Team ID: 1187

"What's the largest payload that could be launched into orbit by slingshot?"

ABSTRACT:

In this report, we considered the maximum mass of payload that could be launched into an altitude of 160 km without using any rocket fuel, to minimise the financial and environmental impact and increase the ease of access to space while minimising the ethical issues. By using a mathematical model based around SpinLaunch's orbital centrifugal slingshot, we concluded that when a payload is projected directly upwards in a path perpendicular to Earth's surface, with the goal to simply reach the desired height - even if only momentarily - the mass of the payload combined with the mass of a capsule (the capsule could be defined as part of the payload if it was constructed with "valuable" material) could be a maximum of 17,619 kg.
We also explored the option of launching the payload at an angle less than 90 degrees to earth's surface, at such a velocity that when it reaches the 160 km altitude orbit, it has decelerated so that it is still at a sufficient speed[1] so that it will stay in orbit. We found that by using the assumption that the path of the projectile will be in a semi circle where the diameter is a tangent to the circle of earth that starts in contact to earth's surface and ends at the 160km altitude orbit, the maximum payload mass would be 525 kg.

INTRODUCTION:

With the fast development of technology in the last decade, inhabiting celestial bodies other than Earth has become a real possibility that has the potential to help with overpopulation. For this to be possible, materials would have to be launched up into space to allow people to live sustainably. The current methods of launching payloads into space are inefficient both financially and environmentally, and the predominant contributor to this is the use of rocket engines and fuel. NASA has signed a contract with SpinLaunch and they plan to start commercial launches using their SpinLaunch orbital L100 accelerator in 2025[2], a design that uses a centrifugal slingshot design to start the launch of the rocket and decrease the use of the engine. However this design still includes the use of a 164,000kg rocket and one minute of rocket fuel per payload of up to 200kg. This is less efficient than the use of larger rockets (such as SpaceX's "Falcon Heavy" which is the rocket currently in service with the most power by lift capacity and can carry 63,800 kg of payload to low earth orbit and has a mass of 1,420,788 kg, containing 362,874 kg of fuel with a ratio of 1,138kg of fuel per 200 kg of payload [3]). However, a rocket that only carried a payload of 200kg would be vastly less efficient (Rocket Lab's "Electron" is the only reusable small launch vehicle, and can carry a payload of 300 kg to low Earth orbit using 13,000 kg of rocket fuel, a ratio of 8,667 kg of fuel per 200 kg of payload). "Currently the lowest cost launch vehicle to put a small satellite in orbit is about $7,000,000 [USD], spin launch is bringing this down to less than $500,000 [USD]" - Jonathan Yaney

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[1] https://www.esa.int/kids/en/learn/Technology/Mission_control/Space_velocity
[2] https://gadgettendency.com/launching-a-satellite-into-space-through-a-huge-centrifuge-on-the-ground-spinlaunch-launch-video-released/
[3] https://www.spacex.com/vehicles/falcon-heavy/

(Founder & CEO at SpinLaunch)

Our initial aim is to calculate the maximum payload that could reach low Earth orbit if there was no use of rocket fuel at all, to minimise the environmental and financial impact. We decided that our payload would reach low Earth orbit at 160km above earth's equator, as this is the low end of the average placements of satellites above Earth which would maximise the possible mass of the payload.

ASSUMPTIONS/DEFINITIONS:

We defined the brief as what is the maximum mass (kg) of payload that could reach an orbit level of 160km above earth's equator by a centrifugal slingshot design and then we explored methods as to how it could stay in orbit:

- We decided to measure the "largest" payload in kgs as a mass because the mass of an object is not affected by gravity which is a minimal variable for the journey of the projectile and therefore the weight of an object would not remain constant.
- Our projectile is designed to reach an altitude 160km, as this is a minimum value in the common range of satellite placement and will therefore allow us to calculate the maximum mass of payload that can be carried.
- Our first mathematical model answers the question literally and includes only the direct projection of the payload up into space in a path perpendicular to Earth's surface, from where it would fall back down to Earth after reaching an altitude of 160km unless a force parallel to Earth's surface was provided at such a quantity to cause it to travel a sufficient speed in which would cause it to stay and orbit Earth.
- Our second mathematical model explores the more realistic possibility of releasing the projectile at an angle so that when it reaches an altitude of 160km it will remain in orbit.
- We defined payload as useful/valuable materials including satellites (not people).
- Although we are aware that the gravitational force decreases in size as an object gets further from Earth's surface, this change is very minimal and so we decided to keep the force constant as we were finding a maximum mass and were therefore able to consider the gravitational force in excess.

