Optimal form factor of small satellites.

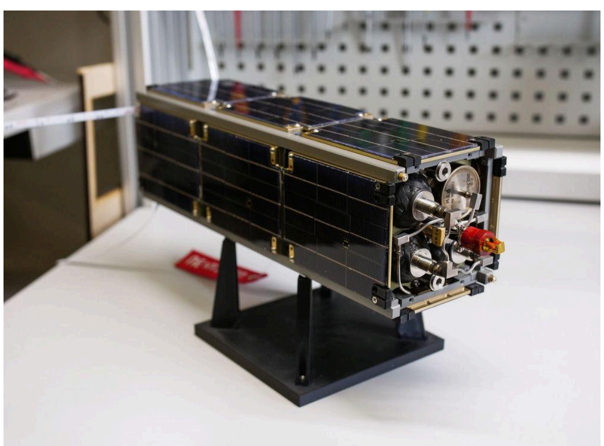
Astrodynamical and economical analysis.

Preface.

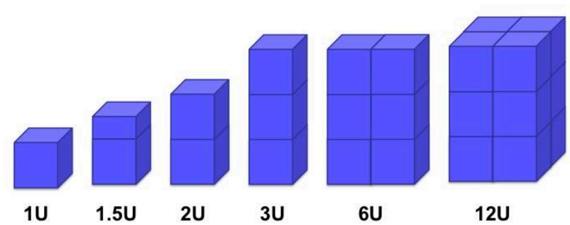
Nowadays, plenty of "new space" companies, especially minor ones, are founding their business on micro-, nano- and pico satellites. As you may know, satellites can be classified by their mass. So, in table below you can see classification of small satellite types:

Small satellite type	**Mass min.-max., kg.**
Micro satellites	11.0 - 200.0
Nano satellites	1.1 - 10.0
Pico satellites	0.1 - 1.0

In the last decade most wide-spreaded form factors of micro satellites became, without doubt, derivatives of CubeSat.



*Typical modern small satellite, form factor CubeSat 3U (**Geoscan Edelveis**, NORAD ID: 53385)*



CubeSat satellite form factor standard sizes comparison.

Pico satellites of form-factor PocketQube also became spreaded and well-known as a cheapest solution for educational and amateur space missions. This form factor became interesting even for commercial space.

During my work with SpaceLab LLC I faced a problem to choose the optimal form factor for small sat produced in big series. Consulting with experts did not give me trustworthy advice on this. So I tried to analyze this problem myself, from the point of view of an astrodynamicist, taking into account economical efficiency. Below you can see what I've got.

Spacecraft from an economical point of view.

Space economy is very different from what people used to imagine under the term "economy". Economics of space projects is something vastly beyond common analysis of business efficiency (for example, in IT).

First things first, in most cases spaceflight itself is not the most important thing in the process. Customers of business which use space systems in its projects are always here on Earth, and businesses selling its services to them. So, it would be correct to say that they get their profit from space indirectly.

Next, in most cases businesses don't receive profit from space itself. Space vehicles required in their business are nothing more than platforms with payload, moved outside Earth "for convenience". Most important things in this scheme are payloads (for which spacecrafts are only "interface and service buses") and data received, processed and transmitted by this payload.

Based on these two statements, it's possible to state that actually, the space segment of any business is nothing more than an infrastructure facility, which is important not itself, but as a part of a bigger scheme. This is the backbone of a project. All services and solutions growing from and around this backbone. Backbone provides structure, but not bringing profit itself.

I can compare this with raising a cathedral or mosque in a vast lifeless desert. Cathedral itself does not bring money, and its construction is a pure loss. But it forms a core for future settlement of people. It is "the center". It attracts other businesses and people. Around it will grow farms, schools, workshops, hospitals...

In any case, typical spacecraft (from an economical point of view) is a pure loss - money thrown into space.

To make their business profitable, **satellite operators need to reduce these losses**.

Ways of optimisation.

First, and most straightforward way, widely spreaded nowadays, is to make spacecraft smaller. Smaller the size - easier to manufacture; less mass - less launch cost. Just common sense. And practice shows that - it works! CubeSat, and, especially, PocketQube (as a form factor) grew from this logic. Many spacecraft manufacturers and operators offer a variety of solutions in this form factors. A huge sector of "new space" grew on this boom of small sats.

Nowadays the form factor of satellites shows a tendency to shrink. Now there is not only CubeSat - there is also "half-cube" and PocketQube form factor family. Different startups offer even smaller form factors - CanSat, TubeSat, ChipSat and so on.

