SMALLSAT LAUNCH OPTIONS: CHOICES AND CHALLENGES

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Abstract

Affordable, reliable, and responsive launch is critical to the survival and growth of small satellite systems. Unfortunately, no small launch vehicle now on the U.S. market offers a perfect solution: low cost, proven reliability, and the flexibility to meet all user requirements. There are several small launchers on the market, and choosing the best launcher for a given mission is a difficult challenge for the smallsat developer. Using the launch of three sample smallsats as a mission model, this paper surveys launch vehicle options currently available or in advanced development. Those launch vehicles capable of launching the mission model satellites into the desired orbits are then evaluated on cost, risk, availability, and payload environment. A combined ranking produced by a computer model indicates the optimal choice for each mission. This exercise demonstrates that selection of the best option does not always mean picking the obvious or best-known vehicle, and that small satellite developers would be wise to thoroughly survey all suitable launch vehicles.

Background

Few will dispute that the perfect solution for small satellite developers does not exist: perfect solutions rarely do. The future of the smallsat industry is intertwined with that of the small launch vehicle industry, but the interests of the two communities do not always coincide.

There are, however, some general rules for launch vehicle selection that can be worked out and applied to most payloads. Matching a three-satellite mission model against the specifications of current and projected launch vehicles yields a decision-making model that is not only useful for payload developers but gives some insight into the best policies to pursue to promote healthy smallsat and small launch vehicle industries.

Mission Model and Approach

A mission model of three small spacecraft was used to evaluate the launch vehicle selection process. Mission 1 employs the 64kg JAWSAT (Joint Air Force Academy-Weber State Satellite), as an example of a research spacecraft, with the actual planned orbital parameters (500km circular at 98.7 degrees inclination) being used. The second and third missions both use CTA's 136kg Gemstar UHF communications satellite. Mission 2 has the Department of Defense (DoD) using this comsat in an operational role to cover the Middle East (35 degree inclination) in a circular orbit 667km high. Mission 3 uses a Gemstar in a commercial role, also with a circular orbit 667km high, but at 88 degree inclination. This was the orbit planned for the first Gemstar spacecraft, lost in the failure of the first Lockheed Launch Vehicle.

Data for this study was obtained by contacting all launch vehicle service companies, along with the builders of the small satellites in the mission model. A computer model using Expert Choice software, which employs the Analytic Hierarchy Processing approach, was used to evaluate the alternatives. Each launch vehicle was ranked based on four mission-related criteria, allowing an evaluation of each possible payload/ launch vehicle combination and the selection of an optimal launcher for each mission.

Special Factors

When evaluating the payload capacity of the launch vehicles studied, exact figures for the specific parameters of each mission in the model were not always available. (For example, some companies provided their capacity for launches to 28.5 degree and 90 degree inclinations, not the 35, 88, and 98.7 being used.) Accordingly, some values were interpolated from the data provided. Payload environment data for the Start launch vehicle was not available and was estimated by the authors based on comparison with similar launch vehicles. Availability of the Start was likewise impossible to determine, so the Start was ranked at the bottom on this criterion.

Under current U.S. policy, operational DoD spacecraft cannot be launched on foreign launch vehicles, so the Start and Cosmos were ruled out for the DoD mission in the model. Also, according to the 1994 National Space Transportation Policy, the U.S. military may not release surplus missiles for use as commercial launch vehicles.[1]

The mission model dictates that all satellites used in this study must be the primary payloads. The model was designed this way in order to reduce the complexity of this paper and focus on the objective of comparing small launch vehicles. Launching secondary payloads along with the mission model spacecraft, while economically advantageous, is not considered in this study. Neither is boosting multiple small satellites on a larger booster, an option applicable when a constellation of smallsats is to be placed in one orbit.

All the U.S. launch vehicles have or plan to develop the capability to launch from sites on both coasts. Accordingly, all such vehicles were assumed to be capable of launching into all orbits in the mission model.

Alternatives not considered

Since the satellites used in this study were quite small, we evaluated only the smallest launch vehicle offered by each launch service provider. Orbital Science Corporation's Taurus was not examined, since the same company's less expensive Pegasus could launch the satellites under consideration.

