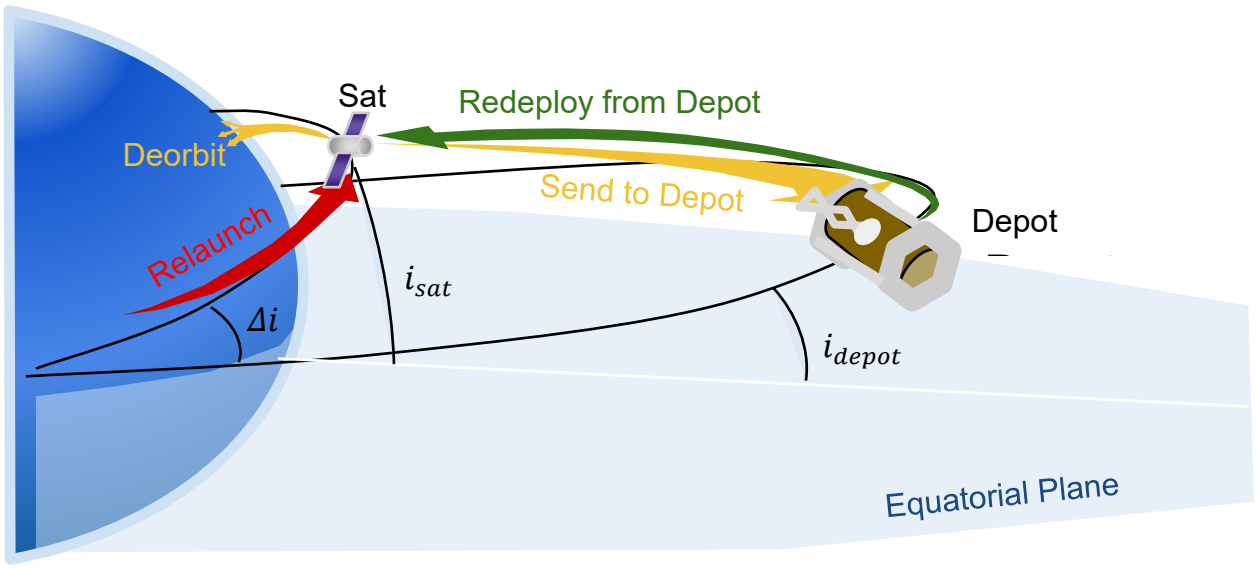

Figure 2. Satellite End of Life Scenarios. A satellite can either be deorbited or sent to a depot. For replacement, a new satellite can be launched from Earth or from the depot.

This replacement consideration changes the breakeven analysis to:

$$\Delta v_{deorbit} + \Delta v_{launch} = 2 \cdot \Delta v_{depot} \tag{7}$$

To simplify the equation, we can combine the fixed velocities terms under a single *relaunch* term (equal to 17.9 km/s), and substitute in this fixed velocity term, $\Delta v_{relaunch}$ to our replacement breakeven:

$$\Delta v_{relaunch} = \Delta v_{launch} + v_{decay} \tag{8}$$

$$v_{rbh} = \frac{2}{15}\left[8v_i + \Delta v_{relaunch} \pm \sqrt{\left(8v_i + \Delta v_{relaunch}\right)^2 - 15\left(4\, v_{depot}^2 - \Delta v_{relaunch}^2\right)}\right] \tag{9}$$

Note that, as with Equation 6, the terms under the radical must sum positively to yield real solutions.

Putting all this together, the simple breakevens and the replacement breakevens, these breakeven velocities represent altitudes via Equation 1, minus Earth's radius of 6378 km. Figure 3 shows the equivalent altitude plots for different inclination planes relative to our notional depot plane on the horizontal axis. We've placed the depot at an altitude of 450 km. The vertical shows the altitude above Earth's surface, logarithmically so that we can get a sense all the way out to GEO.