THEORETICAL APPROACH:

The centripetal forces used by the SpinLaunch slingshot design can be modelled using the equation:

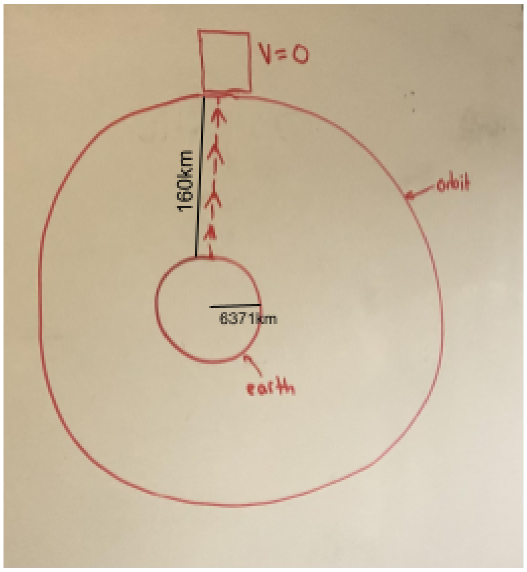
$$Fc = \frac{mv^2}{r}$$

[4] https://www.youtube.com/watch?v=VbrZ3GoobFk&ab_channel=ScientiaPlus [5] https://aerospace.csis.org/aerospace101/earth-orbit-101/
[6] https://techcrunch.com/2022/04/06/spinlaunch-scores-nasa-test-mission-to-demonstrate-its-unique-launch-method/
[7] https://www.youtube.com/watch?v=a1zp4OHJjrw&ab_channel=DrBenMiles [8] https://www.sciencelearn.org.nz/resources/272-launching-satellites
[9[https://www.actionnews5.com/2021/10/08/breakdown-what-is-space-junk-why-is-it-problem/ [10]
https://www.sciencefocus.com/space/are-space-launches-bad-for-the-environment/

Where F_c is the centripetal force, m is the mass of the object, v is the velocity of the object, and r is the radius of the slingshot design. Based on trials in the A33 SpinLaunch test run, theoretical information has been released about the more powerful L100 design[4], the model we are using for our report. This powerful centripetal accelerator has a radius of 45m, with the potential to release an object of mass 11,200kg at a velocity of 8,000km/h[4]. Using the above equation, we can calculate the centripetal force created by the L100 SpinLaunch.

$$Fc = 1.2291 * 10^{9} N$$

MATHEMATICAL MODELS:



Model #1

The first model looks at the case where the mass is slingshotted directly upwards. The majority of satellites that orbit the earth do so at altitudes of 160km to 2000km[5], and to find the maximum mass that can be launched into orbit, we used the minimum distance possible for the payload (higher distance requires more centripetal force for the same mass). As a result, in model 1 the distance the projectile is travelling is 160km. To find the maximum mass of the payload, our final velocity is 0, as this would ensure that all of the speed from the centripetal acceleration has been used.

$$Vf^{2} = Vi^{2} + 2ad \qquad Vi = 1771.78ms^{-2}$$

The equation above can be used to calculate the initial velocity of the object that is launched. Note that gravitational deceleration is estimated as $-9.81ms^{-2}$. This value can be used alongside the previously calculated centripetal force to come up with a value for the maximum mass that could be fired into orbit using the specifications of model 1 and the L100 SpinLauncher.

$$Fc = \frac{mv^{2}}{r} \qquad m = 17618.65kg$$

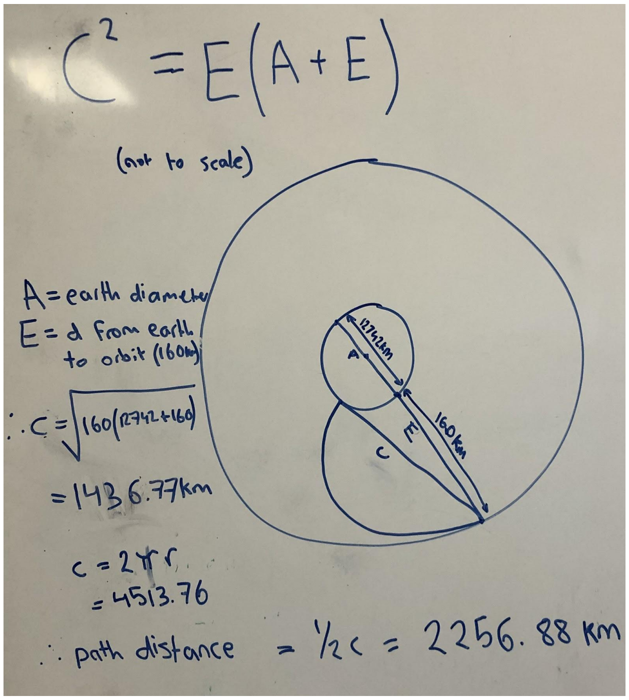
The aim of this model was to slingshot the mass upwards to reach the correct height for a potential orbiting object. This model did not consider what happens once the mass has reached

