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Is it really that hard to get your hardware into space?

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ABSTRACT

Small satellite developers should be encouraged by the fact that reasonably priced access to space is not really the hurdle that it is often perceived to be. An analysis of the small satellites launched in recent years by their sub-classes and annual rates of launches demonstrates that small satellites launch opportunities are widely available, and that a range of methods are utilised including dedicated, shared or piggy-back launch.

Based on experience with a wide range of small satellite launches, it is illustrated how many of the perceived barriers to launching small satellites can be overcome. In particular with regard to affordable launch cost, which is commonly considered one of the major hurdles in the small satellite community.

The methods for small satellite launch are considered, and a statistical analysis is performed to show that, at a macroscopic scale, there are plenty of launch opportunities, and a significant number of small satellites would be launched with minimum expenditures if an approach to a choice of launch method, launch vehicle type and launch operator will be done in a correct manner. Certain recommendations for a realisation of this approach, including proposed empirical criteria are given

INTRODUCTION

In order to operate space borne payloads, significant support infrastructure is required, and mission design involved the complex task of balancing risk, budget, and schedule. Many aspects of missions are still designed and optimised on a case-by-case basis. A lot of time and effort can be devoted to the design of the supporting platform, the control system including the space and ground segment elements, the software and tools to operate the mission. Few applications can justify the expense and timescales required to design or even just customise their launcher, and mission designers are generally forced to design their spacecraft to meet already existing launch methods and opportunities.

The selection of a suitable ride into orbit remains a complex issue to deal with. Launchers are not yet commodity products, and there are few manufacturers, there is little choice, and there are regulatory, political and export issues which need to be solved and addressed, and further restrict launch options. The entry-level cost for launch is relatively high, and as a result launchers are generally only manufactured in small numbers, sometimes only when required.

In the market for geostationary launch, there is some stability with 20-25 launches per year, and many launch manufacturers and service providers design their launchers to maximise their profits from this market. This has led to the existence of large powerful launchers, with 3-5m fairing diameters and with the ability to carry 4,000-15,000kg into geostationary transfer orbit. Their price tags are commensurate with a ~US$250m+ satellite programme cost as reliable launch options do not vary significantly from US$20k per kg for a fully utilised launch vehicle.

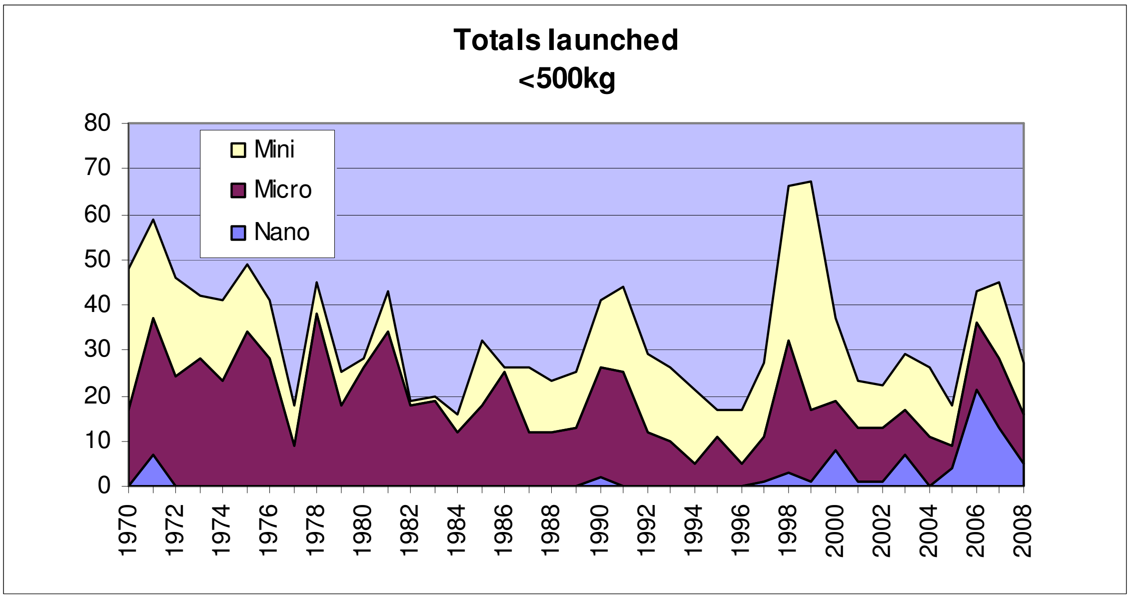

Figure 1. Annual numbers of small satellites launched during 1970-2008

The major space powers have also developed launchers to support their civil and military space objectives. A development in the past decade has also seen some former missile stock piles being converted into launchers. These provide some additional choice for mission designers. Nevertheless, the entry-level cost for any dedicated launch remains high, and the cost and selection of a suitable launcher for a specific mission remains a major factor which impacts the mission design.

