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An analysis of launch cost reductions for low Earth orbit satellites

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Abstract

We explore launch-cost reductions for satellites in low-Earth orbit and find that from 2000 to 2020 per-kilogram launch costs decreased at an average annual rate of 5.5%, while altitude-adjusted average launch costs per kilogram decreased by 4.4% annually. The altitude-adjusted annual rate of decrease was 7.5% for commercial satellites and 3.6% for non-commercial satellites. Regression analysis reveals that declining satellite mass induced an annual 10.4% reduction in average per-satellite launch costs over the period under study. At these rates, average launch costs to low-Earth orbit will fall below $1000 per kilogram between 2045 and 2076 and $100 per kilogram by the next century.

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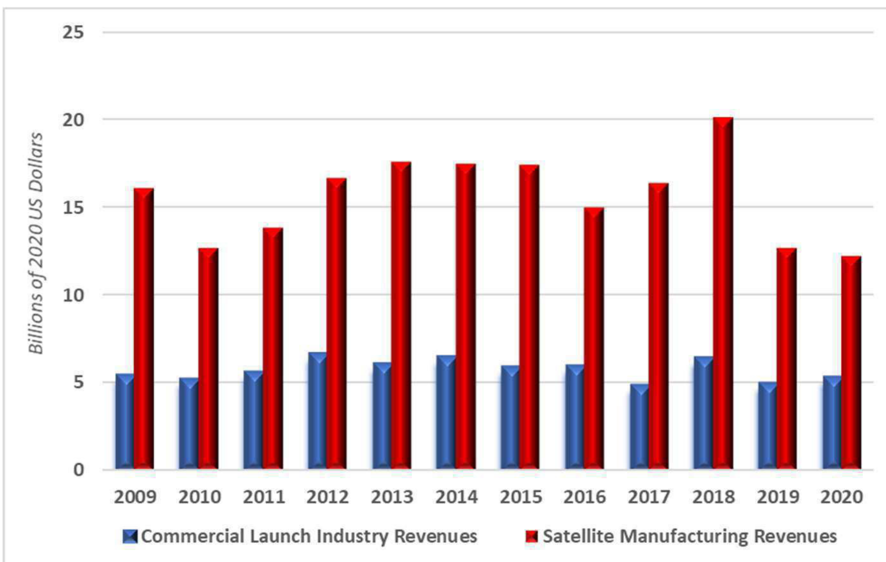
1. Introduction

The number of active satellites in low-Earth orbit (hereafter LEO) increased exponentially between 2006 and 2021 (from 827 to 4550 active satellites).[1] One reason for this increase in orbital population is technological progress that reduced the cost of manufacturing and launching satellites into space. Other factors include increased competition, in-house production, and the use of reusable rockets (Jones, 2018). All else equal, lower launch costs increase a satellite operator's profitability and create further incentives for commercialization of orbital space and investment in new services, such as satellite broadband internet service, space tourism, and space hotels. Mega-constellations of satellites would not be economically viable without these reductions in launch costs. Lower launch costs also yield greater access to space in terms of organizational scale.

Launch costs are typically the second largest cost for satellite operators, after satellite production costs.[2] Consistent with this observation on relative costs, Figure 1 shows that satellite manufacturing revenues are generally two to three times greater than launch revenues. We note, however, that launch costs are often higher than the cost of the satellite for very small LEO satellites (Schenone, 2019).

Figure 1. Global satellite manufacturing and commercial launch revenues[3]



While new developments in launch technology and their effects on launch costs are frequently discussed in the media, detailed information on launch costs is not readily available. Some launchers post list prices, but actual launch contracts are private and not shared with the public. Furthermore, calculating launch prices for government satellites on government-sponsored launch programs is not

[1] Based on the data collected by the Union of Concerned Scientists (UCS, 2021).
[2] The third and fourth largest costs are insurance (if purchased), and financing.
[3] Authors' calculations based on the data from Bryce Tech.

straightforward. Given this paucity of information, it is difficult to determine the actual launch costs faced by a typical satellite operator.

In fact, average launch costs are higher than the lowest costs available in a given year because launch prices vary significantly, as launchers offer highly differentiated services, and commercial satellite owners may have preferences over certain launch dates or launch vehicles due to their suitability, performance, or reliability.[4] For example, a satellite owner may choose to launch with a more expensive rocket due to the available launch date or access to the intended orbit.[5] Thus, mission-specific parameters of the satellite are important non-cost factors that influence launch costs. This is another reason why average prices, rather than the lowest posted prices, more accurately reflect the true economic pressures faced by satellite operators.

The existing literature on launch costs primarily focuses on the cost of employing different types of launch vehicles.[6] For example, Pielke and Byerly (2011) investigate the cost of using the Space Shuttle, Williams (2016) compares Falcon Heavy and Saturn V rockets, and Jones (2018) analyzes trends in launch costs using historical data of various launch vehicles.[7] While launch costs associated with different rockets provide useful information, we suggest average launch prices more closely approximate the economic costs associated with commercial satellite launches.