[4] https://www.youtube.com/watch?v=VbrZ3GoobFk&ab_channel=ScientiaPlus [5] https://aerospace.csis.org/aerospace101/earth-orbit-101/
[6] https://techcrunch.com/2022/04/06/spinlaunch-scores-nasa-test-mission-to-demonstrate-its-unique-launch-method/
[7] https://www.youtube.com/watch?v=a1zp4OHJjrw&ab_channel=DrBenMiles [8] https://www.sciencelearn.org.nz/resources/272-launching-satellites
[9[https://www.actionnews5.com/2021/10/08/breakdown-what-is-space-junk-why-is-it-problem/ [10] https://www.sciencefocus.com/space/are-space-launches-bad-for-the-environment/

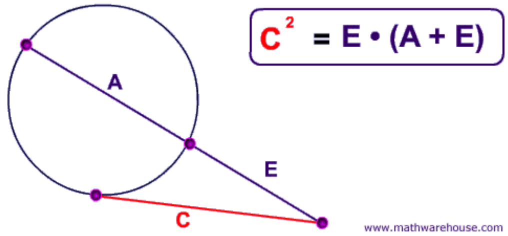
the orbit, and therefore has its flaws and is not fully practical for keeping the payload in orbit, however it answers the surface level of the proposed question.

Model #2

The second model shows a mass being slingshotted from earth at an angle so that it slowly turns to a position that is parallel to Earth's surface. If the payload reaches this position with sufficient speed, then it would be able to remain in orbit, allowing the specifications of the question to be achieved. Our 2nd model assumes that the path that the payload takes is roughly semicircular, similar to projectile motion. As shown by the diagram below, the length of the diameter of the semicircular path is related to the distance from the earth to the path of orbit (160km).



$$C = \sqrt{E(A + E)} \qquad C = 1436.77km$$



Circumference of a circle = 2πr

Circumference = 4513.67km

Due to being a semicircle, path distance = 2256.87km

Now that the path distance that the payload has to travel is estimated, the next variable that must be calculated is the final velocity for the payload to stay in orbit. This can be calculated by combining Newton's law of gravitation with a circular motion equation$_{[8]}$.

$$V = \sqrt{\frac{(G*m)}{r}} \qquad V = 7812.19ms^{-1}$$

Where V is the orbital speed, G is the gravitational constant ($6.6743*10^{-11}$), m is the mass of the earth and r is the distance from the centre of the earth to the orbiting object.

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[4] https://www.youtube.com/watch?v=VbrZ3GoobFk&ab_channel=ScientiaPlus [5] https://aerospace.csis.org/aerospace101/earth-orbit-101/
[6] https://techcrunch.com/2022/04/06/spinlaunch-scores-nasa-test-mission-to-demonstrate-its-unique-launch-method/
[7] https://www.youtube.com/watch?v=a1zp4OHJjrw&ab_channel=DrBenMiles [8] https://www.sciencelearn.org.nz/resources/272-launching-satellites
[9[https://www.actionnews5.com/2021/10/08/breakdown-what-is-space-junk-why-is-it-problem/ [10] https://www.sciencefocus.com/space/are-space-launches-bad-for-the-environment/

$$Vf^{2} = Vi^{2} + 2ad \qquad Vi = 10259.87ms^{-1}$$

With the final velocity, the path distance, and an estimated $-9.81ms^{-2}$ deceleration due to gravity, the initial velocity can be calculated.

$$Fc = \frac{mv^{2}}{r} \qquad m = 525.43kg$$

The initial velocity can be used with the previously calculated centripetal force and radius of the L100 SpinLauncher to calculate the maximum mass that can be launched and subsequently stay in orbit. This maximum mass is 525.43kg. This model is a more practical estimate than model 1 due to it taking into account the required velocity for the payload to stay in orbit.