Many applications only become viable given a certain mission cost in order to and provide commercial, military or scientific value. Although small satellite technology has matured, and an increasing number of meaningful missions can be accomplished in principle with low-cost small satellites, the cost of a dedicated launch is frequently prohibitive. As a result, launch availability and methods have often been raised as a major issue by the small satellite community in the design of missions. A notable exception is batch launch of small satellites as part of a constellation, although the problem of replenishment with single spacecraft could still presents the same issue.

The worldwide market for small satellites, defined as missions weighing less than 500kg here for simplicity, varies between 20 and 60 satellites per year. There are a few launch vehicles which would serve as a dedicated launcher for such missions, with average prices around US$15 million. Market forces have generally been too weak or business plans too marginal, for new launchers to be entered into service in this market segment. One notable exception is the entry of the FALCON-1 launcher by Space-X in the US.

It can be observed that a significant number small satellites fall in the micro-satellites class (10-100kg), or in the nanosatellite class (<10kg here for simplicity). This size satellite is often developed by universities, small private companies and scientific organisations, who have the necessary funds for the satellite development and manufacture, but do not have the means to pay for dedicated launch of their satellites.

An obvious solution for those wanting to launch small satellites has been to use excess capacity on manifested launches, or to find ride-share partners with compatible orbit requirements and schedules. These methods have been used since the early days of the space era, and has become a popular means to reduce the cost of launch. This potentially provides a wide range of opportunities, but in practice there are few incentives for the launch provider and mission prime. Sharing launch capacity is a common practice as well, and leads to a lower cost-of-entry for a launch slot. Both methods have been used many times, and they are highly effective where the demands of the mission are flexible in terms of schedule and orbit. In the majority of cases though, the arrangement of launch becomes more complex and can become a major schedule driver in a programme. Due to this complexity, it may be impossible to find a suitable opportunity before commencing the project. It is very easy to underestimate the amount of effort required to arrange a launch slot, and deal with the potential political issues, export licenses, and logistical planning. It is not uncommon to find organisations with spacecraft fully manufactured and tested, awaiting a suitable launch.

Both SSTL and CST are involved in the arrangement of small satellite launches, either as a developer / manufacturer (SSTL), or as a broker (CST). Because of SSTL's launch rate of about 2 small spacecraft per year, the challenge of affordable access to space is vitally important for both the companies. Each has built up significant expertise in arranging dedicated, shared, or piggyback launch opportunities. SSTL has developed extensive experience with "design to launch" techniques, in order to maximise the launch opportunities, and minimise the incurred costs for associated services. CST also has significant expertise in launch brokering, dealing with the logistical issues and the complex politics involved. Both companies have become increasingly involved in brokering the excess capacity on launches they get involved in

REVIEW OF THE SMALLSAT LAUNCHER MARKET

Firstly, it is necessary to assess the world's market of small satellites and its dynamics. This would allow the demand for launch services to be defined for this market servicing both at the current time and in the near future.

The total annual numbers of small satellites with masses less than 500 kg which were launched in the whole world during the period from 1970 to 2008 are shown in Figure 1 with their distribution by sub-classes of mini-satellites (100-500 kg), micro-satellites (10-100 kg) and nano-satellites (less than 10 kg). However, as it was shown in [1], the statistics for this long period is not a real picture of dynamics for small satellite launches: for example, the sharp increase of these launches in the late nineties was due to the so-called "small communication satellite boom" when the small Low-Earth-Orbit satellite constellations of Orbcomm and Globalstar (Iridium satellite mass was above 500kg) were launched, but without creating a sustained and regular demand

Figure 2 shows annual numbers of all classes' satellites that were launched during the period from 1990 to 2005 which when split into their mass classification, exposes three trends. Firstly, the annual number of all classes of satellites being launched is decreasing (especially if one does not take into account the above-mentioned "boom of 1997-2000) that is underlined in this Figure. Secondly, on the background of this decrease, the proportion of small satellites being launched annually is increasing (this becomes especially apparent when plotted in a normalised fashion in Figure 3). Thirdly,