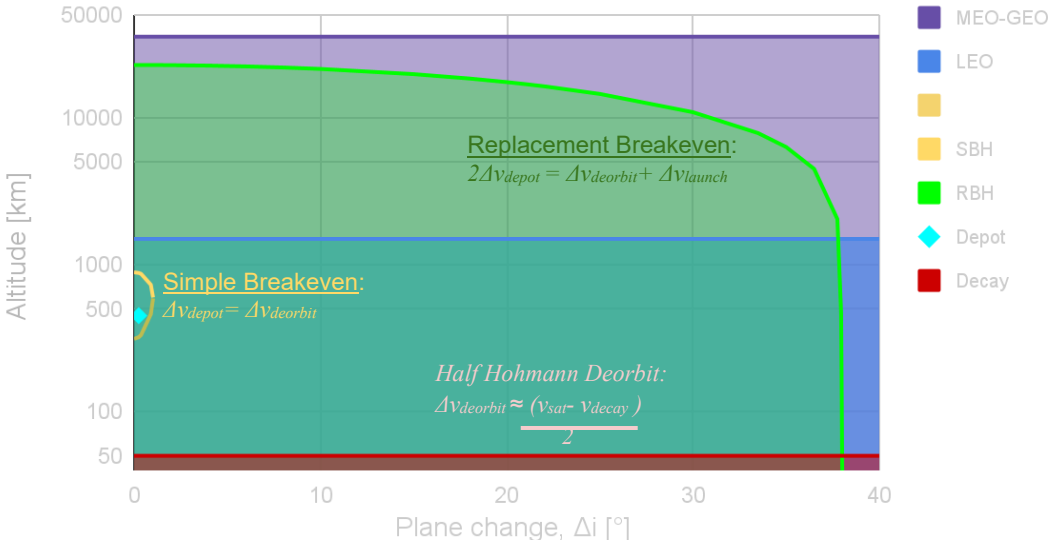

Figure 3. Δv Break-even analysis for Deorbit vs. Recycle Depot Delivery.

The simple breakeven is the yellow/gold trace. Because of the multiple root scenarios for the half-Hohmann deorbit solutions, this is a closed curve, symmetrical about the vertical axis (negative angles are the same, since we are talking about the difference). Outside of this closed area, deorbit is more economical, and inside which the depot transfer makes more sense. However, when replacement analysis is plotted, we get the green curve. This is also a closed curve, but the lower bounds fall within the Earth's surface (well below our decay altitude, so are not shown here). All LEO planes within ±38° are more economically accessed from orbit than from the ground when replacement from a depot is considered. This greatly changes the economics of satellite disposal. Even when the satellite is not being replaced but is being serviced by an OTV, the depot solution is far cheaper.

5. Mass Distribution Analysis

As we saw in the previous section, a depot could be anywhere 45-90° in LEO to make sense for replacement scenarios over deorbit, but for economics, we'd still want to minimize the Δv overall by placing the depot in an inclination where the most resources can be found. Figure 4 shows the distribution of satellite mass as of 2022. Not including rocket bodies and incidental debris, this chart represents about 2,000 metric tons of space grade material (the current mass is now likely closer to 3,500 tons because, while there have been a handful of deorbits, the high launch tempo in 2023-24 and 3x mass increases in newer Starlink versions have doubled the constellation mass).

The largest concentrations of U.S. orbital assets are in the 50-55° inclination and include the ISS (430 tons) and the bulk of the Starlink constellation (> 7,000 sats). There is also a wealth of multinational satellites in polar/sun synchronous (95-100°) orbits.

Because the ISS is by far the largest *single* concentration of mass, co-locating a depot with it would trivialize the transportation cost for its mass, not excluding any of the international modules. Note, however, that inclusion of these international assets means coordination with each nation involved to comply with the dictates of sovereignty.