CONCLUSION:

To conclude, model 1 provides a greater mass (17618.65kg) but only projects payloads into the orbit and does not ensure it will remain in orbit - objects must be travelling at least 28,123.88km/h to remain in orbit.

Model 2 showed a maximum mass of 525kg and a definite possibility of remaining in orbit. As a result model 2's value is likely closer to the real maximum mass that could be launched, but may still be a slight overestimation with current technology.

DISCUSSION/EVALUATION/LIMITATIONS:

There are many variables that would have marginal effects on the kinematic equations used in our mathematical models such as friction from air resistance and changes in environmental conditions. This would introduce a small margin or error.

An important aspect of our answer is that we defined "payload" as valuable or useful material and therefore included the capsule in this definition, meaning that the total maximum mass is only payload. Therefore it is important to note that if the capsule cannot be defined as payload then the maximum mass of payload will be less than our supplied answers.

We found that the mass of the projectile in model 1 will be approximately 17619 kg, and means that in order for our payload to be launched to an altitude of 160km above Earth's surface the speed that our rotated arm must reach is approximately 6378 km/h. In model 2 our approximate values for our mass projectile (payload) was 525kg and our speed was 36936 km/h. When comparing our values to Spin Launch's Orbital values of a speed of 8000 km/h and a payload mass of a maximum of 200kg, we found that it would take longer for our rotating arm to reach our desired speeds in both model 1 and 2. This would mean that due to this increase in time

[4] https://www.youtube.com/watch?v=VbrZ3GoobFk&ab_channel=ScientiaPlus [5] https://aerospace.csis.org/aerospace101/earth-orbit-101/
[6] https://techcrunch.com/2022/04/06/spinlaunch-scores-nasa-test-mission-to-demonstrate-its-unique-launch-method/
[7] https://www.youtube.com/watch?v=a1zp4OHJjrw&ab_channel=DrBenMiles [8] https://www.sciencelearn.org.nz/resources/272-launching-satellites
[9[https://www.actionnews5.com/2021/10/08/breakdown-what-is-space-junk-why-is-it-problem/ [10] https://www.sciencefocus.com/space/are-space-launches-bad-for-the-environment/

needed for one launch to take place, we would have less frequent launches than the Spin Launch's Orbital but carry a larger payload mass.

The most vital aspect of our design is that the journey has no environmental impact other than the electrical energy needed to spin the tether/rotating arm to launch the payload. There are no emissions that are released into the atmosphere that contyribute to pollution through the burning of rocket fuel as none is needed or present (burning rocket fuel causes rocket launches to have a hefty carbon footprint[10]) , and no portion of the projectile is released that will contribute to space junk and therefore we can classify the journey of our design as producing zero emissions. Space junk, or space debris, is any piece of machinery or debris left by humans in space. While there are about 2,000 active satellites orbiting Earth in 2021, there are also 3,000 dead ones littering space[8] and the build up of these useless items orbiting our atmosphere has the potential in future to cause issues in visibility and current potential to cause safety risks to our currently functioning equipment (in 2021 a five-millimetre hole was discovered in a robotic arm of the International Space Station that was thought to have been caused by something no larger than a fleck of paint travelling through space ten times faster than the speed of a bullet[9]). The environmental impact could be even further reduced to almost non-existence if the energy for the spin of the tether was collected sustainably such as through solar panels.

Another large factor in our models is the financial benefit. The SpinLaunch orbital catapult is estimated to cost up to $500,000 USD per 200kg, not including the cost of the payload. Our models provide a financially beneficial route with the only cost being the value of the payload (so up to $500,000 USD cheaper). This benefit allows payloads to be transported from earth to the orbit much more often as there is no cost for rocket fuel or engine.

In model 2, we proposed a semi-circle shape for the projectile to follow during flight. The semi-circle is a rough estimate for the trajectory path of the projectile so it provides a large margin for error. The maximum mass is likely to be less than what we calculated (525kg) due to the high probability of the path distance being longer than our estimate.

We have used many values from the SpinLaunch trials in which we found from sources (quoted above in footnotes). However, using these values meant we were basing our calculations off of SpinLaunches' data and most importantly their conditions. We are assuming that our mass is fired into the orbit in the same conditions and with the same amount of air resistance etc.