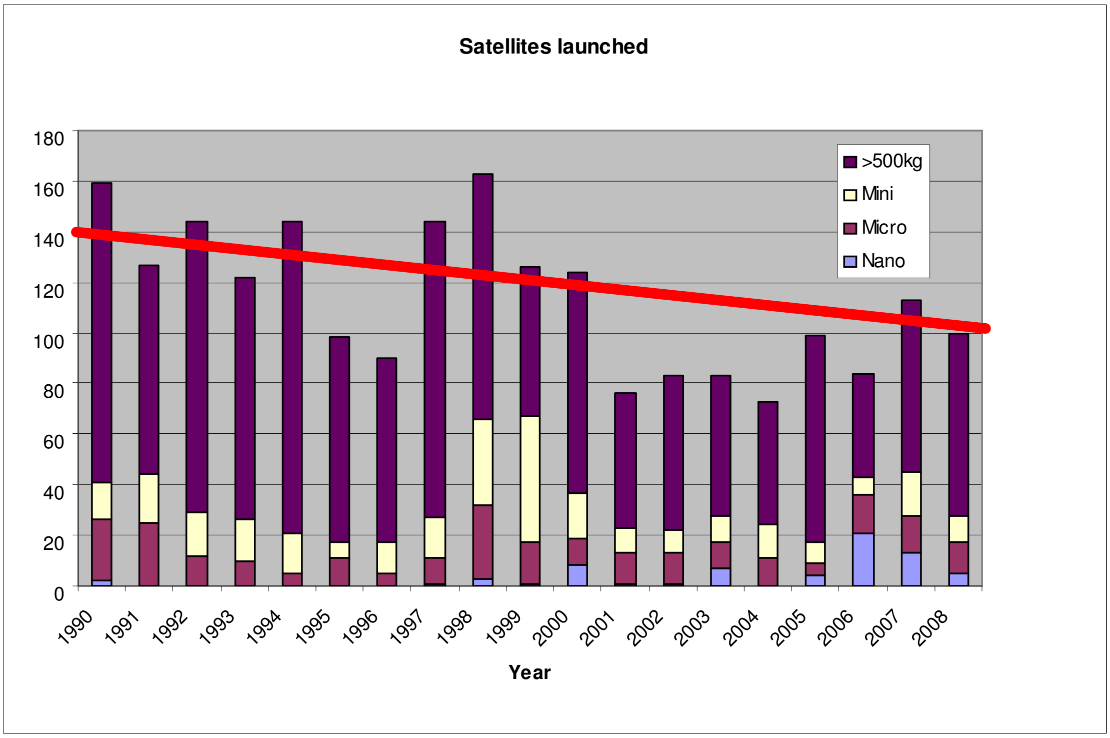

Figure 2 There is a downward trend in the numbers of satellite being launched annually

