

Review Article

A Low-Cost Launch Assistance System for Orbital Launch Vehicles

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The author reviews the state of art of nonrocket launch assistance systems (LASs) for spaceflight focusing on air launch options. The author proposes an alternative technologically feasible LAS based on a combination of approaches: air launch, high-altitude balloon, and tethered LAS. Proposed LAS can be implemented with the existing off-the-shelf hardware delivering 7 kg to low-earth orbit for the 5200 USD per kg. Proposed design can deliver larger reduction in price and larger orbital payloads with the future advances in the aerostats, ropes, electrical motors, and terrestrial power networks.

1. Introduction

Spaceflight is the mature engineering discipline—54 years old as of 2012. But seemingly paradoxically, it still relies solely on the hardware and methodology developed in the very beginning of the spaceflight era. Modernly, still heavily-used Soyuz launch vehicle systems (LVSs) are the evolutionary improvement of the R-7 rocket which launched the very first Sputnik satellite. Although many advanced rocket concepts were proposed and even implemented (most notably the Space Shuttle), these designs did not stand the test of the time. The comprehensive review on the current state of art in field of rocket propulsion can be found in [1]. Nonrocket-based spaceflight was also heavily researched, but the research did not result in practical systems other than the Pegasus LVS which is scheduled for retirement. The main reason why nonrocket spaceflight schemes were not widely implemented yet is their failure to compete with the purely rocket spaceflight schemes in the field of the orbital delivery of the high-value payloads like communication satellites or interplanetary probes. But baseline rocket cost denies many less valuable yet desirable payload classes like orbital power or industrial plants or machinery for extraterrestrial resources utilization. To ultimately enable these payload classes, an interim prototype of the nonrocket launch assistance system (LAS) should be developed to launch experimental payloads. Therefore, an economically viable system-level design of the LAS delivered in this paper may be key

point to the progress in the orbital delivery systems for these additional payload classes.

2. Overview of Previously Proposed LAS

A lot of proposals have been made to implement nonrocket LAS and are listed in Table 1.

The Rumanian Space Agency/ARCASPACE [2] has proposed to launch a moon probe from a high-altitude balloon. If the rocket start altitude of 20 km can be reached, a very light-weight, cheap launch vehicle may be possible. However, at the 20 km altitude, each ton of the rocket needs at least 200,000 m³ for the volume of the solar-heated Montgolfier balloon as proposed by ARCASPACE. So the design of an ultrahigh-altitude ARCASPACE balloon is expensive and technically challenging task. Furthermore, such a huge balloon is expendable, and the long ascent time requires usage of storable propellants in the rocket. Also, ARCASPACE balloons can be launched only in sunny weather, implying delay costs. Finally, their position during the launch is uncertain, complicating the safety area.

The electromagnetic launchers (railguns) for accelerating a small payload from LEO were also proposed [3] in the wake of the SDI program. But the railgun is an intrinsically very high-power device (30–1000 TW in proposed configurations). Such power levels impose weight penalties for the structural and energy storage materials, as well as the distribution and dissipation elements, making orbital

TABLE 1: Previously proposed launch assistance systems.

Method	References
High-altitude free-floating Montgolfier balloon	[2]
Orbital electromagnetic catapult	[3]
Laser ablation drive	[4–6]
Space elevator	[7, 8]
LEO rotovator	[9–11, 13]
Spiral sling (slingatron)	[14–18]
Interplanetary rotating tethers	[19–29]
Rotating, tension supported ring	[30]
Electromagnetic tether for raising orbit	[31–33]
Space fountain	[34]
Ground-based linear accelerator (gun, catapult)	[36–39]
Subsonic launcher aircraft	[40, 94]
Precooled air ramjet launcher aircraft	[42, 43]
Supersonic launcher aircraft in general	[41, 44]

railguns uneconomic. Railgun devices in [3] are capable of launching 0.3 kg payloads with speeds 4–10 km/s (realistic with existing technology), but the launcher itself is likely to weigh more than 300 tons (because at least 200 tons are needed for capacitors alone), with a 5,000-ton weight being a more likely estimate.

An initial proposal for a rocket engine based on the heating of propellant by remote laser was made in [4]. But given the low continuous power of available lasers (below 1 MW level) and bad transmission efficiency, such propulsion method requires many improvements in laser technology beyond the current level. In [5] the power requirement for beamed-energy propulsion from Earth to orbit is estimated to be 0.1–1 GW of continuous beam power per ton of the vehicle mass, which is 3–4 orders of magnitude higher than current state-of-art laser transmitters. As a consequence, the best altitude reached by a beamed-energy aircraft in 2001 was only 71 m [6]. Space elevator system is perceived a viable solution [7] but it is far from being possible with the current material technology [8].