APPENDIX: REVIEW OF CURRENT TECHNOLOGY

Spin Launch is a new spaceflight technology development company working towards mass accelerating technology to transport payloads into space. They have an aim of reducing expenses

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[6] https://techcrunch.com/2022/04/06/spinlaunch-scores-nasa-test-mission-to-demonstrate-its-unique-launch-method/
[7] https://www.youtube.com/watch?v=a1zp4OHJjrw&ab_channel=DrBenMiles [8] https://www.sciencelearn.org.nz/resources/272-launching-satellites
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and produce cheaper and more frequent launches into space but will only ever be used to transport payloads and never to transport astronauts. Spin Launch steps away from traditional largely fuel-powered rockets to an almost fully electric powered system. They decided to approach their technology by accelerating a projectile to be launched into orbit using a huge centrifuge that is placed on the ground. The centrifuge works by using a rotating arm in a large vacuum chamber (10^{-2} Torr) that is powered by electric power, spinning faster and faster until the projectile it's holding is finally released out of an exit tube. In some ways a simple idea (essentially a giant sling). However, test launches starting late 2021 showed that they could at least fire a payload at over 1,609.34 km/h to around 30,000 feet and recover it with the A-33[6]. The A-33 accelerator has a diameter of 110ft (33m) and is 150ft (45m) high and is a third of the size of the orbital that has a diameter of 150ft (45m) and a height less than that of the suborbital as it is placed on the ground at a launch angle of 35º. The orbital is a design that is due to be put into commercial use in 2025 after Spin Launch signed a contract with NASA in April 2022[1]. The projectile itself will be slung and released into the air through the exit of the orbital once the rotating arm has reached a speed of 8,000km/h (2222.22m/s) and to ensure that the rotating arm is not damaged once the mass of the projectile is released, a counter weight on the other side of the arm is also released at the exact same time. Once released, it continues to travel upwards towards the edge of the earth's atmosphere. However, under the influence of gravity, the projectile will experience deceleration. Spin Launch has worked out that to travel the final distance into the lowest earth's orbit, a two stage chemical rocket is released from the shell of the projectile and uses the advantage of the thinner atmosphere and shorter distance to propel the payload into the final distance of the journey into space while using one minute of fuel carried on board.

Two of the main challenges that Dr Ben Miles[7] touched on in his Youtube video reviewing the Spin Launch orbital were reliable release (reliable launch trajectory) and extreme heating. He stated that in order for a reliable and safe launch of the projectile from the orbital will need to be within 1º of the chosen launch angle to avoid wobbling of the projectile after the launch and to make sure that none of the orbital is damaged due to a miscalculation. This is very important as there is only ⅓ of a millisecond available for it to be released as the exit compartment is only open for that long to avoid compromising the vacuum inside. Dr Ben Miles also said that extreme heating in the launch was clearly taken into account by Spin Launch as they operate their mass accelerator in a vacuum firstly as it is known that less air means there is less air resistance to bring the projectile up to speed for release and less heat build up will occur in the system of both the arm and the payload within the projectile. However, achieving this vacuum can also take some days to achieve as it would need to reduce the pressure to a very low amount but it will still allow for more projectiles to be launched into space compared to traditional rockets.

[4] https://www.youtube.com/watch?v=VbrZ3GoobFk&ab_channel=ScientiaPlus [5] https://aerospace.csis.org/aerospace101/earth-orbit-101/
[6] https://techcrunch.com/2022/04/06/spinlaunch-scores-nasa-test-mission-to-demonstrate-its-unique-launch-method/
[7] https://www.youtube.com/watch?v=a1zp4OHJjrw&ab_channel=DrBenMiles [8] https://www.sciencelearn.org.nz/resources/272-launching-satellites
[9[https://www.actionnews5.com/2021/10/08/breakdown-what-is-space-junk-why-is-it-problem/ [10]
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Today, Spin Launch has achieved their wish to be the cheapest available cost per kg per launch at US$2000 per kg compared to other competing rockets launching into space of Falcon 9 produced by SpaceX at US$6000 per kg and Virgin Orbit at US$27000 per kg.

[4] https://www.youtube.com/watch?v=VbrZ3GoobFk&ab_channel=ScientiaPlus [5] https://aerospace.csis.org/aerospace101/earth-orbit-101/
[6] https://techcrunch.com/2022/04/06/spinlaunch-scores-nasa-test-mission-to-demonstrate-its-unique-launch-method/
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