An exception to this guideline was made in the case of the Air Force's surplus missile candidates, the Multi-Service Launch System (MSLS) model B and model D. We included both due to Air Force interest in a comparison of the two closely related launch vehicles.

The study excluded all vehicles whose capacity exceeds 1,500 kilograms to low Earth orbit. This ruled out the Delta, Rockot, Tsyklon (Cyclone) and Proton, along with current Chinese launchers and Japan's H-II. Arianespace also has no small launch vehicle currently on the market, and India is not actively marketing its ASLV internationally. No information could be found on the current status of proposals to market former Soviet sea-launched ballistic missiles.

Israel's Shavit was ruled out because of severe orbital constraints imposed by its launch site (it can launch only into a narrow range of retrograde orbits). It might become an option in the future if a proposed agreement to launch from Arianespace's South American facilities becomes a reality.[2]

Finally, any vehicle not expected to be operational by the end of 1998 was not used in the primary analysis. This ruled out the expendable launch vehicles planned by PacAstro and Microcosm, both of which are intended to offer significant cost savings around the year 2000. The partially reusable vehicle planned by Kistler Aerospace, also intended to sharply reduce costs, may fly around the same time. Further in the future are fully reusable launch vehicles like the Lockheed-Martin VentureStar. Kelly Space and Technology's Eclipse Astroliner will not be available by 1998, but the smaller Eclipse Express is intended to fly in 1998 and so was included in the model.[3] However, the Eclipse's payload limit (90kg to polar orbit) meant it was considered for the JAWSAT mission only.

Evaluation Criteria

Alternatives were evaluated on two sets of standards: thresholds and variables.

Thresholds

Thresholds were defined as critical requirements which must be met in order for a launch vehicle to be considered.

Two thresholds were set:

1. The launch vehicle had to be able to place the mission model spacecraft in their desired orbits.
2. The launch vehicle had to offer a payload environment which the spacecraft would be able to tolerate. NOTE: All the launch vehicles evaluated have payload compartments large enough to accommodate the mission model satellites.

Variables

Cost

Cost is the price quoted by the launch vehicle manufacturer or the best estimate obtained from open literature. Prices quoted for launch vehicles not yet built are increased by a conservative 10% for expendable launch vehicles and 20% for partially reusable vehicles. It is extremely rare for any launch vehicle to produce performance at the price originally estimated when the vehicle is designed (the STS and Pegasus are examples). To simplify the model, negotiating a volume discount for multiple missions is not considered.

Availability

The model is based on the assumption that all three spacecraft would be completed and ready for integration with a launch vehicle on January 1, 1997. We asked all launch vehicle manufacturers to estimate how long it would take after that date to book a flight as the primary payload.

Risk

The risk ranking for launch vehicles was a partially subjective evaluation which took into account real-world performance (for vehicles which have already flown), the technical risk involved with the design, the manufacturer's resources, expertise, and past performance, and the existence of confirmed reservations for future flights.

Payload Environment (PE)

The PE is a composite of four equally important criteria: maximum axial acceleration, maximum lateral acceleration, maximum vibration, and maximum acoustic level. As noted above, threshold requirements for these and other criteria were established by the spacecraft builder for each satellite. The PE ranking in this paper was used to give an advantage to those launch vehicles which offer the most comfortable PE, as this lessens the chance of spacecraft damage during flight.

In the model, the criteria were given the following relative weights:

Risk:	.35
Cost:	.30
Payload Environment:	.20
Availability:	.15

Launch Vehicles Considered

Vehicles Available Today

Pegasus XL

At this writing, this Orbital Sciences Corporation air-launched rocket is the only operational U.S. small launch vehicle which has placed payloads in orbit. The XL, successor to the basic Pegasus, failed its first two launches, then had two successes. Pegasus has a solid backlog of orders and a commanding position in the domestic market.
Launch Record: 4 attempts, 2 successes = 50%
Availability: Next opportunity would likely be in early 1998, with late 1997 a possibility.
Capacity to Mission 1 orbit (98.7 degrees at 500km): 270kg