Yes, these very small sats have their own disadvantages. Their manufacturing and launch cost is relatively higher than for bigger sats. Their lifetime is shorter than even CubeSat lifetime because of the combination of mass and form (they are less dense than CubeSats and thus decaying faster). They can not carry and support bigger payload due their small size and limited power of bus subsystems.

Despite this, many companies offer (and use) such solutions.

There is also another way to optimize the cost of the mission. When we are talking about space, we always need to take into account its "other part" - time. Space missions work not only in space, but in time. How can we use this?

In the table below you can see the approximate cost distribution of a typical modern small satellite mission, built by integral analysis of data from NASA SSRI Knowledge Base.

Mission Component	**Estimated Percentage of Total Cost**
Program Management	5%
Systems Engineering	10%
Design and Development	20%
Payload (Instruments)	15%
Spacecraft Bus Manufacturing	20%
Integration and Testing	10%
Launch Services	15%
Ground Operations and Support	5%

As you can see, costs of manufacturing, launch and flight (M-L-F) takes 50% of overall costs of the mission.

In most cases satellite operators can not greatly reduce the total cost of the mission. But **it is possible to extend mission time to get more profit** (and this way reduce the *relative* cost of the mission).

I.e., if we can find a way to prolongate lifetime of a satellite, and same time, not to raise M-L-F costs of the whole project, then this approach can allow us to deliver "more service from space for less money" (just because a single satellite will provide service longer).

Take in account that in modern times satellites in commercial projects rarely work alone. In most cases for such applications companies create constellations of satellites (with tens, hundreds, and even thousands of them). Accounting for this, if a company needs to keep its presence in space, it may rely on a smaller number of long-living satellites, and this way reduce losses even more by playing with M-L-F costs. For bigger constellations intended for long-time operations, this can reduce costs several times!

Of course, prolongation of the mission isn't a "silver bullet". Space is a harsh environment, aggressive to components of spacecraft. So, during such optimisation, developers of the mission should take into account environmental effects of outer space and reliability of the components.

I will keep this in mind during further analysis.

Lifetime of small satellites.

What factors determine the duration of a small satellite mission?

Well, this is obvious.

First main factor is decay time - i.e., time of flight of a satellite until drag of the upper atmosphere moves periapsis of its orbit into dense layers of an atmosphere (where the satellite will burn). Decay time depends on multiple parameters, especially:

- Orbital parameters (mainly semi-major axis and eccentricity, which determines altitude of flight)
- Mass of the satellite
- Cross-section area of a satellite
- Environmental conditions in space (especially changes of density of upper atmosphere caused by solar activity)

Notice that I do not take into account the shape and aerodynamic properties of the satellite. Following data from references 1, 2 and 5, I will take the drag coefficient of a typical small satellite as C_d=2.2 (aerodynamics of a small high-hypersonic object in a very spreaded atmosphere is still a dark matter). Yes, it is possible to optimise it, but in most cases this would require growth of net cost of the project. Relative to the effects of optimization, this expenditure looks unreasonable.

Second main factor is the max lifetime of components. As I mentioned above, space is a harsh environment for materials and components of satellites. Atomic oxygen at lower LEO, traces of radiation from Van Allen belt at higher LEO, and solar activity - all of this causing degradation of construction materials, electronics and subsystems of satellites. Exact durations before first failure differs, but for a typical small satellite, made with COTS ("common off-the-shelf", i.e., not "space certified") components it is from 3 to 5 years. It is possible to achieve a longer lifespan, but in most cases this can be done with much more expensive "space grade" components, which will, again, increase the net cost of the project.

Main economical parameters of orbital mission.

So, my goal is to find a form factor of a small satellite, providing the longest mission time within lifespan of satellite components with the *best economical feedback* of the whole system. And here one of the most difficult things is a choice of parameters, representing efficiency of a mission.

Based on what I said above, I may state that the most important thing is the *"amount of service"*, which can be done by satellite. Under "amount of service" I understand not only "quantity", but also "quality" of services - i.e., satellite imagery with higher resolution, received from a bigger camera is greater "amount of service".

"Amount of service" in the space industry (taking in account world globalisation and applied technologies) would be by sense equal to the mass of a satellite. I.e., in most cases (because in modern times all space manufacturers using mostly the same technologies and solutions) satellites of the same mass developed for the same task can deliver compatible quality and quantity of, for example, scientific data.