Rotating tether systems [9, 10] can be useful for the reduction of the delta-v from earth's surface to orbit. But the required spaceship guidance accuracy to enable rendezvous with the rotating tether tip is higher than the task guiding an antisatellite missile and cannot be performed reliably with current guidance technology. Normal rocket LVSSs are not agile enough for the last-second speed vector adjustments. In [11] a more robust rendezvous method using a motorized grapple was proposed. It has the advantage that a high-agility engine system is placed on the tether grapple; thus extensive redesign of the rocket LVS propulsion system is not necessary. But for a practical rendezvous time window of 10 seconds with a realistic 25 km long, 1.6 km/s tip speed tether, a rendezvous motor must provide a delta-v of at least 500 m/s for compensating the lateral mismatches. The grapple also must include a 50 kW power motor per 1 kg of grapple weight to wind/unwind the tether to compensate radial mismatches. This power ratio is 2 orders of magnitude above

what is achievable with the best industrial-grade electric motors [12]. Using a chemical-fuel powered turbine for the winding/unwinding may solve the weight issue, but in this case some reaction mass must be spent for radial grapple adjustments as well. Because the power requirements for rendezvous scale as reverse square of tether length, making a realistic motorized-grapple tether rendezvous system with 10 seconds rendezvous window thus requires tethers at least 100 km long. A possible solution for the tether tip rendezvous problem was proposed in [13]. The additional actuator mass necessary to reduce the acceleration of tether tip during the rendezvous places additional strain on tether, causing reduction in either captured payload mass or tether tip speed.

In [14–17] the spiral sling was proposed. That structure does not address the problem of the multigigawatt electrical power required to drive the sling carrying a projectile heavy enough to fly out of the Earth's atmosphere. The smallest slingatron LASs comprise a 2700-ton track 90 km long moving at 139 m/s [18]. Such system is heavier, faster, larger, and more power hungry and has order-of-magnitude higher acceleration than the largest bullet trains ever built.

Kevlar tethers were proposed in [19] as the effective means of orbit change. The figure of merit (1) of the tether used for this purpose was derived:

$$\nu_{\text{tip}} = \sqrt{2 \cdot \delta \cdot \frac{E}{\rho}}, \quad (1)$$

where ν_{tip} is the maximal speed of the unloaded, untapered tether tip fixed on one end, δ is the elongation to break the tether, E is the Young modulus of the tether material, and ρ is the density of the tether. Although [19] overstates the maximal tether tip speed (1) by a factor of 10, their theoretical analysis is valid and was used to select a proper tether (rope) material. Reference [20] proposed a sensible construction to safely couple a motor with a small-diameter tether. That belt transmission-based design does subject the tether to a well-controlled and self-limiting stress, a valuable property for a system with a small safety factor. In [21] rotating tethers were proposed for Earth-Moon transportation. Spectre 2000 (a brand of UHMWPE) was proposed for tether fabrication. The required high speed of the tether tip (1.6 km/s) on lunar orbit makes the tether system 28 times heavier than payload; therefore at least 100 reuses of the tether are necessary to payoff tether deployment. Better tether materials may reduce the capital costs of the systems depicted in [21]. Tethers could also be used for swinging about asteroids [22] without spending propellant. Reference [23] also proposes to use Spectra 2000 tethers for orbital transfer (without engineering analysis). The usage of the tether to capture a payload in planetary orbit while the mothership of the payload performs a flyby maneuver was proposed in [24–26]. To be competitive with state-of-art chemical propulsion, the speed change of the payload is limited to 0.3 km/s. Tethers were also proposed to transport cargo between Mars and Earth [27], but the low strength of existing materials made the tethers too heavy to compete with rocket propulsion. In [28] guidance to the tether rendezvous was discussed. The conclusion was the statement

of absence of the means to prolong the rendezvous interval long enough to enable capture of payload on rotating tether tip. The usage of tethers to provide an abort option for Mars travel was proposed in [29]. With typical delta-v below 1 km/s, a practical tether can be developed. However given the mass constraints of Mars travel, the implementation of the abort capability is unlikely.

A variation of the tether concept, a rotating rim on LEO, was proposed in [30] as LAS implementation. This design allows for easier attachment of spacecrafts, because a continuous attachment line requires less delta-v and acceleration to compensate for guidance errors compared to grapple. Design in [30] demands a material with v_{tip} being $\sqrt{2\pi}$ times more than that of a conventional rotovator.