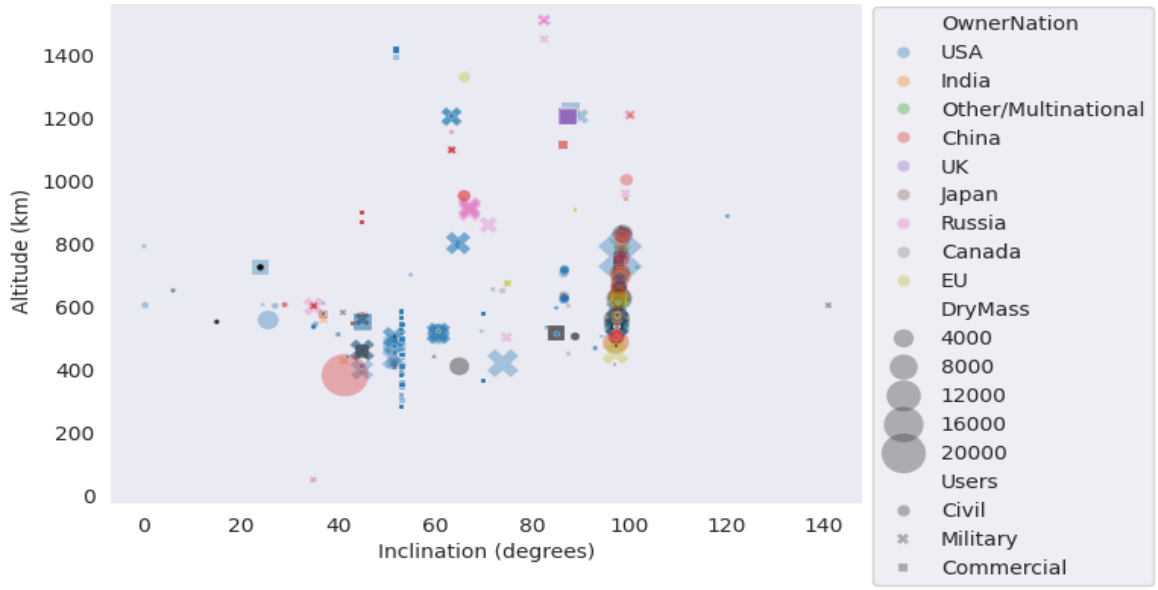

Figure 4. Mass Concentrations in LEO

6. Refueling Analysis

While fuel is sometimes considered *nonrenewable* in terrestrial economics, combustion inside Earth's atmosphere ultimately results in water and carbon dioxide returning to the ecosystem, where natural hydrologic and photosynthetic processes reuse those atoms to eventually turn them back into hydrocarbons. Conversely, fuel/propellant in space is a truly nonrecoverable resource expenditure in the absolute entropic sense, because those reaction products are dispersed out a rocket nozzle to deep space at orbital escape velocities. They'll never again be used by humanity, even in geological timeframes.

While satellites and orbital spacecraft are often deployed with some propellant for maneuvers, propellant depletion is typically the first thing to cause space hardware to be considered nonoperational. Chemical rocket fuel comes from hydrocarbons only found on Earth, through refinery infrastructure, again, only on Earth. Electric thrust propellants favor heavy gases such as xenon (Xe), krypton (Kr), or argon (Ar), and likewise only have production infrastructure on Earth. Figure 5 shows a comparison of various propellants performance versus cost on Earth.