In what follows, we investigate trends in launch cost prices from 2000 to 2020. Our dataset is granular and includes 2,787 LEO satellites with cost per-kilogram (hereafter, kg) estimates. Our analysis generates several useful implications. First, we observe that the average per kg launch cost and the average mass of satellites have declined in the last 20 years. This implies that the average per-satellite launch cost fell at a faster rate than the average per kg launch cost. Second, we find that launch costs for commercial satellites are lower than for non-commercial satellites. Third, our findings imply that the decrease in average launch costs was driven by a faster decline in launch costs for commercial satellites and satellites between 100 and 1000 kg in mass. Finally, our estimates allow us to project when the $1000 and $100 per kg average launch cost "milestones" will be reached (if current cost trends continue).

The paper is organized as follows. Section Two presents the data used in this study and discusses historical trends in launch costs. Section Three presents the model and the estimation results. Section Four estimates future cost projections and concludes.

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[4] See FAA (2001) for a discussion of factors affecting the selection of satellite launch vehicles.

[5] See Crisp *et al.* (2014). Challenges accessing orbital space faced by owners of small satellites are described in Crisp *et al.* (2015).

[6] To our knowledge, Futron (2002) is the only public analysis reporting aggregate launch prices. Specifically, this study analyzes average launch prices between 1990 to 2000 and reports that launch prices to geostationary orbit declined from $18,158 per pound in 1990 to $11,729 in 2000 (constant 2000 US dollars), which is equivalent to a 4.3% annual decrease in average launch prices.

[7] According to Jones, there was a 40-fold decrease in launch costs between the Space Shuttle's per kg launch cost in 1981 to the Falcon Heavy's cost in 2018, equivalent to a 9.5% annual decrease in launch costs. While calculating the annual rate of cost reduction based on price changes from a selected launch vehicle can provide a useful benchmark, the estimates may not generalize well. For example, the Falcon Heavy was the lowest per kg cost launch vehicle in 2018, but the Space Shuttle was not the lowest cost vehicle in 1981. Thus, a 9.5% annual cost reduction rate based on a cost comparison of the Space Shuttle and the Falcon Heavy likely overestimates the actual rate of launch cost reduction. We suggest that using aggregate data will help increase the accuracy of these estimates.

2. The satellite launch data and trends

Launch data that identifies a satellite's launch year, orbit, mass, launch vehicle, and commercial or non-commercial status was obtained from the Union of Concerned Scientists (hereafter, UCS). Non-commercial satellites include military, government, and civil use satellites.[8] The data cover the period from 2000 to 2020, and the analysis is restricted to satellites operating in LEO orbit.[9]

Per-kilogram launch vehicle cost data are collected from the Aerospace Security Project (Roberts, 2020), the Government Accountability Office (GAO, 2017), and various news articles. These cost data specify the average per kg launch cost per launch vehicle but do not report differences in satellite launch prices launched by the same vehicle. Thus, the same per kg launch cost is used for satellites launched by the same launch vehicle. Because we do not observe the private contracts of satellite operators, our launch costs approximate actual costs. All cost data are converted from nominal to real values (2020 US dollars).[10] The list of launch vehicles in the dataset used for the analysis is given in Table A1 in the appendix.

We identified 3,207 LEO satellites launched between 2000 and 2020. Cost and mass data are available for 2,787 or 86.9% of these satellites.[11] The annual summary statistics of the data in our dataset are presented in Tables A2-A4 in the appendix.

Historical trends in average per kg launch cost for commercial, non-commercial, and all LEO satellites are depicted in Figure 2. We use the mass of the satellites as weights when calculating the weighted averages. We observe that average launch costs have declined for both commercial and non-commercial satellites, with average costs decreasing faster for commercial satellites than for non-commercial satellites. In 2020, the average launch cost was $10,313 per kg for non-commercial satellites and $4,092 per kg for commercial satellites. Thus, non-commercial satellite launches usually involve more expensive launch vehicles. Thomas *et al.* (2007) identify the reasons why commercial satellites cost much less than government satellites. We believe some of these factors could also explain the cost differences between commercial and non-commercial launches. Government satellites are built for a specific mission, while the primary purpose of commercial satellites is to generate profit. Therefore, commercial satellite operators have a stronger incentive to reduce launch costs. In addition, not all launchers are approved to launch government satellites. National security and sometimes the law itself may require a government to launch with domestic companies. This restricts the launch vehicle choice for government satellites. As noted in Thomas *et al.*, differences in project oversight could also influence the costs.

Figure 2 provides average altitudes for satellite launches and reveals that the average altitude of newly launched LEO satellites has substantially declined since 2010. The average altitude of satellites launched since 2015 is between 500 and 600 km above Earth.