Thus, in the case of our analysis I may replace the term "amount of service" with a more physical (and more convenient for further analysis) term *"mass"*.

To force this mass to deliver service, operators of a satellite need to apply to it M-L-F costs - i.e., make it from scratch, launch to space and keep it working. In case a company wants to increase efficiency, it needs to achieve the best (i.e., highest) ratio of mass to M-L-F cost. I.e.:

$$E_c = \frac{m}{C_{MLF}} \qquad \text{(eq. 1)}$$

where:

- $\mathbf{E_c}$ - cost efficiency
- **m** - mass of a satellite, kg
- $\mathbf{C_{MLF}}$ - M-L-F cost, $

Here I prefer to make one simplification. As I said earlier, cost distribution for all small satellite missions are almost the same. It's hard to find exact information about costs of design and manufacturing of satellites and about ground operations. But launch prices in most cases are public. So, for approximate analysis I may (and will) drop data about cost of manufacturing and ground operations. Results of my calculations are relative, so the sense of analysis will not change.

So, because I need to analyze the efficiency of different types of small satellites, it would be more convenient to use the inverted value of E_c, i.e., *specific price*:

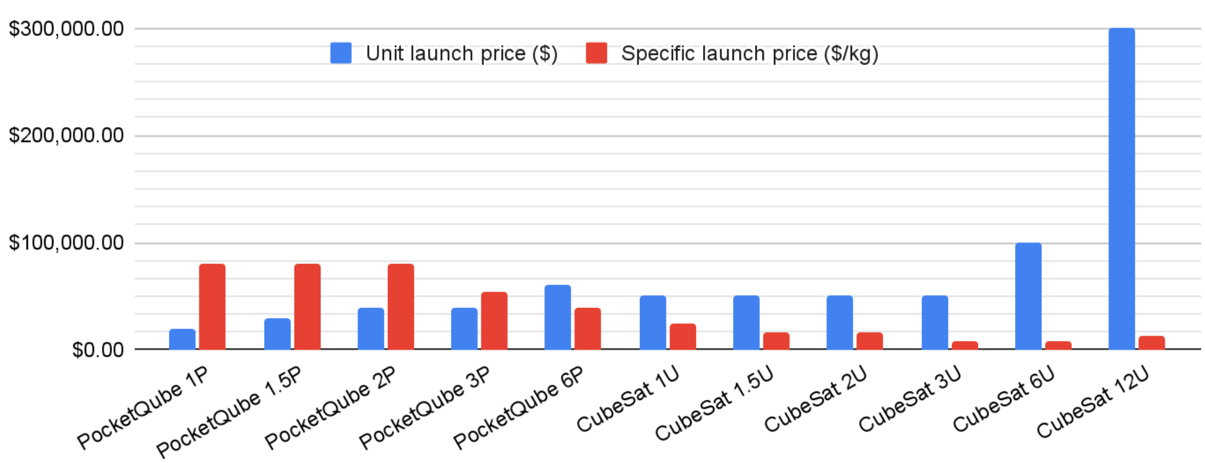
$$P_{sp} = \frac{P_L}{m} = \frac{1}{E_c} \qquad \text{(eq. 2)}$$

Here:

$\mathbf{P_{sp}}$ - specific price, total cost of 1 mass unit (kg) of satellite in space, $/kg
$\mathbf{P_L}$ - price of launch of one satellite of current form factor, $
m - mass of a satellite of current form factor, kg

In the sheet below you can see distribution of P_{sp} for different form factors of satellites.

Table 1. Small sat missions costs.



In this table, all prices are from mid. 2024, as mean from prices offered by multiple companies. As expected, bigger the form factor - smaller the specific price (price of "1 kg of satellite at the orbit").

Now, I will bring up a new parameter, describing "mission efficiency in time". This is *owning costs*, which is the ratio of specific price to satellite lifespan:

$$C_o = \frac{P_{sp}}{T_l} \qquad \text{(eq. 3)}$$

where:

C_o - owning costs, $/kg per year.

P_{sp} - specific price, $/kg

T_l - satellite lifetime, years.

Owning costs can be threatened as inverted economical efficiency. Lower the owning costs - better the efficiency. This is logical - if the satellite is just an infrastructural object, it must be cheap and long-living. As I said before, satellite lifespan depends on its physical parameters and environmental factors. So, to determine the most optimal small satellite form factor, I need to analyze decay times of different satellites on different orbits.

Analysing orbit decay time.