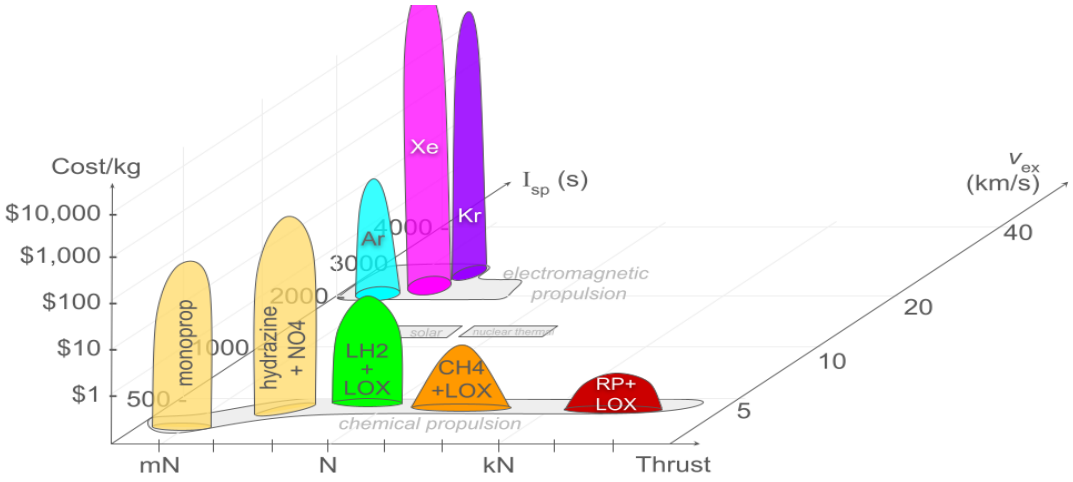

Figure 5. Propellant Comparison. Note that specific impulse (Isp) and exhaust velocity (vex) are related through a rough factor of 100. Costs shown are approximate and do not include the cost of cryogenics (for LOX and LH2), nor do they include the cost of getting to orbit.[10]

What about altitude? Generally the lower the orbit altitude, the lower the launch cost. However, the trade off of low altitude orbits is that they decay faster due to upper atmospheric drag. For stationkeeping of a fuel depot in LEO, there is a physics based "rent", payable in propellant. Atmospheric drag (a, deceleration) is estimated by Equation 9:

$$a = \frac{1}{2}\rho v^2 C_D \frac{A}{m} \tag{9}$$

where ρ is the atmospheric density which decreases (calculated via polynomials from empirical data) with altitude; v is the orbital velocity (as a function of altitude—see Equation 1); C_D is the drag coefficient (~2 for most sats); A is the frontal surface area; and m is the satellite mass. Both ρ and v are also functions of the altitude. The schedule in Table 2 shows for a few spacecraft examples the "orbital rent" cost of stationkeeping needed to offset this drag, viewed as a Δv in meters per second (mps, colloquially "mips") for scaled time periods (color coded). This shows how an economy of scale can be realized by orbital mass consolidation and clustering. A depot would most closely resemble the ISS in terms of mass, at least 100 metric tons (100,000 kg).

Note though that this stationkeeping cost does *not* include the operational cost of collision avoidance maneuvering (CAM). As LEO becomes ever more congested, we can anticipate CAM costs to increase proportionately. Drag also affects debris and acts to self-clean lower orbits, so CAM costs are also a function of altitude, but in the opposite direction. Orbital site optimizing for drag, refueling, and CAM costs is complex and dependent on the specific cash flow model of a depot, likely comprising an ecosystem of companies filling in many niches in the orbital manufacturing supply chain.

[10] J. Seibert, *How Much Does Rocket Fuel Really Cost?,* Space Insider (2024), accessed 2025 from https://spaceinsider.tech/2023/06/13/how-much-does-rocket-fuel-cost/.

Table 2. Cost of LEO station-keeping for various satellite sizes in Δv per time period

Example		2U	8U	Starlink v3	Hubble	ISS
A (m2)		0.1	1	20	50	500
m (kg)		2	50	775	11,110	430,000
ALTITUDE	**150 km**	574 mps/day	229 mps/day	296 mps/day	510 mps/day	13 mps/day
	200 km	71 mps/day	28 mps/day	37 mps/day	6 mps/day	1.7 mps/day
	250 km	17.1 mps/day	6.8 mps/day	8.8 mps/day	1.5 mps/day	0.4 mps/day
	300 km	5.4 mps/day	2.2 mps/day	2.8 mps/day	3.5 mps/wk	0.7 mps/wk
	400 km	5.6 mps/wk	2.25 mps/wk	2.9 mps/wk	0.5 mps/wk	0.5 mps/mo
	450 km	2.4 mps/wk	1.0 mps/wk	1.2 mps/wk	1.0 mps/mo	0.9 mps/mo
	500 km	56 mps/yr	22 mps/yr	29 mps/yr	5 mps/yr	1.3 mps/yr
	600 km	12.5 mps/yr	5.0 mps/yr	6.4 mps/yr	1.1 mps/yr	0.3 mps/yr
	750 km	2.0 mps/yr	0.8 mps/yr	1.0 mps/yr	2.0 mps/decade	0.5 mps/decade
	1000 km	4.06 mps/decade	1.6 mps/decade	2.1 mps/decade	0.4 mps/decade	0.1 mps/decade