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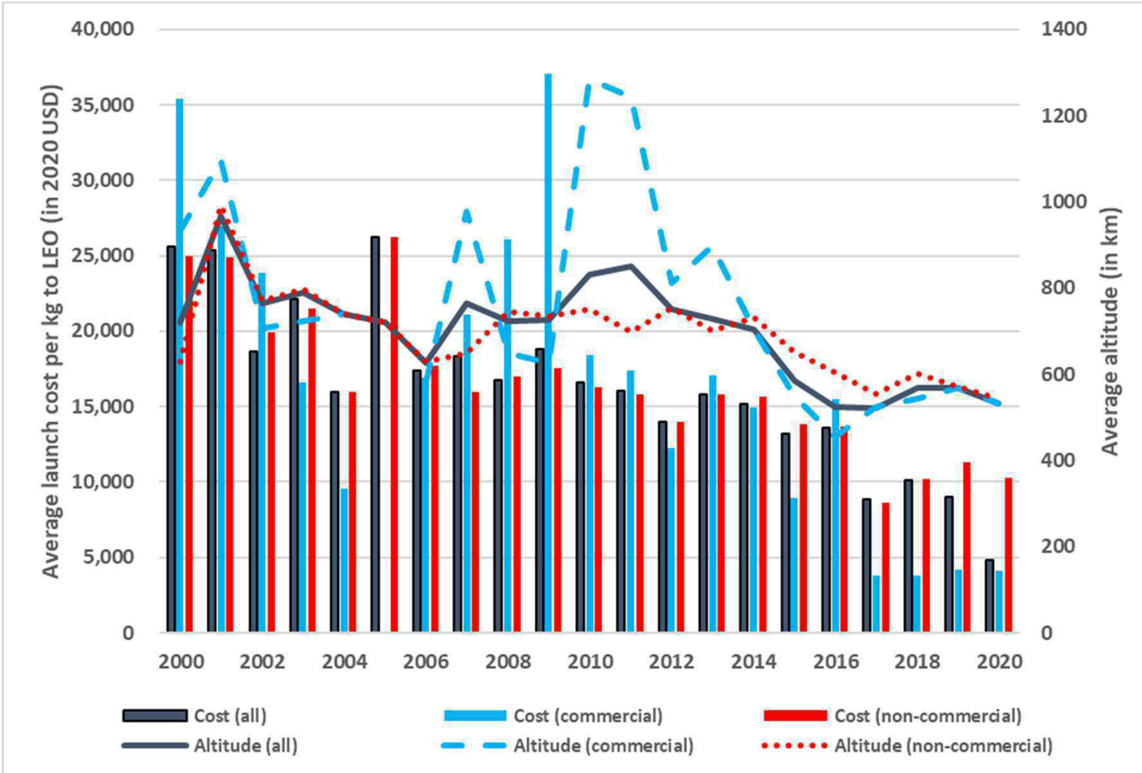
[8] Some satellites are used both for commercial and non-commercial purposes.

[9] In our dataset, LEO satellites operate in altitudes between 200 and 2000 km about Earth. Some LEO satellite launches prior to 2006 may be missing the UCS dataset.

[10] Federal Reserve Bank of St. Louis. *Federal Reserve Economic Data. Annual Implicit Price Deflator, GDPDEF_20210128*, available at https://fred.stlouisfed.org/, accessed March 23, 2021.

[11] Launch cost information is missing for certain launch vehicles and for satellites launched from the International Space Station.

Figure 2. Average per kg launch costs and altitude (2000-2020)

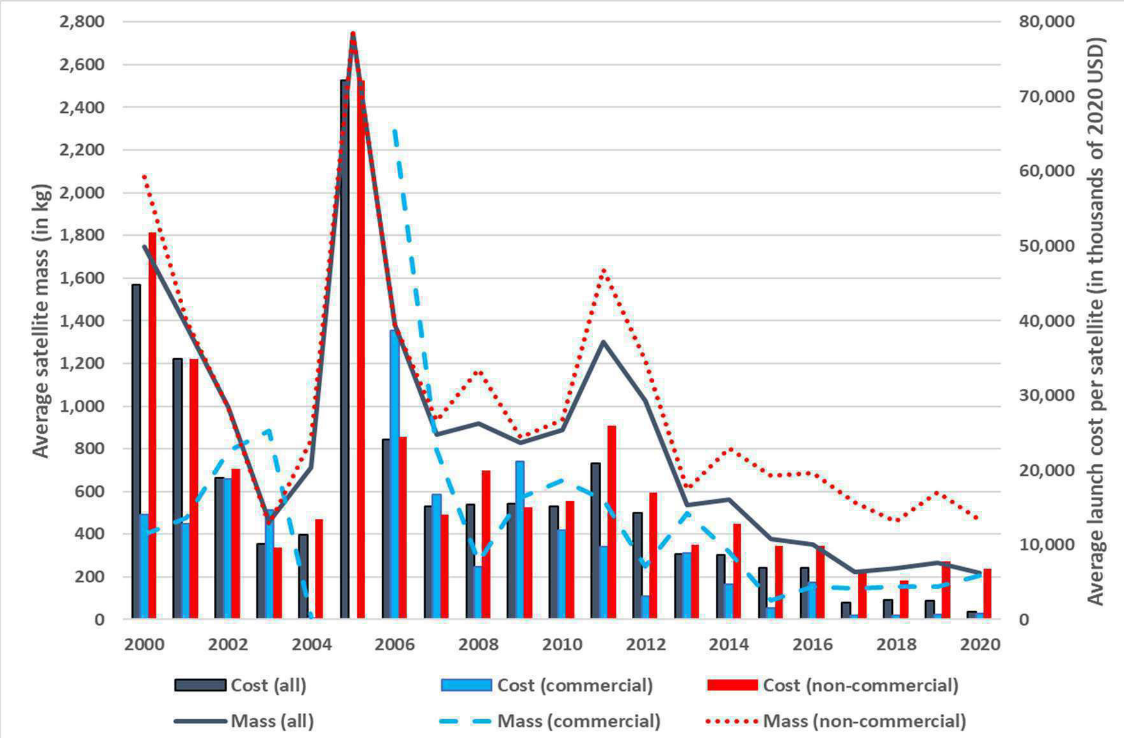


While per kg launch cost is a widely-accepted cost metric used by the industry, we also provide per-satellite launch costs. The per-satellite launch cost is calculated by multiplying the satellite's mass by the per kg launch cost. Figure 3 illustrates the historical trends in average per satellite mass and cost.