To determine the lifetime of satellites of different form factors, I need to model their orbital movement, taking into account the effect of the atmospheric drag.

Simplified model of the orbital decay process is well-described in literature (references 4 and 5) and in corresponding Wikipedia article. It provides precision around 5% proven with practical examples, so it is enough for our analysis.

Following this method:

m - satellite mass, kg

C_d = 2.2 - dimensionless drag coefficient of satellite

S_1, **S_2**, **S_3** - areas of faces of a satellite, m^2

ρ - atmosphere density at given altitude, km/m^3

v - orbital velocity of the spacecraft, km/s

h_0 - initial altitude of spacecraft, km

h_1 = 180.0 km - decaying altitude

First, let's calculate the cross-section area of a satellite. Because satellite attitude in most cases is not optimal for smooth "airflow" (or satellite is just not stabilized, thus rotating and showing its faces to "airflow" equally one by one), cross-section area should be calculated like this:

$$A_{cs} = \frac{1}{2}\left(S_1 + S_2 + S_3\right) \qquad \text{(eq. 4)}$$

Next, drag force generated by atmosphere should be calculated:

$$r = h_0 + R_{Earth} \quad \text{(eq. 5)}$$

$$v = \sqrt{(\mu/r)} \quad \text{(eq. 6)}$$

$$\alpha_{drag} = \frac{1}{2}\rho v^2 C_d\left(\frac{A_{cs}}{m}\right) \quad \text{(eq. 7)}$$

where:

A_{cs} - cross section area of satellite, m^2

r - current radius of orbit, km

R_{Earth} = 6378.137 km - mean radius of Earth

μ = 398600.4418 km^3/s^2 - gravitational parameter of Earth

v - orbital velocity, km/s

α_{drag} - drag force, generated by atmosphere

After this, it's possible to describe flight duration of satellite through next equations:

$$a = r \quad \text{(eq. 8)}$$

$$P = 2\pi\sqrt{\frac{a^3}{\mu}} \quad \text{(eq. 9)}$$

$$t_d = \int_{h_0}^{h_1}\left(\frac{\alpha_{drag}P}{\pi}\right)dt \quad \text{(eq. 10)}$$

where:

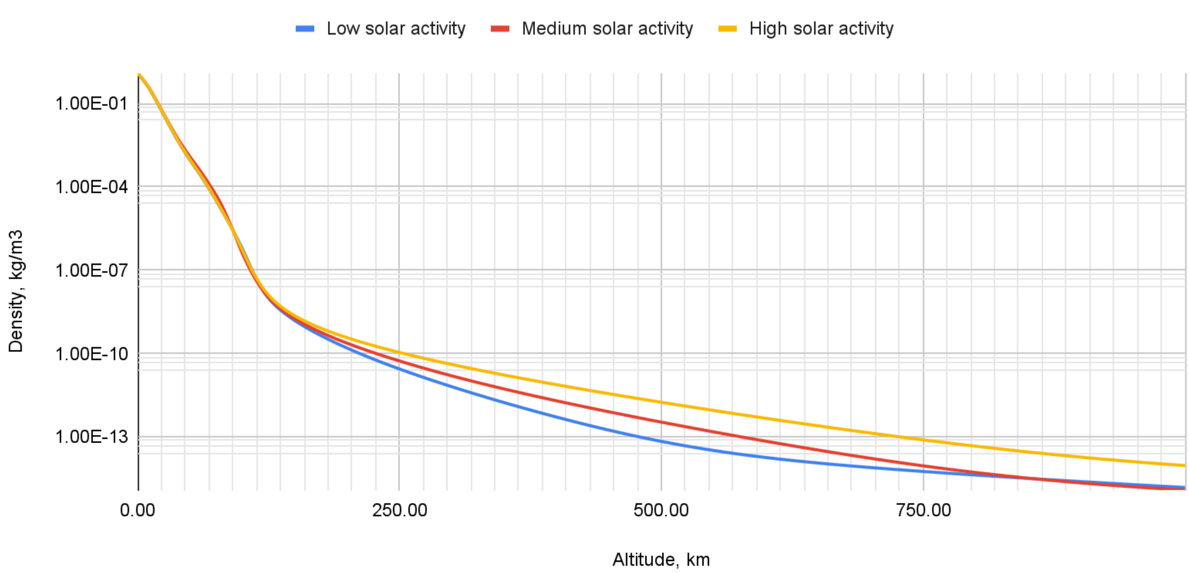
a - SMA of the orbit, km (we treat it as circular, because eccentricity is minimal).