In [31] methods to raise a satellite into orbit using an electromagnetic tether were proposed. But to reach orbit, the apogee of the tether-bearing spacecraft must be above geostationary orbit, and possible acceleration is small. Reference [32] also has proposed a method to extract energy from space plasma using an electromagnetic tether. But this method works only in zones near Lagrange points. Reference [33] also proposes using rotating tethers coupled to the Earth's magnetosphere to change the spacecraft's orbit. Rotating the tether increases tether rigidity, making orbital control more simple compared to a hanging or librating tether.

In [34] a reasonable downscaling method of a space fountain is proposed. But even a small-scale (2.5 km/s, 1-pipe space fountain) system has an upkeep power of 16 GW (2/3 of the electricity produced by Japan), a 56-ton weight suspended in atmosphere (likely more if control and safety devices added), a stored kinetic energy 120 GJ (22 tons TNT equivalent), and a 150 km long building footprint. LAS in [34] features 190 km long pipe span under tension that may be difficult to build using existing materials. Furthermore, the 1.5 billion USD miniature space fountain building budget in [34] is including only materials costs. Upkeep power generators alone (the cheapest option-gas turbine) [35] are expected to cost 6.4 billion USD to build.

Potential economic advantages of ground-based catapults are listed in [36], but a 4 GW average power system with the 100 GJ local energy storage proposed does require a specialized power station. In [37], the vacuum launch tube for small sounding rockets was proposed. Although the design allows for a 10–20% increase of the sounding rocket altitude, the 23.5-meter-long semi-rigid launch tube makes the design uneconomical. Slightly oversizing a 2-meter-long rocket with much smaller fabrication and handling difficulty allows it to reach the same maximal altitude. In [38] a pneumatic sled was proposed as LAS for the orbital vehicle. That LAS is analogous to existing steam catapult used aboard of the US supercarriers. These catapults are known to have an issue with the high cost of maintenance, which is the primary reason for their applications being restricted to launching military airplanes.

Another proposed method of launch assistance is shooting the launch vehicle with high-caliber, high-explosive, ultravelocity shells at machine-gun speeds [39]. Launch vehicle must survive $\sim 10,000$ such impacts, each delivering 10–100 times more kinetic energy compared to the largest

modern gun projectiles at ~ 10 collisions/s. Reference [40] proposes a solution for an air launch system based on exotic propellant chemistry. Reference [41] finds that the delta-v advantage of launching from 30 km altitude is 700 m/s and optimal angle between launch angle and horizontal is close to 30%, while vertical launch from 30 km altitude gives 500 m/s delta-v reduction to reach the LEO.

Among the huge body of the literature discussing air-breathing engines for LVS, the author exhibits one solution—a precooled engine, to illustrate the technological challenges of the solution. In [42], the design of the air heat exchanger for an air-breathing vehicle similar to Skylon was elaborated. But the designs proposed have flow-to-weight ratio below 0.03 s^{-1} for 5.5 Mach speed, so the maximal thrust to weight of the heat exchanger is less than 10 for an exhaust speed of 3 km/s. In [43], a heat exchanger for the air precooler was designed using stainless steel tubes with 2 mm outer diameter and 0.1 mm wall thickness. These pipes will break in the 5.5-Mach airflow if made more than 12 cm long. Furthermore, [43] assumes very light, advanced air-breathing engines. If a thrust to weight similar to the Pratt & Whitney J58 engine can be achieved (which was designed for similar airspeed, but without precooler), the total engine's mass will be the 45% of the vehicle's 12 ton dry mass. With the payload mass fraction of 1.25% of the dry mass, the design still requires many advances in material technology before implementation.

In general, hypersonic launcher aircraft (LAS) plus LVS is more expensive [44] compared to purely rocket LVS, and the reasons for it being too expensive are elaborated in the next chapter.

3. The Critic of the Air Launch Concept

Among nonrocket LASs the high-altitude launch using carrier aircraft should be discussed in more detail, because Pegasus high-altitude launch with carrier aircraft was only LAS method implemented historically, and problems with Pegasus resulting in its planned retirement in favor of the land-based Taurus and Taurus XL rockets will shed the light on the peculiarities of the air-breathing LAS. To understand the motives beyond the Pegasus planned retirement let us first list advantages of the air launch.

References [40, 41, 45] estimate the delta-v saving due to using air launch to be 750 m/s to 1000 m/s for the subsonic carrier aircraft. This delta-v reduction translates to 28% rocket weight reduction for solid-fuel rocket or 19% rocket weight reduction for the LH₂/LOX rocket according to rocket equation [46] have also reported 25% rocket dry weight reduction with the subsonic launcher aircraft carrying LOX/LH₂ rocket. Air launch with carrier aircraft also has significant penalties listed below.