We highlight several observations. First, non-commercial satellites have a greater mass than commercial satellites. The average mass of a commercial satellite in 2020 was 220 kg, while that of a non-commercial satellite was 467 kg.[12] Second, the average mass of satellites declined over time but has stabilized in recent years. Third, because both the average satellite mass and the average launch cost per kg have been falling in the last 20 years, there was an even larger decline in the average per-satellite launch cost. The average per-satellite launch cost of commercial and non-commercial satellites has declined by a factor of 16.5 and 7.7, respectively, from 2000 to 2020. A major contributor to this cost reduction was a decline in the average mass per satellite. As satellites got smaller and lighter, the per-satellite launch cost to LEO declined faster than the per kg launch cost.

[12] One Web's mega-constellation satellites are 146 kg in mass and Starlink's mega-constellation satellites are 223 or 260 kg in mass.

Figure 3. Average satellite mass and per satellite cost (2000-2020)



3. Model and results

Launch costs are assumed to follow the trend equation:

$$\mathrm{COST_t} = \alpha\ (1-\gamma)^{\mathrm{t}}\mathrm{ALT}_t{}^{\beta}\ \varepsilon_t \tag{1}$$

In equation (1), t denotes a time variable, where t=1 for the year 2000. The rate of technological change that reduces launch costs is represented by γ. For example, launch costs decrease by 5% per year when γ = 0.05, all else equal. Positive values of γ indicate cost reductions, and negative values indicate cost increases. The initial cost level parameter for the launch industry is given by α, variable ALT denotes the altitude, and ε is an error term associated with mismeasurement. For empirical estimation, a logarithmic transformation of equation (1) is used:

$$\ln(\mathrm{COST_t}) = \ln(\alpha) + (\mathrm{t})\ \ln\,(1-\gamma) + \beta\ \ln(\mathrm{ALT}_t) + \ln(\varepsilon_t) \tag{2}$$

We estimate equation (2) using the Newey-West estimator. The model was estimated separately using the log of the average per kg launch cost and the average per-satellite launch cost as a dependent variable. The regressions were run separately for commercial, non-commercial, and all satellites. In addition, we estimated the model both including and excluding the altitude variable. The results for per-kg launch costs are presented in Table 1, and for per-satellite launch costs are presented in Table 2.

The coefficient on the time variable t is statistically significant at a 1 percent level in all regressions. We can calculate the annual launch cost reduction rate γ from the estimates for the coefficient on t. The calculated values of γ are within a 1 percent range of estimates reported for the coefficient on the variable t. Using the values of γ, the average launch cost declined at an annual rate of 5.5% from 2000 to 2020 (model 1). Adjusted for the launch altitudes, the average launch cost declined at an annual rate of 4.4% (model 2). The 95% confidence interval for the rate of decline is 2.8-6.1%. The altitude-adjusted average launch cost declined by 7.5% per year for commercial satellites (model 4) and by 3.6% per year for non-commercial satellites (model 6). When looking at per-satellite cost regressions, the annual rate of decline was 13% for the pooled satellite data (model 7). After adjusting for altitude, the annual rate of per-satellite cost reduction was 10.4% (model 8). For commercial satellites, the annual reduction rate was 10.3% (model 10). The annual rate of cost reduction for non-commercial satellites was 8.0% after controlling for the average altitude (model 12). The variable ALT is significant only in two of the regressions at the 5 or 10 percent level (models 2 and 10). This could indicate that the altitude, while important, is not the primary factor affecting the average launch costs of LEO satellites in our dataset.

We note that the magnitudes of launch cost reductions are generally larger in regressions without the variable ALT. This implies that the change in average launch altitude may explain some of the decline in launch costs, and the rate of annual per kg cost reductions for LEO satellites was about one percentage point smaller when we adjust for the launch altitude. In addition, we note that the rate of cost reduction is higher for commercial satellites than non-commercial satellites. We suggest that commercial satellites face stronger market pressures to reduce their costs than non-commercial satellites for the reasons listed in the previous section. Average per-satellite launch costs have declined at a faster rate than average per kg launch costs for both commercial and non-commercial satellites. As noted earlier, this is due to the decline in the average mass of the satellites. When comparing models 2 and 8, the difference in the rate of annual decline is around 6%.

Table 1. Regression results: Cost per kg

	All satellites		**Commercial satellites**		**Non-commercial satellites**	
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
a	10.251***	6.675***	10.511***	7.464***	10.142***	7.470***
	(0.091)	(1.645)	(0.275)	(2.314)	(0.042)	(1.549)
t	-0.056***	-0.046***	-0.089***	-0.078***	-0.043***	-0.037***
	(0.010)	(0.0080)	(0.022)	(0.023)	(0.004)	(0.005)
ALT		0.529**		0.444		0.399
		(0.247)		(0.318)		(0.230)
N	21	21	20	20	21	21
F	33.24***	17.38***	16.89***	11.63***	106.67***	56.82***

Note: Newey-West standard errors are in parentheses. The lag m=2 is used in the estimations. ***-significant at 1%; **-significant at 5%; *-significant at 10%.