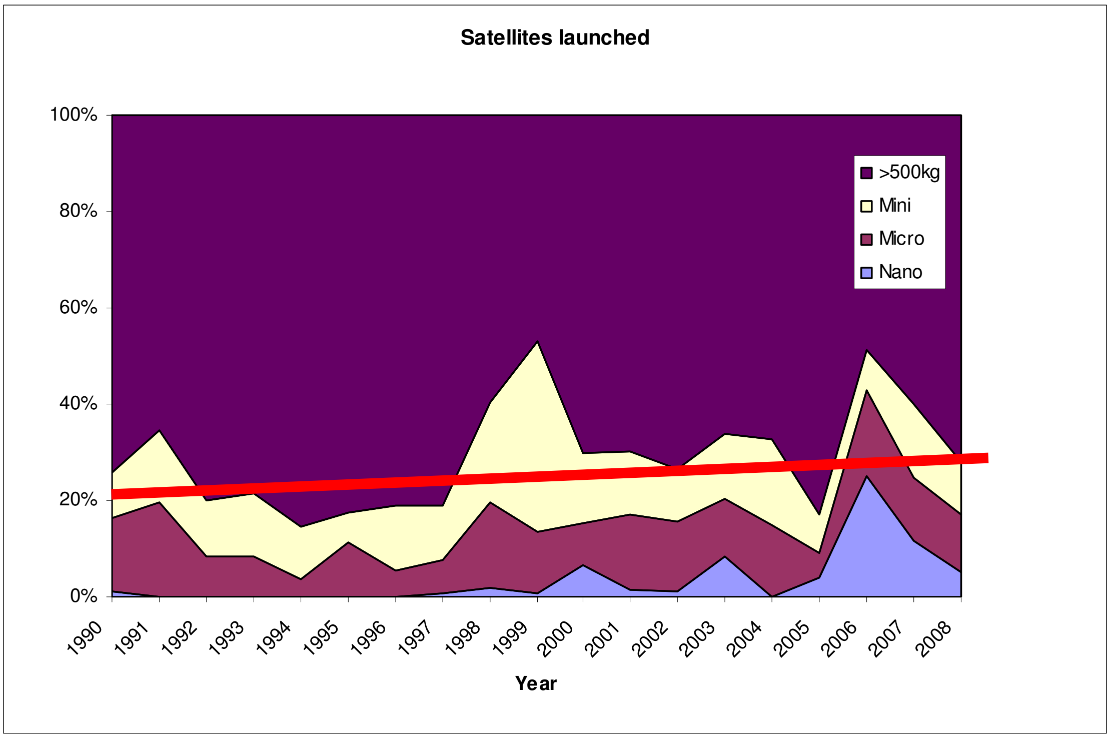

Figure 3. The ratio of small satellites being launched is increasing

the number of nanosatellites is increasing annually.

Although the statistical data shows the trend of an increasing annual share of small satellites, it is necessary to assess the constituent data points in greater detail. This would allow us to understand the demand for these satellites launches, which initiates the development and putting into a full-scale operation those small launch vehicles which would provide these launches with an acceptable launch price. The Figures 1-2 show that, on average, ten mini-satellites and ten micro-satellites find their way to orbit every year while the average annual numbers on nano-satellites, has also just approached his number. As was shown in [1], the total annual number of the small satellites with masses less than 500 kg would scarcely exceed 30-35 pieces per year while a share of micro- and nano-satellites in this figure would be the dominant one.

Indeed, there is an indication that even the entry-level prices for small launchers are still too high to satisfy the developers of small satellites with dedicated launcher needs. In Russia some of the dedicated launch opportunities are based on converted missiles, and have been available for the past decade for entry-level costs of US$6-8 million. This did not have a significant effect on the market, and it is therefore difficult to assess whether the small satellite market would grow significantly should new a launcher address this market sector. The establishment of Falcon-1 in the market will be an interesting case to watch because of the particular challenges faced by US launch customers. In the US, government customers are restricted to select from only US launch vehicles. Commercial organisations do not have such restrictions as they can largely select based on value, but are faced by a complex and expensive export controls. Some have been able to benefit from the lower prices outside the US [7], but few have the necessary in-house capability to do this successfully without expert support.

These indices, both for current time and for the near future, are evidently insufficient justification for the development of a dedicated small launch vehicles that would have a payload capability at the level of 100-300 kg and would provide a launch price less than US$ 3-5 million. So, it is reasonable to rely upon those launch vehicles that either are in operation at the current time, or are being currently developed with high chances for realization.

Summary of launch methods

Several methods are currently being used to launch small satellites. These methods include:

- **Dedicated** launch, in which a single small satellite is a prime (sole) payload,
- **Rideshare** (or shared) launch in which the launcher's payload consists of two or more

identical satellites (the "batch" option) or satellites that have approximately equal masses and dimensions,

- **Cluster launch** in which the launcher's payload is a cluster of more than three different small satellites
- **piggy-back** launch in which one or several small satellites are the secondary payload ("piggy-back") in a regard to the primary payload that is one of more spacecraft of significantly more mass
- **Sub-satellite,** in which the secondary small satellites is separated from a host spacecraft after it has been deployed into space. In the past the space stations have been used for this, but recently it has been used to deploy cubesats and smaller spacecraft.

The annual distribution of these methods for the 1990 to 2008 period is shown in Figure 4. As can be observed, the share of piggy-back launches is currently more than 50%. The second most popular method is the rideshare method while a use of the dedicated launch method has had an average share of less than 20% and has remained relatively stable during the period investigated.

Figure 5 also illustrates the countries where these small satellite launches take place. It shows that the majority of small satellite launch opportunities are in Russia, with the remainder in the USA.

The launchers used by small satellites are based on launch vehicles from across the world, and are listed in Table 1 alongside the parameters that are of importance for their selection for small satellite missions (payload capability, launch price and specific launch price).

The launchers listed include those small launch vehicles which are being used for both the dedicated and rideshare launches of small satellites, and medium/heavy classes' launchers that are providing currently piggy-back launches in a process of their certain primary missions. It can also be observed that medium launchers were used regularly for batch launches, and that have all but disappeared since 2003. Further analysis reveals that these were the clusters of communication satellites. It is also noted that shared launch is becoming an increasingly popular method of launch for small satellites.