- (1) Design compromises of the air-launched rocket, requirement for storable propellant, carrier aircraft crew safety [47], additional structural weight due to additional load direction of horizontally carried rocket [48], result in rocket weight reduction of only 15% out of maximal 28%.

- (2) The second is effect of the capital and maintenance costs of aircraft, especially effect of engine power of carrier aircraft on flyaway cost. Reference [49] predicts whether higher-speed carrier aircrafts will be increasingly uneconomical as LAS. For example, Concorde [50] is predicted to have running costs 43% of equivalent expendable solid-rocket booster, and higher speed aircrafts (including all tentative scramjet designs) will be even less economical. Breakeven point with the solid rocket boosters is around Mach 3 for the current technology level. The authors of [44] have also concluded why hypersonic launcher aircraft cannot be economical despite significant delta-v savings for the carried rocket.
- (3) The total cost of the orbital launch is dominated not by the flyaway cost. Instead R&D amortization, certification, range safety, payload integration, and profit margin comprise up to 81% [51] of the launch costs. These costs reduce with the increasing launch rate and independent of launch technology.

To summarize, a classical air launch system fails to reduce the cost of LVS more than 3% because air launch technology is subject to the same technological and procedural limitations as purely rocket LVS. This is not surprising given that space launch technology has grown mostly using an aircraft manufacture and service infrastructure.

4. The Required Properties of the LAS

Summarizing the data in chapters II-III, a list of the desired traits of the economical nonrocket LAS can be made.

- (i) The power to operate must be deliverable by the modern power network on demand ($P < 10 \text{ MW}$).
- (ii) The mass of the airborne part of the LAS should be kept to minimum.
- (iii) Local energy storage should be minimized (to avoid hazards of uncontrolled energy release).
- (iv) Acceleration by LAS must be in same direction as by rocket engine (LVS must have only 1 structurally strong axis).
- (v) Propulsive force by LAS must not exceed the force by equivalent rocket booster.
- (vi) LAS-related hardware on board of LVS must be light.
- (vii) No pilot aboard of airborne part of LAS is allowed.
- (viii) LAS must deliver LVS to separation point promptly to use cryogenic fuels in the LVS.
- (ix) Reusability of all components of LAS at least few times.
- (x) Small launch turnaround time (no more than 1 day) to facilitate high launch rate.
- (xi) Low payload mass to facilitate high launch rate.
- (xii) Weather independence.
- (xiii) Launch point and launch vector stability.

- (xiv) No high-acceleration rendezvous until much better guidance systems will be developed.

None of the proposals in sections II-III satisfy all criteria for the economical LAS. Therefore, an original proposal loosely based on the combination of the features of [2, 20, 30] is described in chapter V. To summarize the most important principles, LAS must operate rapidly, at low power and low weight, meaning most likely low payload mass, and therefore a large starting altitude for the rocket to keep the air resistance loss reasonable same as what was aimed by the Orbital Sciences Corporation in their Pegasus project. No revolutionary breakthroughs are expected for rocket LVS itself. For example, [52] was written 20 years ago, and all perspective technologies listed within are still under development (except for the Li-Al alloys usage). To summarize, SSTO, ultralight rockets engines, air-breathing or rocket flyback boosters were not developed. The lack of rapid progress in the field was illustrated by the cancellation of the project RASCAL [53] aiming to reach the same goals using the purely rocket LVS. Therefore, the nonrocket LAS may be the only short-term path to the more economical, albeit small-scale, orbital delivery.

5. Proposed LAS Concept

Author's proposal calls for the high-altitude balloons cluster used as anchors for the cable traction system. The design parameters of the LAS/LVS are provided in Table 2. Tethered balloon is much easier to reuse compared to the floating balloon in [2]. Reuse of balloons is obligatory because these comprise the heaviest and most expensive component of the LAS. Also, the positioning of the tethered balloon can be precise to the fraction of meter [54]. Tethers (cables) connected to the high-altitude balloons can be used to accelerate an LVS if needed or simply to deliver launch vehicle to launch altitude before cryogenic propellants will boil off. Advantage of the tethered balloon over carrier aircraft system is the extreme simplicity of the flown hardware and advantageous initial speed vector for light payloads (vertical or nearly vertical).