Capacity to Mission 2 orbit (88 degrees at 667km): 235kg
Capacity to Mission 3 orbit (35 degrees at 667km): 315kg
Maximum axial acceleration: 13g for a JAWSAT-size payload, 10g for a Gemstar-size satellite.
Maximum lateral acceleration: 6g
Maximum vibration (power spectral density (PSD)): .07
Maximum sound pressure level (SPL): 133.5db
Cost: ~$11.5M for a DoD launch (the military pays range costs), $12.5M for a commercial flight, (includes range costs), and $7.7M for a nonprofit research craft using the NASA-OSC Ultralight Expendable Launch Vehicle Services contract.[4]

Lockheed-Martin Launch Vehicle

This vehicle was formerly named the Lockheed Launch Vehicle. The LMLV-1, the smallest of a planned family of vehicles, failed in its first launch attempt. A second will come in December 1996. The design has at least six firm orders and the financial and technical muscle of Lockheed-Martin behind it, so its future appears secure.
Launch record: 1 attempt, 0 successes
Availability: Next primary payload opportunity 1998.
Capacity to Mission 1 orbit: 380kg
Capacity to Mission 2 orbit: 380kg
Capacity to Mission 3 orbit: 590kg
Maximum axial acceleration: 8g
Maximum lateral acceleration: 2.5g
Maximum PSD: .014
Maximum SPL: 133.5db
Cost: ~$16M (plus range costs)[5]

Cosmos

The Cosmos, one of the workhorses of the Russian space program, is being marketed principally by Cosmos USA, a partnership which includes the U.S. company Assured Space Access. The Cosmos is launched from inland sites at Plesetsk and Kapustin Yar, which do not permit launching into orbits with an inclination below 50 degrees. Cosmos USA could develop a launch capability in other locations, but there are no current plans to do so.
Launch record: 730 launches, 711 successes = 97.4%
Availability: Within 6 months of request (June 1997).
Capacity to Mission 1 orbit: 890kg
Capacity to Mission 2 orbit: 900kg
Capacity to Mission 3 orbit: Not applicable.
Maximum axial acceleration: 6.5g
Maximum lateral acceleration: 1.3g
Maximum PSD: .084

Maximum SPL: 140db
Cost: ~$10M (Includes range costs: Cosmos tries not to undercut comparable US launchers (Pegasus, in this case), by over 15% due to political sensitivity)[6]

Start

The Start vehicle, a Russian ICBM-based launcher, has a 50% success rate (1 for 2), although it has many successful suborbital launches in its missile configuration. We were unable to locate complete information on this or certain other former Soviet vehicles, but, since the Start has launched with Western payloads, it was included using the information available. The Start is subject to the same geographically imposed orbital constraints as the Cosmos.

Launch record: 2 launches, 1 success = 50% (success with four-stage Start-1 version: failure with five-stage Start).
Availability: Unknown.
(Capacity estimates are for Start-1.)
Capacity to Mission 1 orbit: 415kg
Capacity to Mission 2 orbit: 415kg
Capacity to Mission 3 orbit: Not applicable.
(NOTE: PE numbers are estimated from similar vehicles)
Maximum axial acceleration: 10g
Maximum lateral acceleration: 4g
Maximum PSD: .06
Maximum SPL: 140db
Cost: ~$10M (presumably includes range costs)[7]

Planned Expendable Launch Vehicles

MSLS

The Air Force/Lockheed-Martin Multi-Service Launch System will use surplus Minuteman II ICBMs. The MSLS B replaces the Minuteman II third stage with a commercial equivalent. Current U.S. national policy keeps this vehicle off the commercial market, but limited use for government and research payloads has been approved. JAWSAT, which will launch in combination with four Falconsat microsatellites, is the only payload definitely scheduled so far, although at least one of the Mightysat research satellites planned by the Air Force Phillips Laboratory's is expected to use the MSLS.

Launch Record: 1st orbital launch projected 1998, first suborbital August 1996.

Over 200 suborbital flights in missile configuration with reliability over 90%.