Beside the operational launch vehicles listed in Table 1, there are a certain number of small launch vehicles that have either rarely been used for launches of small satellites (as a rule, in dedicated launches), or are in the process of being brought into operation in the near future. These are also listed alongside their key

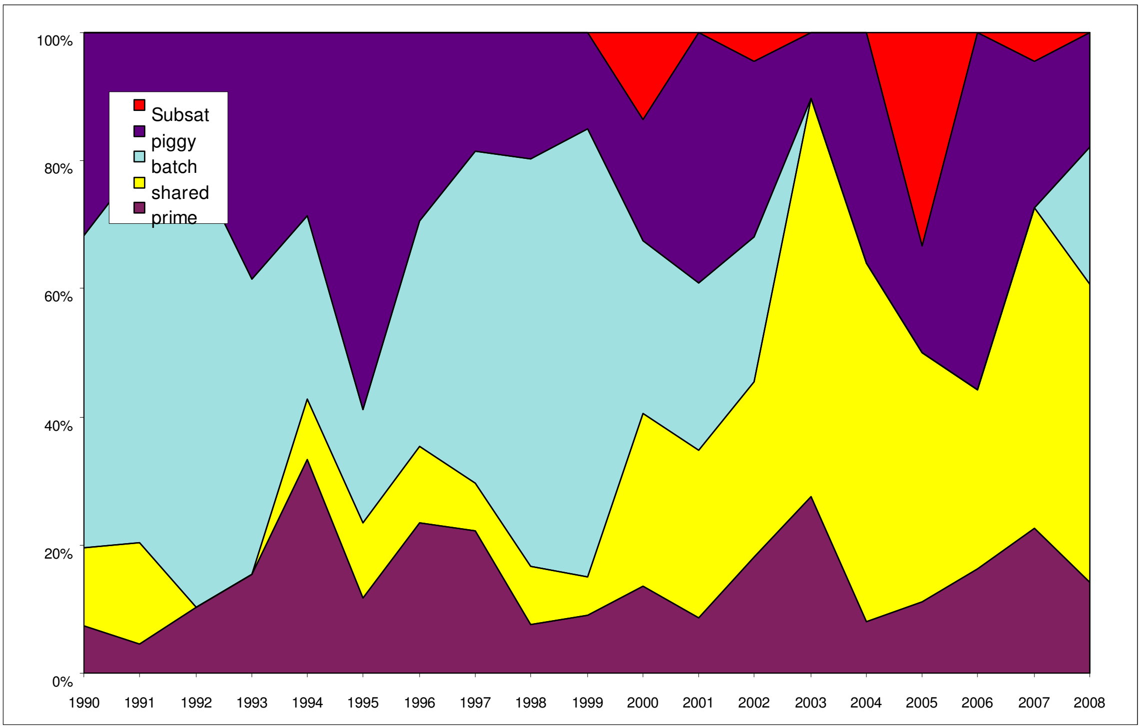

Figure 4. Uses of various launch methods for small satellites

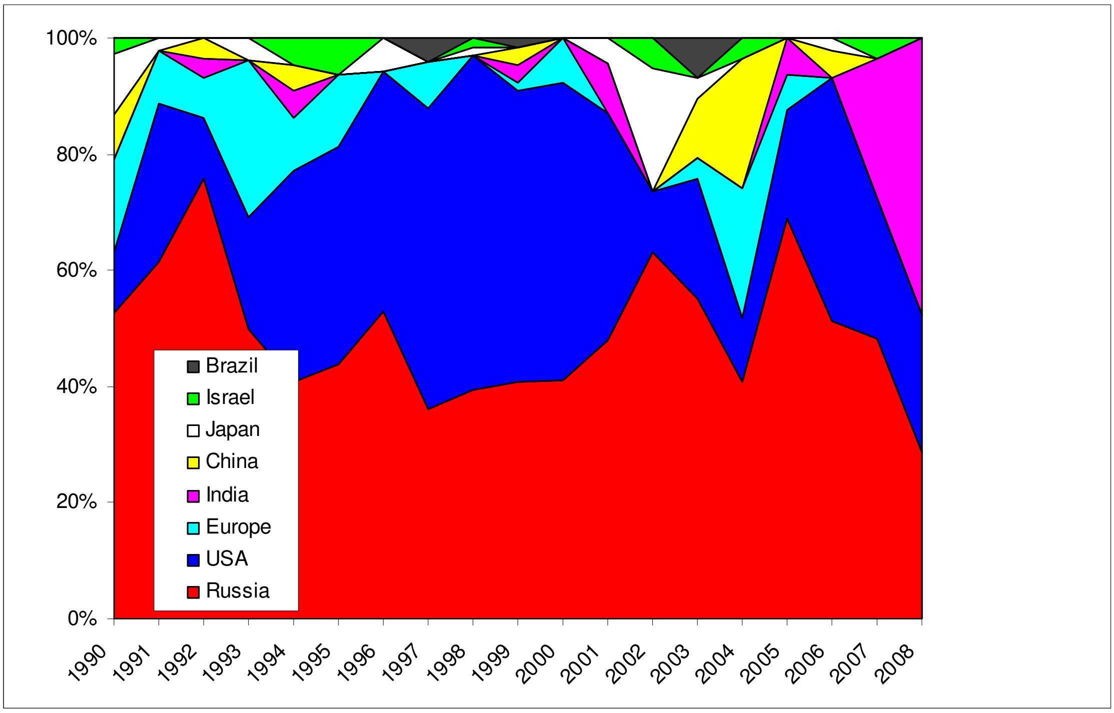

Figure 5. small satellite launch numbers by launch nation

parameters in Table 2.