Table 2. Regression results: Cost per satellite

	All satellites		Commercial satellites		Non-commercial satellites	
	(7)	**(8)**	**(9)**	**(10)**	**(11)**	**(12)**
α	10.829***	0.962	9.933***	2.826**	10.514***	11.607***
	(0.329)	(6.460)	(0.590)	(3.962)	(0.252)	(3.654)
t	-0.139***	-0.110***	-0.135***	-0.109***	-0.081***	-0.084***
	(0.026)	(0.032)	(0.042)	(0.042)	(0.016)	(0.019)
ALT		1.459		1.035*		-0.163
		(0.947)		(0.545)		(0.544)
n	21	21	20	20	21	21
F	29.08***	16.77***	10.54***	9.71***	24.40***	11.79***

Note: Newey-West standard errors are in parentheses. The lag m=2 is used in the estimations. ***-significant at 1%; **-significant at 5%; *-significant at 10%.

We also estimated equation (2) using satellite-level data instead of average launch cost data. The estimation results are presented in Table A.5 in the appendix. The model is estimated for per kg launch costs for all satellites (model 13), for commercial satellites (model 14), for non-commercial satellites (model 15), and satellites above 1000kg (model 16), between 100 and 1000kg (model 17), between 10 and 100kg (model 18), and below 10kg (model 19) in mass. Satellite-level regressions are weighted regressions with robust standard errors.

The satellite-level data provide additional insights into launch cost trends. The coefficient on the variable t is statistically significant in all regressions. Similar to our earlier analysis, we calculated the values of γ based on these estimates. When looking at all satellites, the altitude-adjusted per kg costs faced by satellites decreased at an 8.2% annual rate. The annual rate cost decrease was 12.2% for commercial satellites and 5.0% for non-commercial satellites. We note that these rates are larger in magnitude than the rates derived by looking at annual launch prices. One possible explanation is that the average launch price differs from the launch price faced by a typical satellite. Looking at regressions by satellite mass, we find that the largest cost reductions are observed for satellites between 100 and 1000 kg in mass. These satellites represent 55% of satellites in our dataset, and their altitude-adjusted per kg launch costs decreased at a 10.7% annual rate. The annual per kg launch cost decrease was around 3% for satellites that do not fall into this mass category. We note, however, that there is a large variation in launch costs for satellites greater than 1000 kg in mass and less than 100 kg in mass, and our model explains only a fraction of the variation in costs for satellites in these mass categories.

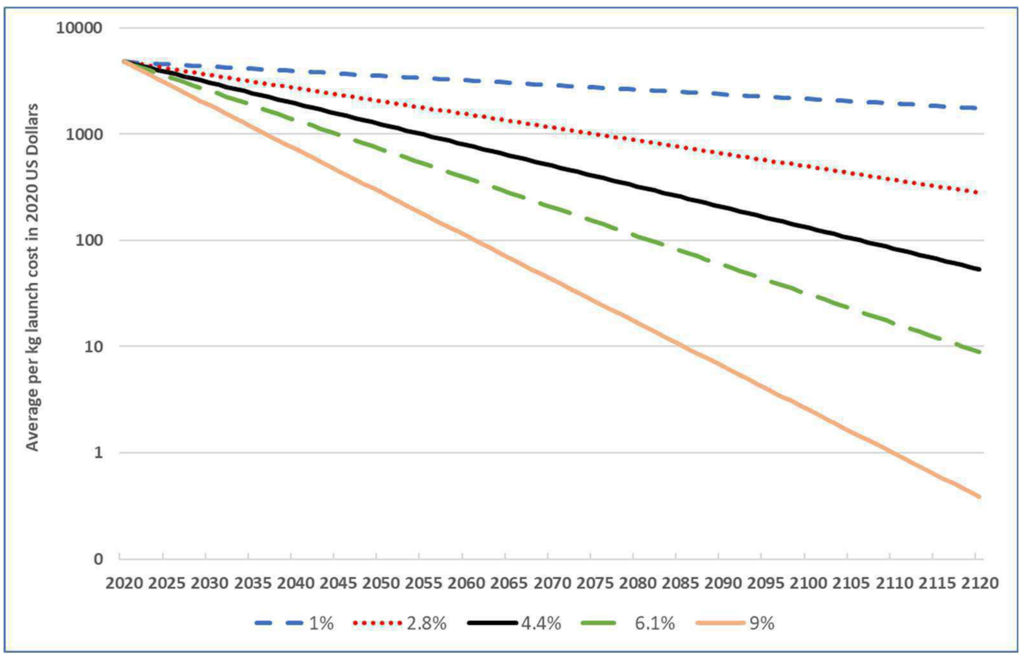
4. Conclusion

Reduced access costs to Earth orbits provide further incentives for commercializing space and space exploration. Lower launch costs also increase the number of nations and individual companies that will engage in space activities. Our analysis of the rate of launch cost reductions for LEO satellites from 2000 to 2020 estimates that the average per kg launch cost for LEO satellites declined at a 5.5% annual rate when not adjusted for the altitude and a 4.4% annual rate after adjusting for the average altitude of the satellites launched. The launch cost of commercial satellites has declined at a faster rate than that of non-commercial satellites. Cost reductions are greatest for satellites between 100kg and 1000kg in mass, where launch costs are estimated to have decreased at an average annual rate of 10.7%.