Availability: A primary payload could fly in mid- or (more likely) late 1998.
Capacity to Mission 1 orbit: 160kg Capacity to Mission 2 orbit: 140kg
Capacity to Mission 3 orbit: 225kg
Maximum axial acceleration: 14g: Used in model: 6 (See NOTE below.)
Maximum lateral acceleration: 6g: Used in model: 3
Maximum PSD: 0.4: Used in model: 0.2
Maximum SPL: 156.5 db
Cost estimated by Air Force: $6.9M
Cost used in model: $7.6M

The MSLS D adds a STAR-48 motor as a fourth stage.
Available: 1998
Payload environment remains approximately the same as the B.
Capacity to Mission 1 orbit: 315kg
Capacity to Mission 2 orbit: 285kg
Capacity to Mission 3 orbit: 400kg
Cost estimated by Air Force: $9.06M
Cost used in model: $9.9M[8]

NOTE: The suitability of the MSLS for many payloads, including the Gemstar satellite, depends on the construction of a shock isolation system now being designed by CSA Engineering under a Phillips Laboratory contract. The goal of this passive isolation system is to reduce axial acceleration by two-thirds and the lateral acceleration and PSD by one-half. Preliminary estimates are that the system will cost in the tens of thousands of dollars and reduce payload capacity by less than 10kg. Without this system, the MSLS vehicles will not meet the threshold requirements to launch the Gemstar payloads. We have assumed the availability of the shock isolation system. We have been conservative in our estimates of how much it will reduce stresses on the payload, and all payload capacity estimates for MSLS vehicles have been reduced by 10kg to allow for the weight of this modification.[9]

<u>Conestoga 1229</u>

The 1229 is the smallest in the line of launch vehicles being marketed by EER Systems. It was a Conestoga 1620, a much larger model, that failed in its first and only launch attempt. The 1620 does use the same solid rocket motors and guidance system, so its launch record is relevant. Negotiations to fill the manifest for a second launch, tentatively scheduled for fall 1998, are in progress.

Launch record: No bookings yet for the 1229.
Availability: A 1229 could be ordered for fall 1998.
Capacity to Mission 1 orbit: 220kg
Capacity to Mission 2 orbit: 220 kg
Capacity to Mission 3 orbit: 300kg
Maximum axial acceleration: 9g
Maximum lateral acceleration: 2.5g
Maximum PSD: .08
Maximum SPL: 139db
Cost estimated by company: From $11M to 14.3M, depending on whether customer specifies motors already in storage or new motors now on order.
Cost used in model: $12.1M[10]

Eaglet

The Eaglet is the smallest of E' Aerospace's planned family of Eagle launch vehicles. These vehicles are based on the same solid-fuel stages used for the Peacekeeper missile.
Launch record: first flight projected for January 1998.
No bookings announced.
Availability: Could book the first flight in early 1998.
Capacity to Mission 1 orbit: 825kg
Capacity to Mission 2 orbit: 825kg
Capacity to Mission 3 orbit: 1290kg
Maximum axial acceleration: 6.5g
Maximum lateral acceleration: 2.2g
Maximum PSD: .06
Maximum SPL: 139 db (average)
Cost estimate by company: $10M to low-inclination orbits, $12M to polar or sun-synchronous (cost due to reconfigured 3rd stage)
Cost used in model: $11M, $13.2M respectively.[11]

Planned Partially Reusable Launch Vehicle

Eclipse Express

The Express, originally designed as Kelly Space and Technology's proposal for the NASA X-34 contract, would use a modified F-106 drone aircraft, equipped with a Russian-built rocket engine. The Express will be towed to 12,000m by a Boeing 747, then released. Near the apogee of its flight, it would release a solid expendable upper stage with the payload. Kelly has a contract from the Air Force's Phillips Laboratory to develop and demonstrate the aerial towing capability.
Launch record: First flight planned before the end of 1998.
Availability: The 1998 first flight is available.
Capacity to Mission 1 orbit: 90kg
Capacity to Mission 1 orbit: 90kg

Capacity to Mission 1 orbit: 130kg
Maximum axial acceleration: N/A
Maximum lateral acceleration: N/A
Maximum PSD: N/A
Maximum SPL: N/A
NOTE: According to the developer, the payload environment will impose very low stresses, compared to conventional launch vehicles. Since this is a logical assumption, given the flight profile, the model assumes the Express will have the most benign payload environment of the vehicles considered.
Cost estimated by company: $2M
Cost used in model: $2.4M[12]