Undoubtedly, dedicated launches are preferable for the majority of missions, with the possible exception of those missions being performed with multiple satellites. However, the provision of dedicated launch arrangement with a minimum launch price would require that the launcher's payload capability has to be fully utilised. i.e. a launch mass of the satellite to be launched has to be approximately equal to the launcher's payload capability. The world's launcher inventory does not currently have many operational small launch vehicles that have their payload capabilities at or below the level of micro-satellites' mass. The only exclusion is the Russian "Shtil-1", however, this small launcher is converted from a submarine-launched ballistic missile (SLBM), and its use has significant limitations for commercial operations, stipulated by both organizational and political reasons. It is however suitable for small satellites developed by organisations with government funding, which still covers a large fraction of the small satellites launched. The only exception where a dedicated launch can be cost-effective is where the launch risk is still high, for instance with the first few test and operational launches of a launch vehicle being brought into full operation.

With the increasing interest in responsive space in several countries now, it is possible that governments will support several developments of low cost and responsive, dedicated launchers for small satellites. These missions are generally required to fulfil missions for defence or national security, and must be launched within a very short period of time. A realization of this concept requires not only the use the dedicated launch method (excluding the cases when a cluster of the same type's satellite should be launched in a frame of the "responsive access" concept) but also the corresponding launch vehicle that would provide this launch on request (see [2]). If the requirement to provide "responsive access [to space]" increases, it will become feasible for more small satellites to be launched via a dedicated launcher, even in the micro-satellite sub-class.

Non-dedicated launch methods provide lower prices for the launch of small satellites, especially for micro- and nano-sub-classes. Although a comparison of specific launch prices presented in Tables 1-2 shows that certain ones achieve levels of less than US$10,000/kg both for small and medium/heavy launch vehicles, it should not be forgotten that these specific launch prices are calculated based on using the complete payload capabilities. Since the current small launch vehicles have payload capabilities that exceed a maximum mass of single micro-satellite by 5-10 times in the best case, it is evident that the presented specific launch prices can be achieved for micro-satellites only if these satellites are launched by these launchers in rideshare missions, and with a single customer interface to the launch agency. This, in turn, creates the problem to gather together a necessary number of small satellites with a total launch mass near to a payload capability of the chosen small launch vehicle and to arrange and provide these satellites' mutual readiness by the scheduled term of launch.

In some cases, manufacturers of small satellites pool together to buy a launcher and perform a rideshare launch. Such a shared launch provides some control, and the concept is similar to a bus: No one gets exactly where they want to go, but it is cheaper than hiring a taxi for your exclusive use. SSTL has recently manufactured sufficient small spacecraft that it can afford to buy an entire launcher at times, and sell the excess capacity – this is the example how the similar pool for a launch of several small satellites by a single small launcher would be arranged.

The example of small satellite rideshare launch preparation is shown in Figure 6.

Figure 6. Accommodation of small satellites for a rideshare launch on the "Cosmos-3M" small launch vehicle

The piggy-back launch method is providing fewer difficulties in this regard since the primary payload has been already defined for every potential launch i.e. for that launch in which the reserve of the launcher's payload capability would allow to accommodate some piggy-back payload (payloads). This method gives still less control over the piggy-back payload in terms of the final orbit, or the date/time at which they launch than for small satellites launches by the rideshare method since these parameters are being defined by requirements of the primary mission while the same parameters for a rideshare launch would be agreed between partners-customers of this type's launches.

Nevertheless, the piggy-back launch method is providing lowest launch prices for small satellites. In a majority of the cases, heavy launch vehicles are having certain reserves of payload capability in their missions and these reserves are comparable with masses of single or two-three micro-satellites. In order to gain an additional profit, the launch vehicle operators are welcoming this sort's missions. Besides this profit, launching more spacecraft per launcher also is good PR as one can quote more "spacecraft launched". An example of piggy-back small satellites accommodation on the primary payload is shown in Figure 7.