To make the system a statically stable with only tensile-loaded (and therefore lightest) spans, at least 3 balloons and 3 tethers (traction cables) arranged in axis-symmetric pattern are necessary. Balloons should be connected by clustering cable (2 on Figure 1) to set a stable small spacing between them. Static and dynamic load due the LVS being launched and tropospheric wind load acting on launch vehicle, cables, and balloons was calculated. Because the operational altitude of proposed balloon system is well above the top margin of the jet streams (at approximately 20 mBar pressure while jet stream subsides above 90 mBar level) [55], the jet stream winds affect only balloons during LAS deployment (there caution is necessary) and rocket LVS during launch. Because cables cross-section in jet stream zone and rocket LVS cross-section is small compared to the balloons, the jet stream load is insignificant to the LAS subsystem, although LVS still must withstand larger wind shears. The estimated 60 m/s jet stream lateral force on LVS is 400H, higher than the

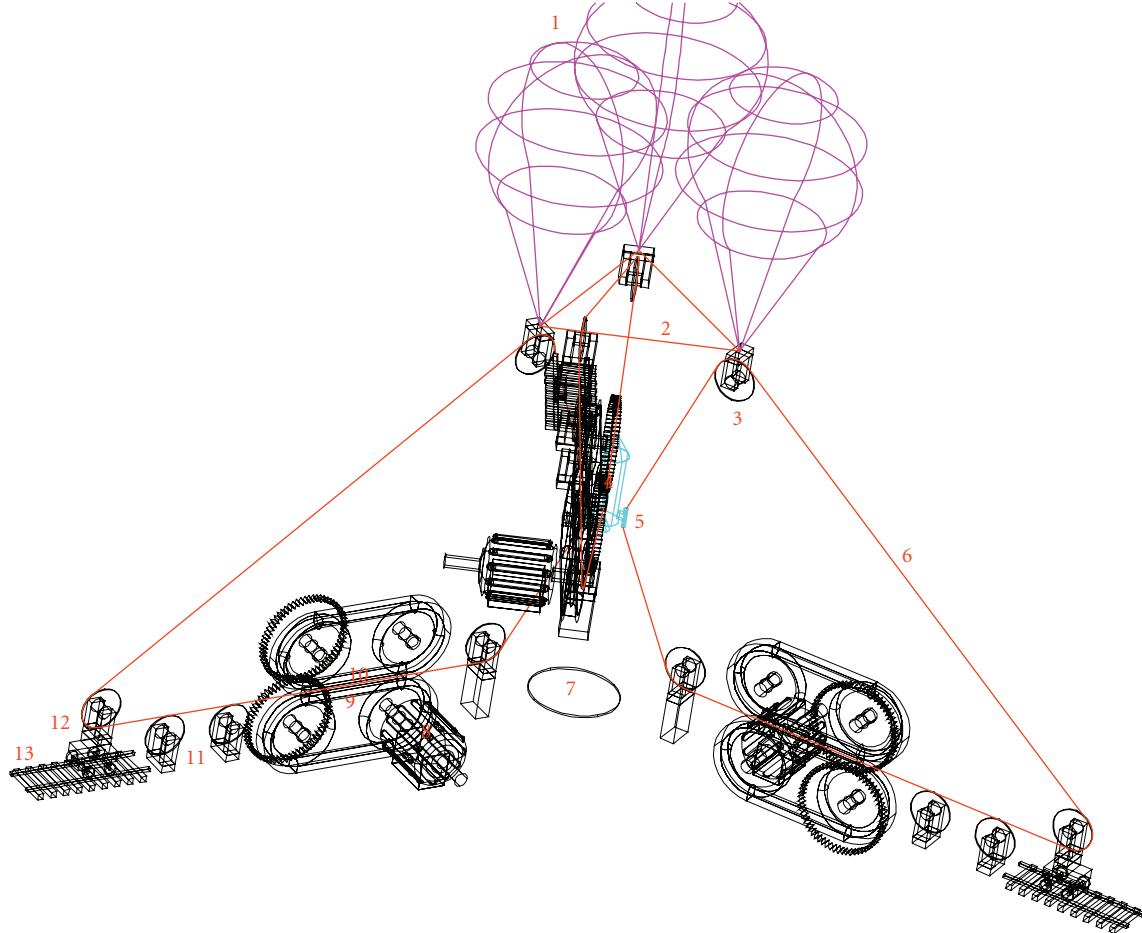


FIGURE 1: 3D model of the LAS (proportions distorted for clarity) (1): balloons, (2): clustering cable, (3): top block, (4): rocket LVS, (5): rocket attachment points to traction cables, (6): traction cables, (7): launch pad, (8): electric motors, (9): lower coupling belt, (10): upper coupling belt, (11): antisagging towers, (12): tension adjustment block, (13): rails for tension adjustment block.

rated ground-level wind load. But anyway the LAS/LVS design is not intended to withstand the jet stream loading because majority of the Earth surface including the most advantageous equatorial belt is not affected by the strong jet streams. The structural strength margin of 1.5 was selected for the entire LAS design to ensure survival of block bearings for at least 10000 loading cycles [56]. Angle between traction cables (5–3–12 on Figure 1) should be nonzero to effectively resist wind load on the balloons and ensure the repeatable launch vector. The larger the angle between the LVS rope (5–3 on Figure 1) and return rope (3–12 on Figure 1), the better rigidity of LAS can be achieved, but the return rope weight is also increased. Horizontal tether segment (12–7 on Figure 1) length was selected to be 7% of the balloons altitude, but depending on the land lot availability up to 30% may be advisable. The overview of the LAS/LVS parameters and the components breakdown of the LAS are provided in Tables 2 and 3, respectively.