An important question is whether these cost reductions will continue in the future. If the current trend persists, how will launch costs fall in the future? We present projections in Figure 4. The projections for average per kg annual launch costs are reported for 1%, 2.8%, 4.4%, 6.1%, and 9% annual reductions in launch costs.[13] The graphs allow us to illustrate the length of time it takes for the average per kg launch cost to fall below the critical benchmarks of $1000 and $100 per kg. We emphasize that these are average, not minimum, launch costs as some launch vehicles could reach these milestones well before average launch costs.

All else equal, at a 4.4% annual rate of cost reduction, the $1000 average per kg launch cost level will be reached by 2055. The range for our projection is between 2045 and 2076. At a 9% annual decline in launch costs, the average launch cost will fall below $1000 by 2037. The $100 per kg launch cost milestone will be reached by 2106 at a 4.4% annual rate of cost reduction, but it could occur as early as 2082 at a 6.1% per year cost reduction.

Figure 4. Projections of average per kg launch costs to LEO



Our projection that the average launch price will fall below $1000 between 2045-76 is plausible given expected technological advances in the industry. We reiterate, however, that our analysis is based on average launch prices and that launch prices for individual launch vehicles may fall below $1000 prior to our estimated timeframe. For example, Elon Musk, the CEO of SpaceX, has suggested that its Starship rocket could reach a per-launch marginal cost of $10 million within a few years after it

[13] We note that 2.8% and 6.1% denote the 95% confidence interval for our estimate of 4.4% average altitude adjusted decline in average launch costs.

becomes commercially available (Maidenberg, 2022). Using the $10 million per launch price at 100 metric tons of load capacity to LEO[14], Starship's per unit launch cost will correspond to $100 per kg.

Some argue that this cost projection by SpaceX is overly optimistic, and that Starship's actual commercial launch price will be much higher and priced at around $150-$250 million per launch (Berger, 2022). At $150 million per launch, Starship's launch price to LEO would be equal to $1500 per kg, which is close to SpaceX's Falcon Heavy launch rocket's per unit launch price. Despite the differences in the range of price estimates, the Starship rocket is expected to put significant downward pressure on launch prices in the industry. Beyond the Starship rocket, future reductions may also come from increased competition and learning by doing as more nations develop space programs and engage with orbital space.

References

Berger, Eric (2022) "Rocket Report: Meet the Gravity-1 rocket; will Starship really cut launch costs?" *Ars Technica*, May 27, 2022. Available at https://arstechnica.com/science/2022/05/rocket-report-meet-the-gravity-1-rocket-will-starship-really-cut-launch-costs/3/, accessed July 4, 2022.

Crisp, Nicholas, Smith, Katharine, and Hollingsworth, Peter (2014) "Small Satellite Launch to LEO: A Review of Current and Future Launch Systems," *Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan* **12**(ists29), Tf_39-Tf_47.

Crisp, Nicholas, Smith, Katharine, and Hollingsworth, Peter (2015) "Launch and deployment of distributed small satellite systems," *Acta Astronautica* **114**, 65-78.

Federal Aviation Administration (FAA) (2001) United States Department of Transportation. "Selecting a Launch Vehicle: What Factors Do Commercial Satellite Customers," *Second Quarter 2001 Quarterly Report Topic*, available at https://www.faa.gov/about/office_org/headquarters_offices/ast/media/q22001.pdf, accessed March 29, 2021.

Futron (2002) Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000. Futron Corporation White Paper, September 6, 2002.

Government Accountability Office (GAO) (2017) "Surplus Missile Motors: Sale Price Drives Potential Effects on DOD and Commercial Launch Providers," Report GAO-17-609, August 2017, available at https://www.gao.gov/assets/gao-17-609.pdf.

Jones, W. Harry (2018) "The Recent Large Reduction in Space Launch Cost," 48th International Conference on Environmental Systems, paper ICES-2018-81.

Maidenberg, Micah (2022) "SpaceX's Elon Musk Expects Starship to Deliver Launches at Lower Costs; Space Company Has Been Developing a Launch Site for Its Enormous Rocket in

[14] Technical specifications for a Starship rocket are listed on SpaceX's website at https://www.spacex.com/vehicles/starship/, accessed July 4, 2022.

Southern Texas but Still Needs FAA Approval for Orbital Tests." *The Wall Street Journal*, February 10, 2022.

Pielke, Jr., R., and Byerly, R. (2011) "Shuttle programme lifetime cost," *Nature* **472**, 38.

Roberts, Thomas (2020) "Space Launch to Low Earth Orbit: How Much Does It Cost?" *Aerospace Security web resource*, available at https://aerospace.csis.org/data/space-launch-to-low-earth-orbit-how-much-does-it-cost/, accessed March 22, 2021.

Schenone, Robert (2019) "Space Insurance Update 2019," International Union of Aerospace Insurers presentation, available at https://iuai.org/IUAI/Study_Groups/Space_Risks/Public/Study_Groups/Space_Risk.aspx, accessed March 30, 2021.