P - period of the orbit, s

t_d - decay time, lifespan of the satellite, s

Looks like it's enough, but things are more complex here. Take a look at table 2:

Table 2. Atmosphere density at different periods of solar cycle



Solar cycle (also known as "Schwabe cycle") is a natural periodic 11-years change of solar activity. At different periods of solar cycle activity of the Sun ("space weather") changing parameters of Earth's upper atmosphere at altitudes from 200 to more than 1000 km.

Graphs on table 2 were built using Python module PyAtmos, implementing the NRLMSISE-00 Earth atmosphere model. These lines show fluctuations of density caused by solar wind and radiation. Clearly visible, that at periods of low solar activity and high one density at altitudes about 500 km differs about 2 orders (i.e., 100 times!).

Of course, absolute values of atmospheric density are pretty low. But such differences (especially at orbital speeds!) definitely will affect trajectories of satellites.

To take into account these density changes, I calculated decay times of satellites of different form factors in different periods of solar cycle. Then I calculated weighted mean decay time for each satellite. As weights I used ratios of total length of solar cycle to decay time of each satellite form factor:

$$W_{LSA} = \frac{T_{sc}}{t_{d\,LSA}} \qquad W_{MSA} = \frac{T_{sc}}{t_{d\,MSA}} \qquad W_{HSA} = \frac{T_{sc}}{t_{d\,HSA}} \qquad \text{(eq. 11,12,13)}$$

$$t_{d\,mean} = \sum_{LSA}^{HSA}\left(t_d W\right) / \sum_{LSA}^{HSA}(W) \qquad \text{(eq. 14)}$$

where:

T_{sc} = 11 years - approximate length of solar cycle

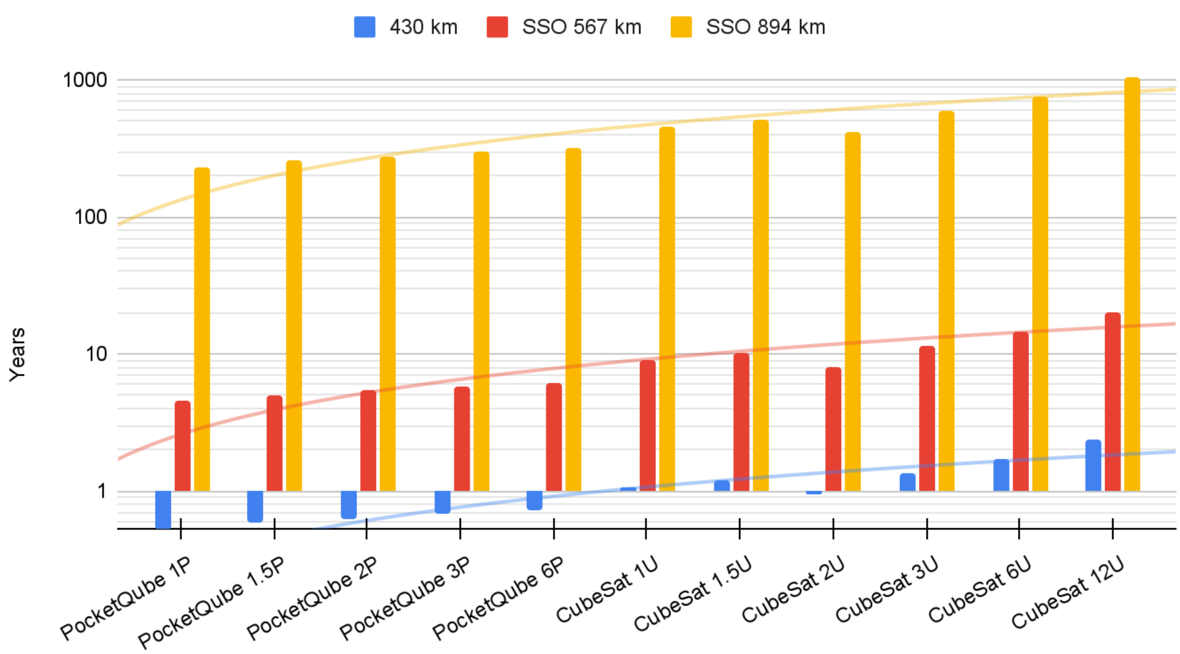
$t_{d\,LSA}$, $t_{d\,MSA}$, $t_{d\,HSA}$ - decay times in case of different solar activity levels, years