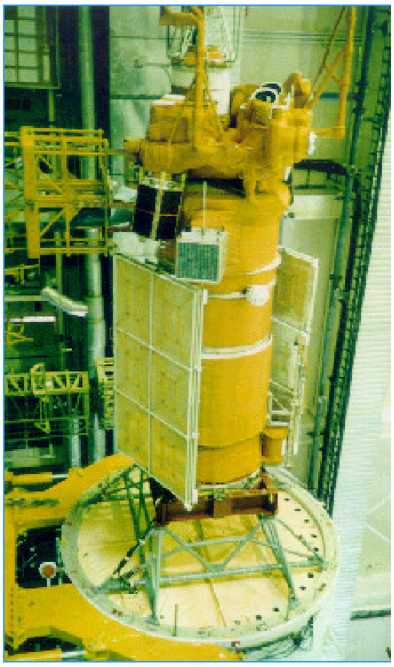

Figure 7. Accommodation of the FASAT and Techsat small satellites for a launch as piggy-backs

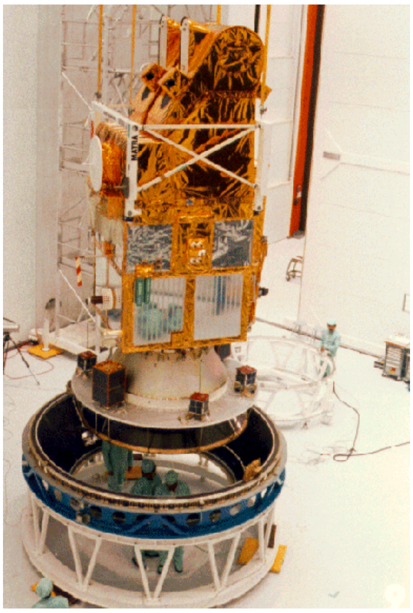

Figure 8. Piggy-backs of the SPOT missions on the "Ariane-4" launcher's ASAP platform

Some launch operators provide a standardised platform for accommodation of small spacecraft to be launched as piggy-backs (the example of this platform, the Arianespace's ASAP is shown in Figure 7).

Some governmental agencies have done the same in order to stimulate opportunities in their market (e.g. US Air Force with the EELV ESPA ring, and JAXA with their launcher). Certain operators such as Arianespace have made a conscious business decision in the belief that manufacturers of small satellites would become large satellite customers later.

It is necessary to note that the participation in any mission on a launch of multiple satellites, both a rideshare launch and a launch with piggy-backs, inflicts certain obligations on those small satellite manufacturers that are using these launches for launches of their satellites. Thus, the calculations of launcher's dynamics takes into account the whole payload including all its components, therefore, an absence of any of these components, either a rideshare small satellite, or a small satellite-piggy-back, at the moment of launch is inadmissible. SSTL has been forced to supply a dummy mass payload for certain such launches to ensure the launch would not be delayed in case the smaller spacecraft will be not yet ready by the scheduled term of the launch.

So, the approach to solving the problem of concrete small satellite launch has to be begun from a choice of the launch method proceeding from the satellite mission's main requirements. If there are not the strict requirements on exact parameters of final orbit, term of launch and, moreover, a necessity to provide the responsible access for the satellite to be launched, the piggy-back method would be most preferable from the point of view of launch cost reduction.

Each payload also imposes requirements on the launch agency, in terms of additional analysis, safety, facilities etc. Launch prices typically comprise fixed administration costs, and costs of launch themselves that are defined by the launcher's specific launch price (per kilogram of mass to be launched). For smaller spacecraft, the administration costs are often most significant. For piggy-back launches, the specific launch costs for 100-kg spacecraft (micro-satellites) are typically at the level of US$10-20 K/kg with taking into account the administration costs. The resulting launch prices can be considered sufficiently admissible (US$ 1-2 mln. for a launch of 100-kg small satellite and US$ 100-200 K for a launch of 10-kg nano-satellite). Not the launch cost, but finding a suitable launch is probably the biggest problem, as there is little benefit for the primary buyer of the launcher to sell excess capacity (it just introduces risk and complexity). An overwhelming majority of heavy launchers launch into undesirable orbits as far as small satellite applications are concerned (GTO, to get into Geostationary orbit is little use for anything else than GEO communication satellites). Therefore, if the difficulty to find a suitable launch by the piggy-back method on medium/heavy launchers for some concrete small satellite is found to be insurmountable, it would be possible to apply to small launch vehicles.