Thomas, D., Snow, L., and Connelly, M. (2007) Commercial vs. Government Satellite Cost Drivers, t the 2007 ISPA/SCEA Joint Annual International Conference and Workshop presentation, June 2007, available at http://www.iceaaonline.com/ready/wp-content/uploads/2017/09/MLL-6-Thomas-Paper-Revision-Commercial-vs-Military-Space.pdf, accessed January 1, 2022.

Union of Concerned Scientists (UCS). "UCS Satellite Database," available at https://www.ucsusa.org/resources/satellite-databaseD, accessed March 4, 2021. Database versions used: 11/15/2005, 3/17/2006, 6/19/2006, 9/21/2006, 1/4/2007, 4/9/2007, 7/12/2007, 9/25/2007, 1/7/2008, 4/9/2008, 7/8/2008, 10/6/2008, 1/21/2009, 4/10/2009, 7/1/2009, 10/1/2009, 1/1/2010, 4/1/2010, 7/1/2010, 11/1/2010, 2/1/2011, 5/1/2011, 9/1/2011, 1/1/2012, 4/1/2012, 8/1/2012, 6/1/2013, 9/20/2013, 2/2/2014, 8/1/2014, 2/2/2015, 9/9/2015, 1/1/2016, 7/1/2016, 2/2/2017, 11/1/2017, 5/1/2018, 12/1/2018, 4/1/2019, 10/1/2019, 4/1/2020, 8/1/2020, 1/1/2021.

Williams, M. (2016) "Falcon Heavy Vs. Saturn V," *Universe Today*, July 25, 2016, available at https://www.universetoday.com/129989/saturnv-vs-falcon-heavy/, accessed March 30, 2021.

Appendix: Tables

Table A1. Launch vehicles of LEO satellites with launch cost per kg information

Antares	Delta IV	Kosmos	Minotaur I	SS-520-S	Titan IV
Ariane 5 ECA	Dnepr	Kuaizhou	Minotaur C	Shavit	Tsyklon 2, 3
Athena 1	Electron	Long March 11	Minotaur IV	Soyuz	Vega
Atlas II	Epsilon	Long March 2C	Minuteman 2 ICBM	Soyuz 2	Zenit 2
Atlas III	Falcon 1	Long March 2D	PSLV	Space Shuttle	
Atlas V	Falcon 9	Long March 2E	Pegasus	Start	
Ceres 1	Falcon Heavy	Long March 3B	Pegasus XL	Strela	
Delta 3910	H IIA/B	Long March 4B	Proton M	Taurus	
Delta II	Jielong 1	M-V	Rockot	Titan II	

Table A2. Summary statistics data on per kg launch costs

	All satellites			**Commercial**			**Non-commercial**		
Year	**N**	**Mean**	**Std. Dev**	**N**	**Mean**	**Std. Dev**	**N**	**Mean**	**Std. Dev**
2000	15	25628.4	10415.9	4	35400.3	6046.0	12	24978.4	10368.2
2001	19	25349.1	10354.4	3	26980.2	18321.3	18	24887.1	10265.3
2002	27	18663.9	11678.9	10	23838.1	13709.8	24	19877.9	11847.3
2003	26	22108.5	18925.5	3	16574.0	14027.1	24	21487.4	19699.1
2004	26	15978.3	13627.2	4	9570.0	0.0	22	15995.0	13690.7
2005	18	26268.4	10580.1	0			18	26268.4	10580.1
2006	27	17424.6	12205.8	4	16900.2	4037.1	26	17721.9	12342.2
2007	51	18303.0	13251.9	19	21097.7	11632.3	34	15998.1	13567.2
2008	41	16781.6	12851.9	13	26076.8	13466.4	31	16988.0	13105.9
2009	55	18789.3	12164.0	5	37096.8	4351.1	50	17564.0	11519.7
2010	32	16567.7	7627.7	8	18383.0	2103.8	25	16243.9	8325.1
2011	48	16040.5	8210.0	15	17365.6	686.3	33	15833.2	8849.2
2012	45	13964.5	8115.0	10	12253.0	6214.7	37	13988.1	8186.1
2013	96	15833.9	5669.6	23	17059.3	2704.1	76	15796.4	5883.6
2014	89	15185.4	5063.4	37	14906.3	4930.9	56	15678.1	4879.0
2015	98	13159.3	4404.2	36	8906.1	6075.7	66	13809.9	3932.8
2016	85	13610.5	5503.7	32	15505.2	3136.8	54	13688.1	5710.6
2017	293	8878.8	8222.5	236	3785.3	4602.2	97	8600.2	7983.9
2018	275	10120.0	8358.7	170	3782.3	2575.4	133	10201.7	8567.9
2019	313	8977.0	7272.0	239	4185.4	4707.5	83	11312.6	7136.1
2020	1108	4793.4	4663.2	1065	4091.6	4081.0	43	10312.7	5295.7

Note: Per kg average launch costs are weighted averages by satellite mass. All prices are in 2020 US dollars.