W_{LSA}, W_{MSA}, W_{HSA} - "weights", most probable time of effects of solar activity to a satellite

$t_{d\,mean}$ - mean decay time for satellite of selected form-factor

This way, **I have got this chart of mean decay times for different satellites**:

Table 3. Mean decay time of small satellites at different orbits



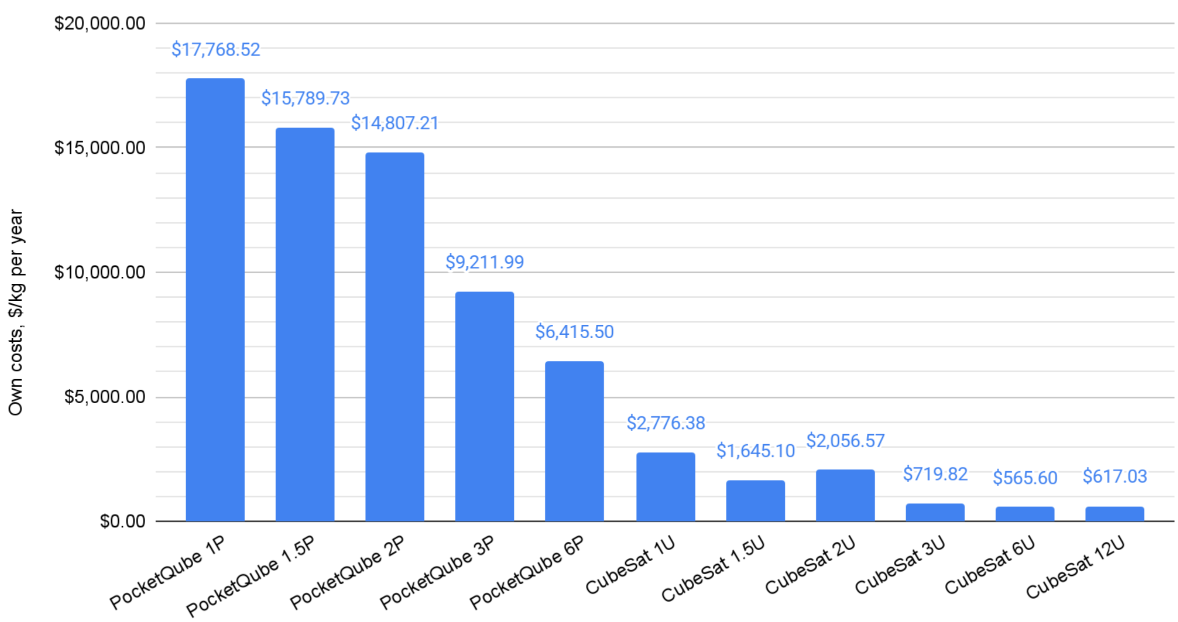
As visible at table 3, satellites of different form factors have different mean decay times. Also, it is clearly visible that their decay times notably vary. To show this, I added trend lines to the graph. Easy to notice that, for example, the lifespan of CubeSat 2U at SSO 567 km is shorter (for almost 3 years!) than it could be expected!

Determination of optimal form factor.

Based on data calculated above it's possible to get back to analysis of economical efficiency of different small satellite form factors. Using calculated values and eq. 3, I calculated owning costs of different satellites:

Table 4. Own costs for different form factors of small satellites

Sun-synchronous orbit, 567 km



In the table 4 clearly visible economical efficiency of different small satellite form factors.

Keeping it simple, this chart shows *how much money you need to spend per year to keep the presence of 1 kilogram of your equipment in space (at SSO), if you are using small satellites of different form factors*. To say more roughly, ***how much of your money ate (at the moment of launch) each kilo of your flying stuff for each year of its work in orbit***.