Overall, proposed LAS/LVS has weight and performance similar to the oldest Japanese launch vehicle Lambda-4S (9.4-ton wet weight and 26 kg to LEO, resp.). But similarity ends here, because heaviest and most expensive components in

the proposed system can be made reusable, as illustrated in Table 4.

The data in Tables 2–4 was generated using Microsoft Excel calculation sheets. Input data to the calculation sheets was derived from numerous datasheets (especially for on-board battery and power distribution subsystems), mass estimating relations [57], and from the output of the Scilab script used to simulate the ascent of the rocket to the LEO. The Scilab script was calibrated by simulating ascent of Proton-M, Delta 7920, Pegasus XL, H-IIA LVS. The calculation sheets and Scilab script are available on request.

In the current work it is not proposed to reuse the rocket LVS, because the potential advantages will not be decisive. References [58, 59] argue that reusable rocket LVS may be advisable only if launch demand is much increased compared to current level, which is unlikely according to [60]. The many capital costs of the LAS are order-of-magnitude approximations, but accuracy of these approximations does not matter as long as the ground part of the LAS can be reused 10000 times or more. Although such heavy reuse is not uncommon for the ground-based traction cable systems, the limiting factor is the demand

TABLE 2: Parameters of the proposed LAS.

Parameter	Value
Launched LVS weight	340 kg
Payload to LEO	7 kg
LAS engines output power	13.1 MW
Balloons total volume	0.5 mln · m ³
Acceleration during launch assistance	5.7 m/c ²
Acceleration duration	161 sec
Separation airspeed	0.45 km/s
Separation altitude	36.1 km
Flown structure weight (with ballast and launch vehicle)	8.6 tons
Flown structure structural factor (loaded by ballast and launch vehicle)	1.5*
Design maximal wind speed in lower troposphere	18 m/s

* 10% margin for the ropes strength degradation included.

TABLE 3: Mass budget of the proposed LAS.

Component	Mass, kg	Fraction, %
LVS rocket mass	270	3.7
LVS aeroshell	30	0.4
LVS-LAS attach points	40	0.5
Traction cables	1551	21.3
Clustering cable	49	0.7
Top blocks	91	1.2
Joints of traction cable	670	9.2
Balloons, uninflated	4566	62.6
Balloons avionics block	25	0.3
Total	7292	100.0
Balloons lift at 39.6 km	8649	118.6
Ballast of balloons	1357	18.6

for the orbital launch. If 10000 launches of 7 kg payloads (70 tons total) within 30 years interval may be required for any realistic mission scenario, then the proposed LAS can be made cheap compared to the rocket LVS it propels. Also problem may be with the finding of the miniature high-performance rocket engine. For the proposed rocket an Ottobrunn 300 N LH₂/LOX thruster with the specific impulse 430 s and maximal thrust 500 N was selected for the preliminary simulation of the LVS. LH₂/LOX is the best fuel for mass-produced LVS, if all considerations are taken into account [61]. It is not obvious whether the better engines will be developed; reference [62] has described the regress in the field of the liquid-fuel rocket engines design. Main problems described were failure to use the results from academic community in the engineering companies, failure of engineering companies to share or inherit design information, and many incompatible or proprietary software tools used for the rocket engines design. Small divisible payloads may be economically attractive [63], if associated penalties [64] are minimized (see Table 5).

TABLE 4: Life-cycle budget of the proposed LAS/LVS system.

Component	Price, k\$	Fraction, %
#LVS rockets	26.6	72.8
LVS aeroshell + attach points, 5 reuses	1.3	3.6
Traction cable, 100 reuses	3.4	9.3
*Balloons, 200 reuses (160 k\$/balloon [95])	0.8	2.2
Traction motors cost, 10000 reuses (10 hp/\$) [12]	0.17	4.3
Coupling cost, 10000 reuses	0.08	
Variable frequency drivers, 10000 reuses	0.08	
Line protection equipment, 10000 reuses	0.02	
10 km high-power transmission line, 10000 reuses	0.6	
Antisagging masts, 10000 reuses	0.4	
Blocks cost, 1000 reuses	0.1	
3 km light railway for tension adjustment, 10000 reuses	0.1	
Technician salary, 2 men for 30 years (10000 launches)	3	8.2
Total cost per launch	36.5	100
Cost per kg of payload to LEO, k\$/kg	5.2	—

* Require NASA superpressure high-endurance balloons or equivalent [96, 97].