7. Solar Power Considerations

For a depot, power collection is also an important consideration. While solar power is "free" after the capital expenditure costs, it is affected by orbit selection. At Earth's solar distance, the maximum instantaneous insolation that can be achieved is 1.366 kW/m^2. The inclination angle as a classical orbital element is measured relative to Earth's equatorial plane which varies its relation to the sun throughout the year, so here we introduce the *Beta angle,* which is a function of the inclination angle and how it precesses relative to the sun throughout the year. For every altitude, there is a critical Beta (β_{crit}), above which satellites experience full sunlight. This is shown below in Figure 6, along with other fractional sunlight levels.

It should be noted that *all* LEO orbits exceed the average power flux of 500-600 W/m^2 for photovoltaics on Earth's surface, but this insolation factor lends weight to orbital real estate at higher inclinations and altitudes, at least for power intensive applications. Such orbital activities will include beamed space-based solar power (SBSP) and many orbital manufacturing applications, to include satellite recycling.

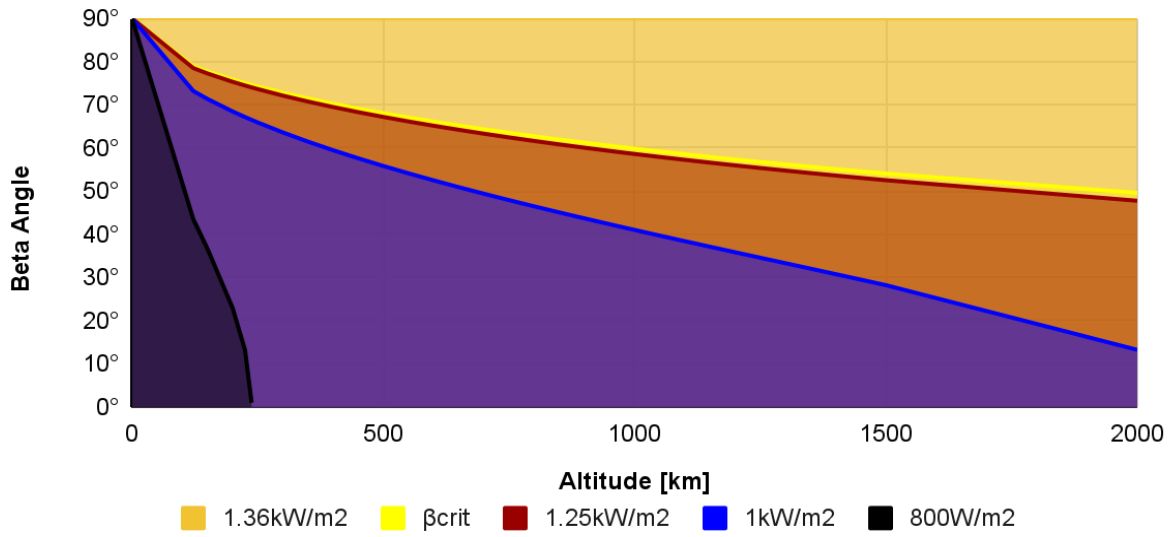

Figure 6. Insolation Power Flux in LEO.

As on Earth, photovoltaic power continuity can be mitigated with batteries to level absorbed solar power with the instantaneous load demand. Because power can be stored, it is not going to limit *what can be done* at a depot (the way mass will), but power will inherently limit *processing rates*. Processing rate is going to be the primary factor in determining Equivalent Mass Return on Investment (EMROI): the time it takes to process a mass equivalent to the processing equipment launched. In other words, this is the product that *does not* need to be launched from Earth, because it is made in orbit from materials already present in orbit (i.e., orbital debris).