There is a few important things viewers should notice:

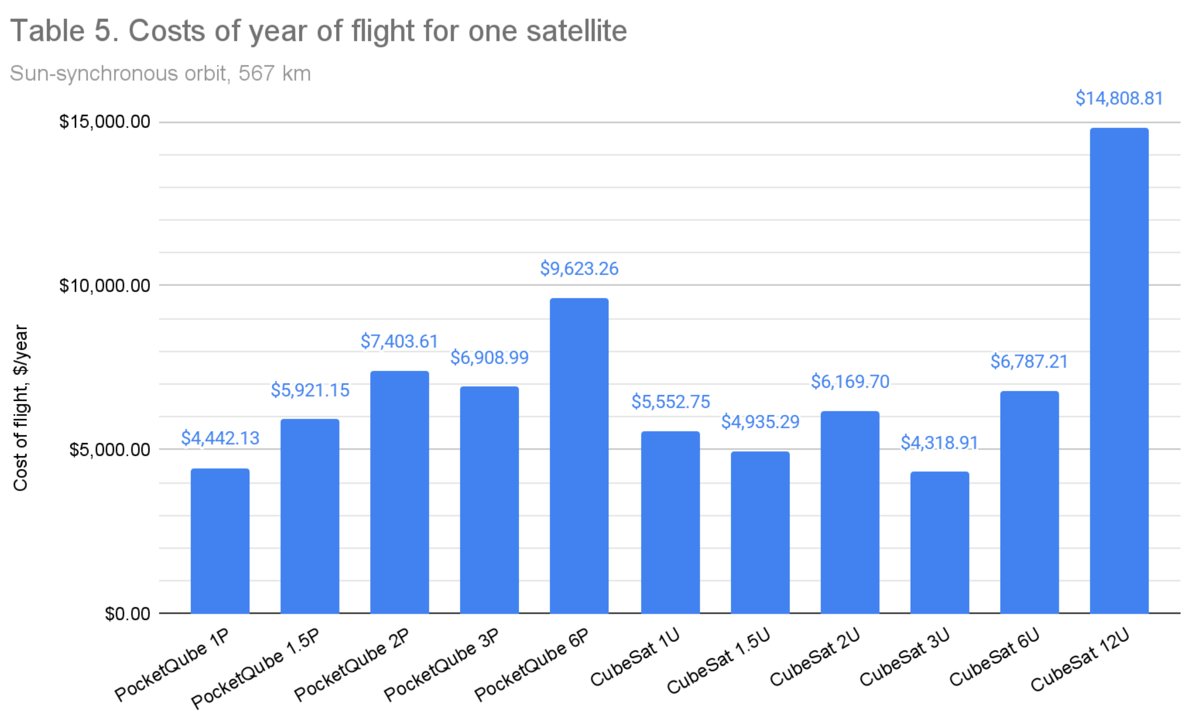
1. **In common case this is not an "actual price"** - this is representation of economic efficiency, *synthetic parameter*. These values should be used only for relative comparison.
2. This data *can be* threatened as "actual price per kilo of satellite per year" **only** if you are planning a long-time (multiple years) mission for a big constellation.

Now, on the chart it is visible that some form-factors provide better own costs than others. First, PocketQube 3P and PocketQube 6P provide much better efficiency than their smaller relatives. But no PocketQubes can beat the economical efficiency of CubeSats - **even the smallest CubeSat 1U is almost 3 times more effective than the biggest PocketQube 6P**.

Actually, that is understandable. First, bigger sats are much heavier. Cross-section area grows by power of 2, but mass grows by power of 3 - square-cube law as it is. Heavier object has more inertia, so it stays in orbit for a longer time. For a satellite without a propulsion system it's more profitable to be bigger, denser and heavier. Next, modern rockets, because of physics and economics, are still optimised (and will be optimised!) to deliver heavier and bigger loads. Small satellites require too much "additional activity" with adapters, deployers, etc. So their launch price will always be slightly higher than for bigger and more standardized sats.

Interesting things are visible in the CubeSats segment. CubeSat 1.5U, becoming more popular in the last few years, really shows greater economic efficiency than CubeSat 1U and even than CubeSat 2U. And, what is more important, the most popular CubeSat 3U showed almost the same efficiency as heavier relatives (6U and 12U)!

To perform better analysis, I will build another graph. At table 5 is represented relation between launch costs and decay time for each form factor of small satellites:

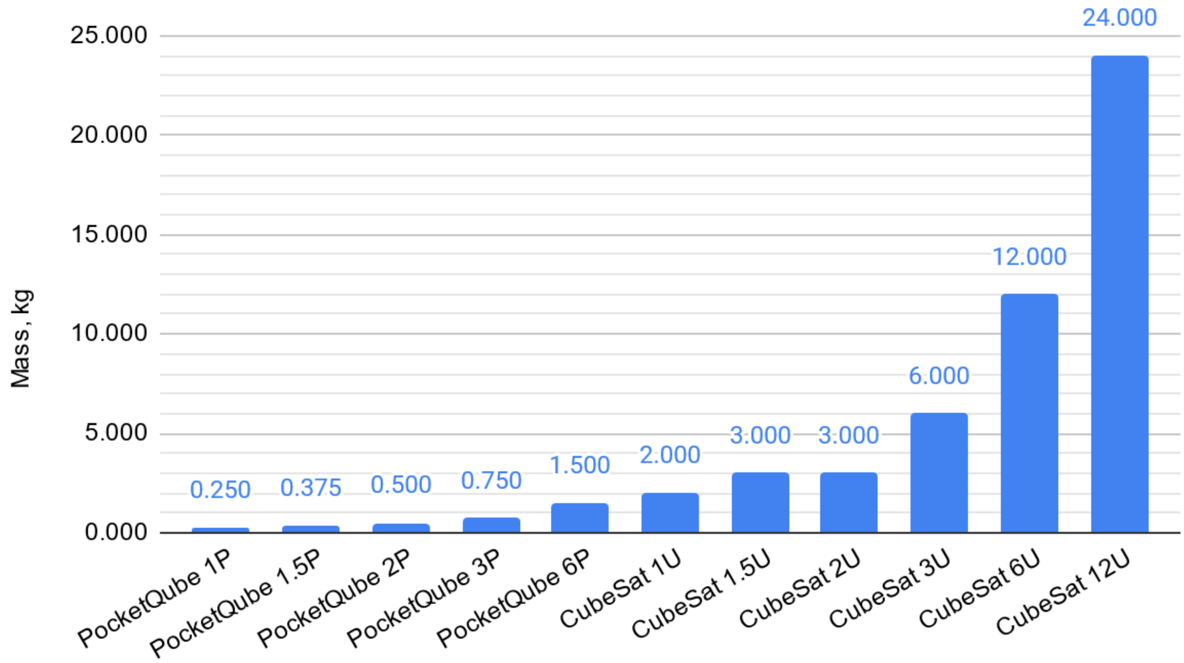


This chart is more "natural". To keep things simple, this is a representation of ***how much of your money ate (at the moment of launch) your satellite (as a unit) for each year of its work in orbit***.

This is, in a nutshell, a "relative price to get to orbit" - "cost of flight". As expected, the cheapest solutions show the lowest prices. CubeSat 3U, CubeSat 1.5U and PocketQube 1P winning. But it is visible that here CubeSat 3U is also the leader.

Now, to finalize the analysis, I will plot a new graph. It would be very simple, just a mass of sats of each form factor analyzed:

Table 6. Mass off small satellites of different form factors



This table finalyzing my analysis. As I said earlier, mass in case of commercial space flights equals "amount of services" a satellite can provide. Mass distribution of small satellites shows actual powers of each form factor.

Now, **what conclusions could be done from this information**?

Conclusions.

1. Satellites of **CubeSat 3U form factor are trustworthy leaders in economic efficiency**. Nowadays, there is no better solution in cost/efficiency ratio.
2. Smallest satellites, like PocketQube, definitely are the cheapest way to reach orbit. But their cost/efficiency ratio is **lower** than one of CubeSat 3U. For almost the same flight cost, CubeSat 3U has 6 kg of mass, where PocketQube has 0.25 kg. Think twice before using them.
3. **Think bigger.** It's more profitable for commercial satellites to be bigger, heavier and denser.

Additional questions.

You may think that I forgot about *another way* of prolonging satellite lifetime - a propulsion system. My answer would be - no, I did not.

In logic I used for this investigation, max of the mass of a commercial satellite should be spent for commercial payload - the stuff providing services (i.e., bringing profit). Propulsion systems for small sats are bulky and not too effective. It increases M-L-F costs of a mission, and in the end is not worth its mass.

Attention! *I am not against actively flying small sats!* But, in my opinion, commercial satellites should only provide services, and maneuvers should be done by a tug, able to place them into correct anomalies. This tug should be a small satellite, equipped with powerful ADC and propulsion systems, and its task should be only maneuvering with a number of attached commercial satellites towards their drop points.

Another expected question would be about usage of higher orbits to reduce costs of the missions. Indeed, as my calculations show, higher orbits will guarantee longer lifespan of satellites, and this way will help to reduce costs. SSO with altitude 894 km provides a decay time of almost 500 years for CubeSat 3U.

So it is profitable to send satellites higher.

But these altitudes raise other questions, especially about lifespan of satellite and payload components, radiation danger, hoarding of space debris and so on. So, higher orbits are attractive, but their usage now is a reason for other studies.

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