#No. calculated using NASA cost model from [98] with 85% learning curve.

TABLE 5: Sources of the spending for the orbital assembly of the vehicles.

N	Factor
1	Fuel efficiency of the interorbital transport
2	Maximal launch rate capability of earth-to-orbit transport
3	Assembly reliability
4	Mass and utilization of the orbital support equipment

Although factor 2 may be not of the concern for the proposed LAS/LVS, factor 1 may be critical. The state of art of electric propulsion as in 1998 has lacked hall thrusters and ion thrusters with mass below 10 kg threshold [65], although no obvious physical limit exists for miniaturization. Reference [66] suggests whether the lack of small engines may be due to insufficient R&D. In [67] the historical overview of the orbital launches statistics was provided, and no apparent upward trend was found; therefore the only way to reach an economic, high launch rate is the reduction of the unit payload mass. In [68] a trend was mentioned to use smaller, cheaper spacecrafts for the planetary exploration. Therefore, very small rocket LVS may be useful to increase the launch rate if divisible payloads will become common. Miniature LH₂/LOX engine is the key for minimizing the liftoff weight and associated infrastructure, security and fly-away costs. To use the miniature LH₂/LOX engine with the small fuel tanks, the interval between the leaving fuel topping facility and engine ignition (cable ride time) must be short. For proposed

TABLE 6: NASA standard balloon sizes.

Volume, m ³	Balloon weight, kg	Suspended weight, kg	Equipment weight, kg	Ballast weight for 12 h flight, kg	Ballast weight, kg for 36 h flight, kg	Nominal altitude, km	Sensitivity, m/kg
328475	776	953	184	100	315	36.6	4.5
328475	1461	2495	295	238	714	30.5	2.2
659783	1701	1950	272	215	658	36.6	1.7
*804198	1522	1361	227	170	522	39.6	2.2
804198	2066	2495	295	272	828	36.6	1.8

*Model selected for mass budget calculations.

LAS, maximal cable ride time may be derived from the self-pressurization equation for the LH₂ tanks; these are most difficult to keep cool. For the most miniature 0.2 m diameter LH₂ tanks with mediocre insulation (100 W/m²), pressure rise 1 MPa and 1-g conditions [69] give self-pressurization time of 7 minutes. LAS cable ride time below this limit is achievable with the 5.0 MW minimal powers of traction motors combined in the proposed LAS configuration.

6. Off-the-Shelf LAS Hardware

The balloons suitable for use in the LAS prototypes are the NASA standard zero-pressure balloons. Balloons performance extracted from [70] is summarized in Table 6.

From Table 6 it is seen that even smallest NASA balloons can perform the desired LAS task, although at reduced altitude 30–33 km. Medium-size and large balloons can easily boost the proposed LVS up to 36–39 km altitude.

For the tethers, only commercially available ropes (not single fibers) were evaluated. Carbon fibers can offer best performance in fibers, but in ropes its low notch resistance results in absence of long ropes. Carbon fibers also have an elevated electric conductivity. Electrically conductive fibers for the high-altitude ropes should be avoided because of the possibility to trigger a lightning propagating along the rope. Exhaust plume of rocket vehicle starting its engines near the top of the ropes may provide a conductive connection between the rope itself and surrounding air. Lightning triggered by launch vehicle exhaust plume is known phenomenon [71, 72] and was detected first during the launch of the Apollo-12. Another promising ropes material is the polyamide (Kevlar). In [73] the Kevlar cable was proposed to suspend geostationary satellite at half the geostationary altitude. Search for the commercially available Kevlar (or related poly-aramid ropes) did result in the ropes with maximal tip speed 1.7 km/s. But best tip speed can be achieved with the UHMWPE fibers. The material selected for the tethers was the SK-90 Dyneema rope with 3 mm diameter and with the UV-absorbing and antiabrasion coating [74]. The selected rope model has a maximal tip speed 2.07 km/s, including 10% strength margin to minimal breaking force. This is not the first proposal to use this material in tethers; authors of [11] have favored the selection of the UHMWPE fibers for the rotating space tethers and provided the 1.75–3.0 range of the engineering safety factor