The solar environment affects more than just power, however.

8. Other Considerations

While the radiation environment in LEO is considerably less severe than in other orbital regimes (due to the shielding of the Earth itself and its magnetic field), the flip side of more solar exposure is that the solar wind increases the annual dose rate from ionization radiation.

The Total Ionizing Dose (TID) experienced by electronic components in LEO is a key factor in mission design and component selection. The TID dose rate, measured in rad(Si) per unit of time, is dependent on the ion flux, energy level, and the amount of component shielding provided by the spacecraft design. Flux is governed by solar activity, orbital altitude, and orbital inclination. For LEO orbits, typical dose rates vary primarily with orbital inclination. These figures represent the TID absorbed by the silicon material of the electronic component[11]:

[11] NASA. (n.d.). *Space Radiation Effects on Electronic Components in Low-Earth Orbit*. Retrieved from https://llis.nasa.gov/lesson/824

- **Low Inclination Orbits (e.g., equatorial, < 28°):** Typical dose rates due to trapped Van Allen belt particles are in the range of 100 to 1,000 rad(Si)/year.
- **High Inclination Orbits (e.g., polar, > 28°):** The dose rates are higher due to an increased number of trapped electrons, ranging from 1,000 to 10,000 rad(Si)/year.

Part of this is that Earth's surface is protected from solar winds and ionizing radiation by its magnetic fields, which have trapped charged particles into the toroidal Van Allen Belts. In Figure 7 below, the solar wind is mostly represented by the high energy proton and electron flux (yellow and green), galactic cosmic radiation by the low energy flux (red). The Van Allen belts interact with these flows following the field lines emanating from Earth's north and south poles. The flux levels shown are at 45° inclinations, halfway between equatorial and polar planes, and also representative of the ISS plane. The radiation belts (LE flux) are less dense at higher inclinations and lower altitudes, that include much of LEO.

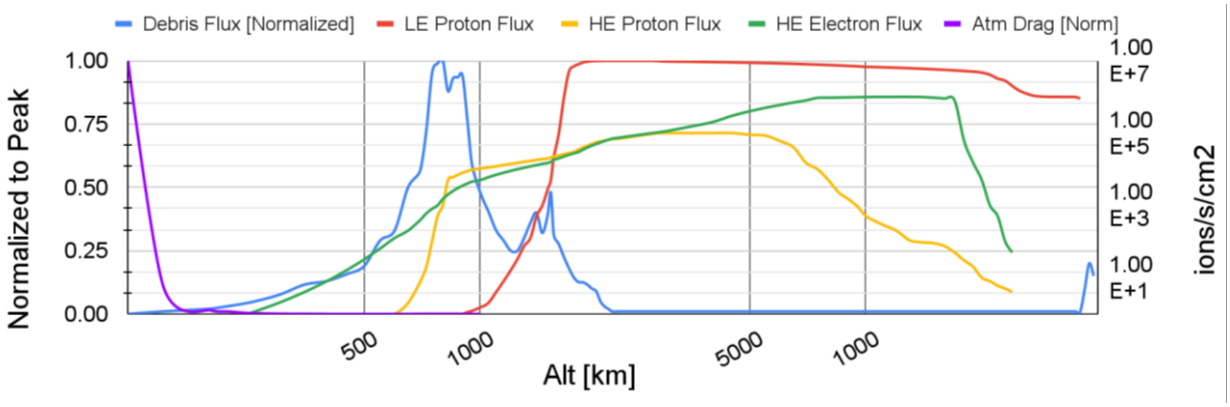

Figure 7. Orbital Flux Hazards in 45° Inclination (based on ORDEM 3.2 and AP8 MIN)

Figure 7 also shows the drag as a function of altitude (normalized here by satellite mass and frontal area), and where debris is distributed (using ORDEM dataset). Due to collisions and antisatellite tests done by Russia, India, and China, the worst debris resides at an altitude of 750-850 km and does not clear up until well into medium Earth orbit (MEO). Note that the U.S. has also done antisatellite testing in the past, but at low orbital altitudes, such that debris has already deorbited due to the atmospheric drag (purple) which increases substantially below 300 km.