Table A3. Summary statistics data on satellite mass

	All satellites			Commercial			Non-commercial		
Year	**N**	**Mean**	**Std. Dev**	**N**	**Mean**	**Std. Dev**	**N**	**Mean**	**Std. Dev**
2000	15	1748.6	3632.0	4	397.5	105.0	12	2073.3	4026.7
2001	19	1378.2	4068.1	3	477.0	410.5	18	1401.9	4184.7
2002	28	994.0	1605.4	10	787.7	836.6	25	991.2	1626.7
2003	26	458.5	494.3	3	882.3	544.7	24	446.7	508.6
2004	26	713.5	1234.0	4	12.0	0.0	22	841.0	1304.6
2005	18	2748.2	5281.7	0			18	2748.2	5281.7
2006	27	1380.9	1925.4	4	2290.0	2935.9	26	1381.7	1963.5
2007	52	865.7	1243.0	19	796.1	1151.0	35	930.6	1274.0
2008	41	919.8	1644.3	13	272.0	507.7	31	1169.8	1827.6
2009	55	826.9	1378.0	5	570.6	1246.3	50	852.6	1399.5
2010	33	887.7	1415.3	8	651.3	154.7	26	936.7	1597.5
2011	48	1302.1	2959.1	15	563.5	282.6	33	1637.8	3529.0
2012	45	1025.3	1838.1	10	250.2	337.3	37	1213.2	1978.3
2013	100	536.8	2024.0	24	499.2	1197.6	79	609.3	2267.5
2014	90	562.8	1357.2	37	316.1	1052.8	57	801.8	1621.6
2015	137	378.4	1206.0	71	89.8	164.7	70	675.6	1633.9
2016	124	352.4	1098.9	68	153.2	773.5	57	687.5	1524.4
2017	345	222.8	706.5	250	147.4	313.2	135	551.2	1049.3
2018	298	241.0	562.5	178	154.4	314.6	148	457.5	734.5
2019	330	265.1	1059.2	243	155.7	172.9	96	597.9	1923.6
2020	1,140	219.6	239.9	1,080	205.4	78.8	61	467.1	957.0

Table A4. Summary statistics data on per satellite launch cost

	All satellites			Commercial			Non-commercial		
Year	**N**	**Mean**	**Std.Dev**	**N**	**Mean**	**Std.Dev**	**N**	**Mean**	**Std.Dev**
2000	15	44813.9	108711.8	4	14071.6	5704.0	12	51786.4	121557.5
2001	19	34935.0	122368.1	3	12869.6	19828.2	18	34888.9	125915.6
2002	27	18991.5	23148.5	10	18777.3	10765.8	24	20225.8	23880.9
2003	26	10136.8	12255.9	3	14623.8	4071.1	24	9598.6	12606.0
2004	26	11399.9	24495.3	4	114.8	0.0	22	13451.8	26184.8
2005	18	72190.8	154221.4	0			18	72190.8	154221.4
2006	27	24062.0	30761.5	4	38701.4	51576.6	26	24486.9	31289.8
2007	51	15186.1	28758.9	19	16795.5	38590.3	34	14054.5	20952.3
2008	41	15435.9	33054.7	13	7092.9	19964.6	31	19871.7	37060.2
2009	55	15537.5	28488.0	5	21167.4	47032.9	50	14974.6	26650.4
2010	32	15165.8	24102.3	8	11971.9	2842.7	25	15823.1	27342.5
2011	48	20885.9	47689.8	15	9785.7	4982.8	33	25931.4	56969.6
2012	45	14318.3	27641.6	10	3065.8	3187.2	37	16970.2	29864.0
2013	96	8798.7	34170.9	23	8885.2	21147.1	76	9936.5	38268.3
2014	89	8634.5	22658.7	37	4711.2	17811.5	56	12781.0	27337.8
2015	98	6940.4	21443.9	36	1542.4	2353.1	66	9891.3	25658.9
2016	85	6963.2	17684.2	32	4968.5	18871.9	54	9919.4	21194.4
2017	293	2320.8	10615.7	236	589.7	1060.4	97	6580.5	17729.2
2018	275	2631.9	9448.0	170	608.4	1073.5	133	5182.0	13117.5
2019	313	2504.9	17436.1	239	662.4	884.1	83	7802.9	33409.3
2020	1,108	1081.3	3072.1	1,065	851.9	692.1	43	6762.6	14220.8

Note: The costs are in thousands of 2020 US dollars.

Table A5. Regression results: Satellite-level cost per kg

	All	Commercial	Non-comm	>1000kg	100-1000kg	10-100kg	<10kg
	(13)	(14)	(15)	(16)	(17)	(18)	(19)
α	9.454***	10.425***	9.758***	8.985***	8.628***	10.874***	15.489***
	(0.823)	(1.239)	(0.800)	(0.834)	(0.613)	(2.265)	(1.789)
t	-0.085***	-0.130***	-0.051***	-0.026**	-0.113***	-0.034***	-0.027**
	(0.006)	(0.012)	(0.008)	(0.011)	(0.005)	(0.011)	(0.012)
ALT	0.143	0.065	0.048	0.139	0.301***	-0.177	-0.898***
	(0.124)	(0.165)	(0.122)	(0.127)	(0.087)	(0.343)	(0.257)
n	2787	1936	962	187	1533	273	794
F	100.03***	111.23***	18.96***	3.61**	501.39***	5.51***	6.51***
R2	0.366	0.536	0.165	0.075	0.516	0.059	0.031

Note: Robust standard errors are in parentheses. ***-significant at 1%; **-significant at 5%; *-significant at 10%.