Satellites in the Mission Model

The Gemstar was designed for the LMLV (then LLV) with a minimum safety factor of 10% added to the expected stresses. Accordingly, the Gemstar's approximate PE tolerances are:
Maximum axial acceleration: 8.8g
Maximum lateral acceleration: 2.75g
Maximum vibration (power spectral density (PSD)): .015
Maximum sound pressure level (SPL): 146db
NOTE: Given these stress limits, Gemstar is not suitable for flight on Pegasus XL. As the Pegasus is the leader in the U.S. market and should be included in any model of launch vehicles, we assumed that, since the Pegasus has substantial spare capacity, the satellite could be strengthened and/or shock isolators added.
Envelope required: the Gemstar is launched as a cube less than 1m in diameter.[13]

The JAWSAT structure is identical to CATSAT, built by the University of New Hampshire. CATSAT was designed for a Pegasus XL environment. Assuming a minimum 10% safety factor, this makes the approximate PE tolerances for JAWSAT:
Maximum axial acceleration: 14.3g
Maximum lateral acceleration: 6.6g
Maximum PSD: .08
Maximum SPL: 147db
Envelope required: the JAWSAT is launched as a cube approximately one-half meter across.[14]

Modeling Results

Mission 1 (JAWSAT research payload)

All the candidate launch vehicles were technically feasible candidates. There are no U.S. government restrictions against use of any launch

vehicles for nonprofit research missions.
Computer ranking (1 is best):
1. Cosmos
2. Express
3. MSLS-B
4. Pegasus
5. LMLV-1
6. MSLS-D
7. Eaglet
8. Start
9. Conestoga

If the Express were not available in 1998 (not an unusual slippage for a vehicle still in the design stage), the ranking would be:
1. Cosmos
2. MSLS-B
3. LMLV-1
4. Pegasus
5. MSLS-D
6. Eaglet
7. Start
8. Conestoga

Mission 2 (DoD using a Gemstar satellite)
The Express' payload capacity was too small, and the Cosmos and Start were prohibited both by U.S. policy and by the orbit involved.
Computer ranking:
1. Pegasus
2. MSLS-B
3. LMLV-1
4. MSLS-D
5. Eaglet
6. Conestoga

Mission 3 (Commercial Gemstar satellite)
The MSLS vehicles were ruled out based on U.S. government policy against allowing surplus ICBMs to compete in the commercial sector. Again, this satellite is outside the Express' payload capacity.
Computer ranking:
1. Cosmos
2. Start
3. LMLV-1
4. Pegasus
5. Conestoga
6. Eaglet

Observations

The poor showing of the Conestoga and Eaglet in this model does not reflect any basic flaw in the designs or the concepts of operation being used by their manufacturers. Their problems reflect the status of companies getting a late start in a market crowded by vehicles with similar capability. Express shares a similar status, but offers the promise of radical improvements in cost and payload environment if built and tested successfully.

Of the launch vehicles available today, the Cosmos is the dominant choice for nonmilitary missions. This creates a dilemma for U.S. policy makers. The best choice from a payload developer's point of view is not one which will foster development of the domestic launch vehicle manufacturing industry.

This problem of conflicting interests affects nearly all launch vehicle options. For instance, the Pegasus XL and Lockheed-Martin Launch Vehicle both have many positive attributes and should have a solid future if they can demonstrate reliability. However, both are undercut on price in the commercial market by the foreign-built Cosmos and Start. Assuming the successful testing of the Minuteman-based launch vehicles and the shock isolation system, the MSLS B and D boosters would also become strong competitors for those payloads they are allowed to launch.

Conclusions

This model is not the definitive solution to the problem of selecting a small launch vehicle. It is, however, a useful tool, provided it is updated to reflect continually changing conditions. Events constantly occur in this market which will affect the rankings. Examples are launch successes and failures, the entry of new launch vehicles, the financial collapse or buyout of small companies, and changes in U.S. government policy. The model also provides a starting point for development of a more complex decision-making aid which could take additional factors and launch options into account.

The model does allow payload developers to compare dissimilar alternatives. For example, the company needing to launch a 140kg satellite may not consider the Cosmos, since it has a great deal more capacity than required. However, if this system *is* considered, the cost, reliability, and availability of this launch vehicle make it the optimal choice in spite of the wasted capacity.

In today’s market, the payload developer must examine all options. As already noted, one point made very clear by this modeling exercise is that the interests of the small payload user and the U.S. commercial launch community will not, in all cases, coincide. For smallsat builders, the optimum situation is one in which as many candidate vehicles as possible, including foreign launchers and surplus missiles, are made available.

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