As mentioned in the previous section, the altitude dependence suggests a simple optimization with drag factors. Because both cases are fitted empirically, the easiest way to do this optimization is via visual inspection of the data in Figure 7. It should be noted that neither radiation nor debris nor drag are insurmountable, but mitigating them does come at an economic cost. Based on these other considerations, it appears the "prime real estate" for siting infrastructure will lie somewhere below 700 km where debris and radiation flux fall off, but above 250 km where drag becomes a weekly boost concern instead of a daily operation.

There is also an argument for depot siting near to where the debris flux is to minimize Δv for consolidating it back to the depot. However, this material (in the 700-900 km altitude range) is more characterized by

sub-centimeter fragments, and the capture technology for sub-centimeter debris is much more nascent than the capture technology for trackable satellite scale (0.2-5 m) objects. While there is potential value in enabling cleanup of the high LEO orbits (800-1500 km), this is probably a direction for future consideration when fragment capture becomes more feasible, and the depot infrastructure itself already matured in more benign conditions.

9. LEO Depot Conclusions

Because of the Δv costs and related nonrecoverable mass expenditures, it makes sense to collocate the various depot functions to at least a cluster architecture. This integrated value chain model (encompassing refueling, salvage operations, and the various manufacturing and assembly processes needed to transform feedstock into new satellite hardware) can engender a circular economy for kickstarting in-space servicing, assembly, and manufacturing (ISAM). A variety of considerations were discussed for such a depot siting in LEO.

Based on atmospheric drag, there is a practical floor of around 300 km altitude for a long-term 100+ metric ton depot. Flux hazards of radiation and micro debris constitute a practical ceiling above 700 km. Most of the current mass concentration and constellation growth are in the 350-660 km range, which suggests that this “prime real estate” range is optimal across several considerations.

Selecting an inclination is less straightforward. While refueling launches from U.S. facilities suggest an optimal 25-35° inclination, orbital mass concentrations suggest optimums at either 50-55° or in polar inclinations (90-100°). Power considerations push low inclinations to higher altitude orbits for depots.

Ultimately, depots will need to be sited in a variety of orbits, depending on how such a logistics ecosystem is funded. Corporate depots would logically align to the inclination of their associated constellations to provide competitive advantage in satellite lifecycle renewal, ground coverage, and continuity of both service and orbital real estate occupancy. If the U.S. Government was inclined to kickstart such a depot infrastructure to address its own constellation needs, the ISS current orbit at 420 km and 51.6° would be a good place to start and might provide a mechanism for developing international commerce in space as well.

Siting a depot in LEO would provide a critical hub of infrastructure to fuel an in-space economy not just in the literal sense of propellant logistics but as a place to consolidate material resources for future use as new orbital manufacturing and service capabilities are developed. This could propel the space industry beyond the current sustainability limits reliant only on launch and provide a clear Δv advantage over deorbiting.

Appendix A: Glossary of Terms

Altitude – the distance above Earth's surface (typically using sea level as reference).

Ar – Argon, a heavy gas sometimes used as propellant in electric thrusters.

Beta angle – the inclination of a satellite's orbital plane relative to ecliptic midnight

Breakeven – a delta-v analysis setting two alternative maneuver schemes equal.

Breakeven with replacement – as above, but considers the delta-v of replacing a satellite.

CAM – Collision Avoidance Maneuver, an operation undertaken by operational spacecraft to mitigate risks of conjunction with other space objects traveling at high relative velocities.

C_D – drag coefficient, shape dependent, 1 for spheres, 2 for cubes.

CH4 – methane, used with LOX as chemical propellant, "methalox" propulsion.

CST – Capture, Service, Transport: an economic niche in the in space service economy (includes OTVs).