to implement a practical design. But authors in [11] have used mechanical data for the individual fibers, not the ropes. Selected structural factor of 1.5 for ropes corresponds to safety factor of 2.3 of individual SK-90 Dyneema fibers. But Dyneema drawback for the aerospace applications may be material (UHMWPE) susceptibility to the UV damage. Dyneema manufacturer never gave out the actual resistance of the Dyneema to the ultraviolet radiation. Empirical study [75] claims 3-year service life for 30% tensile strength decrease of the Dyneema SK78 fiber on the sea level, which translates to 2000 hours of the solar irradiation at 90 degrees elevation angle. Reference [76] uses controlled solar imitator and concludes whether 200 hours of peak sea-level solar radiation are enough to cause 30% tensile strength degradation. Also, [76] points out the oxidation as the main pathway of the UV-related Dyneema degradation. Therefore, Dyneema photodegradation may be accelerated in the presence of ozone. The actual level of the ultraviolet radiation at 30–35 km altitude is also very variable and model dependent. Reference [77] mentions 50% UV penetration for the wavelength range 205–300 nm at altitude 30–40 km with 30 km minimum at 205 nm wavelength, while light with wavelengths shorter than 200 nm (UV-C) is penetrating only to 40–60 km altitude, making protection from it largely irrelevant for the proposed design. The authors in [78] have observed synergy between UV-C radiation level and atomic oxygen erosion of polyethylene (and thus Spectra and Dyneema filaments). The polyethylene-derived products are degraded 10 times faster compared to polyimide (Kevlar), which have 22 mg/g baseline erosion rate divided by atomic oxygen flux. Therefore, long life of the Spectre or Dyneema ropes will be difficult to achieve in the LEO environment or high stratosphere. But both atomic oxygen and UV-C are absent below 40 km altitude, making protection from them not important for the balloons-anchored tethers. Reference [79] says the pure UHMWPE fibers are not absorbing any light with wavelengths above 190 nm, but commonly processed grades have impurities absorbing light up to 270–330 nm wavelength. Therefore, the conclusion can be done whether the Dyneema rope strength degradation in stratosphere will be caused mostly by the UV light with 200–300 nm wavelengths (UV-B). Simple model of the UV-B light level is the irradiation increase by 10–17% per each km of the altitude, given the 30% strength degradation time of Dyneema SK78 at 35 km as small as 0.8 hours. This estimate is only lower limit. Model uncertainty, geometric factor (low

incident angle on the near-vertical ropes at times of the maximal UV flux), and usage of UV absorption coatings (as planned) should improve the lifetime of the rope. Rotation of the tether through blocks to spread UV damage, and lowering balloons a few kilometers than not in use, will improve rope lifetime hundreds to thousands hours.

7. Conclusion

The system-level design of the nonrocket LAS and rocket LVS for the ultralight payloads was proposed. System can deliver 7 kg to LEO with launch rate 1 launch per day. Estimated single launch full cost is 36400 USD and flyaway cost is 26600 USD, making the proposed system one of the cheapest launch systems in both launch price and price per payload mass category. The previously proposed applications for the similar LAS/LVS may be orbital fuel depot resupply, space station resupply, or Earth sensing. Among these, most researched was the interorbital tugs design. Cryogenic orbital storage [80, 81], transfer [82], operation model [83–85], and interorbital tugs designs [86–88] were elaborated. But [89, 90] was skeptical on feasibility of interorbital tugs. Supplying the Space Station with consumables and fuel may be easier, but this business segment is already taken. Therefore, the Earth sensing application may be also feasible. Reference [91] proposes a subkilogram satellite constellations, and [92] proposes swarms of subgram mass satellites on LEO for Earth sensing, and these can be easily deployed and replenished by the proposed LAS/LVS. The DARPA has also a requirement for the fast-reaction suborbital delivery, and Andrews Space Company proposes an hypersonic aircraft-based Peregrine/Falcon system [93] to fill this role. The proposed LAS/LVS may be technically and economically fit also for DARPA fast-reaction suborbital delivery. But because the proposed LAS/LVS is most suitable for orbital delivery of CubeSat-class satellites, some national space agency may choose to build described LAS/LVS to provide advanced service to the technology demonstration (or other purpose) CubeSat satellites manufacturers and therefore to improve a technological prowess of the respective country. The proposed launch scheme allows much more design, orbit and schedule flexibility for the technology demonstrators, effectively outcompeting current practice of riding CubeSats as secondary payloads in large commercial LVSs. The number of CubeSats produced in world per year is still too small (18 is planned in 2012) to fully utilize the launch rate potential of the proposed LAS, but it may rise if convenient LAS/LVS will become available.

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