Delta Vee (Δv) – change in velocity, a physics based accounting method to determine the cost of orbital maneuvers, agnostic to propulsion method or spacecraft mass. Used with Tsiolkovsky's rocket equation to calculate propellant needs specific to spacecraft thruster configuration.

E, eccentricity – orbital parameter designating orbital shape. e=0 for circular orbits.

EMROI – Equivalent Mass Return on Investment, the time it takes to process a product mass equivalent to the processing equipment mass (on orbit).

EO – Earth Observation, satellites whose function is to image Earth, includes weather sats.

g_e – Earth gravity (9.81 m/s^2).

GEO – Geostationary Earth (or geosynchronous equatorial) Orbit, a specific circular orbit at 35,786 km altitude where the rotational velocity of the satellite matches the Earth's rotation, such that the satellite appears in the same point in the sky at all times.

GPS – Global Positioning System.

HE – high energy, referring to ions with energy greater than 400 MeV.

HEO – Highly Elliptical Orbit.

i – inclination, a major orbital parameter, the latitudinal angle measured from Earth's equatorial plane.

Δi – delta inclination, inclination angle using depot orbital plane as reference.

I_{sp} – specific impulse, a measure (in seconds) of rocket performance based on nozzle and propellant characteristics. Related to exhaust velocity of rocket, normalized to acceleration of earth gravity, $I_{sp} = \frac{v_{ex}}{g_e}$

infosat – commercial satellite sector that primarily creates value from satellites by providing information to Earth customers, includes EO, GPS, and communications satellites.

ISRU – In situ Resource Utilization, the capability of using local raw materials.

ISS – International Space Station, largest artificial satellite in Earth orbit 1998-2030.

Jevon's Paradox – an economic theory established by William Stanley Jevons that increasing the efficiency of a technology will lead to higher, not lower, demand for or consumption of the technology.

Kg – kilogram (1000 grams), measure of mass, approximately 2.2 pounds in Earth gravity.

kps or "Kips" – measure of (Δv) in kilometers per second (km/s), useful for orbit transfers.

km – kilometer, measure of distance, 1000 meters or roughly 3.33564 x 10^{-6} light seconds.

Kr – krypton, a heavy gas sometimes used as propellant in electric thrusters.

LE – low energy, referring to ions with energy less than 400 MeV.

LEO – Low Earth Orbit, a class of orbits at various inclinations generally below 1500 km (although some sources include orbits out to 2000 km).

LH2 – liquid hydrogen, H_2, cryogenically cooled hydrogen combusted with LOX as propellant.

LOX – liquid oxygen, O_2 cryogenically cooled oxygen used as oxidizer for many fuels.

m (italic) – mass (in kg in this document).

m – meters.

MEO – Medium Earth Orbit, a class of orbits at various inclinations between LEO and GEO.

mps or "Mips" – measure of (Δv) in meters per second (m/s), used for stationkeeping adjustments, and local transport.

MMOD – micro-meteoroid and orbital debris.

Outer Space Treaty, a multilateral treaty governing space law since 1967.

OTV – orbital transfer vehicle, space tug.

PV – photovoltaics, solar power production.

r – radial distance from Earth's center.

RP or RP-1 – kerosene based rocket propellant, used with LOX, in "keralox" chemical propulsion.

SBSP – Space-Based Solar Power: power collected via orbital photovoltaics and beamed on demand to another location.

SSO – sun synchronous orbit, high inclination polar orbits >75° typically with a high Beta angle.

Tsiolkovsky's rocket equation – derived from conservation of momentum, relates fuel flow to delta-v: $\Delta v = I_{sp} g_e \, ln\left(\frac{m_o}{m_f}\right)$

v – velocity, directional speed; with regard to orbital velocities positive numbers indicate travel in eastward direction.

Xe – xenon, a heavy noble gas often used as propellant in electric thrusters.

ZBLAN – a class of ultra-low-loss optical materials made from zirconium, boron, and lanthanum fluoride, often cited as the poster child for microgravity manufacturing.