As this is mentioned above, these launchers are being most often used for launches of micro-satellites by the rideshare launch method while nano-satellites can be launched also as piggy-backs with small satellites of larger small satellites. In both these cases, it would be possible to meet the specific requirements for a concrete small satellite mission to a greater degree since almost all the small launchers are limited to inject their payloads into low-Earth orbits (LEOs) and, therefore, there are more opportunities to match one of the primary missions announced for the required range of orbit's parameters (for piggy-back launches of nano-satellites) or to agree these parameters in an acceptable range with other partners by a rideshare launch.

At the same time, the specific launch prices can only slightly higher than for piggy-back launches by medium/heavy launchers, however, this statement is not relevant to all the launchers of small class. These specific launch prices are different for various countries' small launch vehicles. It is understood that this factor is influencing significantly on these countries' shares in the world's market of small satellite launches.

The distribution of these shares is shown in Figure 5. On the face of it, there is a contradiction – while Russia with its cheap (see Table 1) small launchers predominates in this market, the United States with their more expensive launchers (see the same Table) are in the second place nevertheless. However, the simple explanations are both for this circumstance and for lower launch prices of Russian small launch vehicles. Firstly, while a majority of small satellites that have been launched by the Russian small launchers belong to foreign customers, the U.S. launch vehicles were and are launching mostly small satellites of U.S.-based companies and organisations (these companies and organisations have difficulty in accessing launch agencies outside the US due to strict export controls in "knowledge", and as such incur difficulties in accessing launchers outside their nation). Secondly, actually all the Russian small launchers are being converted from ballistic missiles that are removed from military operation and, therefore, their operators have the opportunity to keep lower launch prices purchasing main ready hardware by low prices as well. Customers of small satellite launches outside the U.S.A. have not the U.S. restrictions, and they (and SSTL in their number) have broadly used Russian converted small launch vehicles to launch their spacecraft [3]. Any potential customer of small satellite launch would use this opportunity as well.

However, as it is preferred in [4], this opportunity would be in presence not longer than around 10 years due to a complete consumption of basing missiles stocks while the new non-converted Russian small launch vehicles would have higher launch prices (see Table 2). These prices should be comparable with launch prices of new European ("Vega") and U.S ("Falcon-1") small launch vehicles. With this renewal of the world's small launcher inventory, the SpaceX company in the U.S.A. with the promised launch price ~US$ 8.5 mln. for their "Falcon-1E" launch vehicle is by many seen as the most likely to succeed. Increasingly, manufacturers of small satellites are already considering Indian and Chinese launchers [5]. Therefore, the future potential customers will have a broader range of available launchers for their choice.

There are also some launcher manufacturers who have started to develop launchers specifically for dedicated launches of small satellites, especially in a frame of the "responsive access" concept realization (these launcher manufacturers see this as a niche in the market). Many of them have failed with their preliminary projects, however, in the future, certain similar projects would be realized if the market would show the corresponding demand. This would expand still more a range of available launchers, especially if the mission of the small satellite to be launched will foresee the requirement of 'responsive access" provision.

Analysis

So, the above approach to the problem of concrete small satellite launch has to be continued by a choice of the launcher class if the earlier chosen launch method is the rideshare or piggy-back launch.

After the choice of the launcher type, the last stage of the launch problem solving is either a choice of concrete rideshare mission among the announced missions of this sort (or an arrangement of this mission by a selection and invitation of partners for this launch mission), or a final choice of the concrete launcher in the case if the earlier done choice was in a favour of the dedicated launch method. These general statements can be analysed in more details.

Various factors influence on the choice of launch method for any concrete small satellite launch. The main ones of them are the necessity to provide the satellite launch at the defined term (with certain tolerances), the necessity to provide the satellite orbit with required parameters (in a certain range) and the necessity to provide the satellite launch by a minimum launch price.

The first of these factors can be designed as F_t . Its value is equal to zero if the launch should be provided at any time by request ("responsive access") and it is equal to 1 if the time of launch is with indifference (for example, during a period of three years).

The second factor, F_o can be equal to zero if especially defined parameters of orbit are not needed for the satellite mission (this is typical for certain scientific missions) but it is equal to 1 if the orbit with clearly defined parameters (with minimum tolerances) is necessary for the mission.

The third factor, F_c can be assumed to be equal to zero if the cost of launch is with indifference (for example, due to importance of the satellite mission). It is equal to 1 if it is required to provide the launch by a lowest cost while, in the opposite case, the mission would be not realized.

All the factors can be used for a calculation of the K_1 criterion:

$$K_1 = F_t \; F_o \bullet F_c$$

As one can see, this criterion is equal to zero if either the small satellite should be launched at the clearly defined time, or this satellite should be inserted into the orbit with clearly defined parameters, or the launch cost is with indifference. It is understood that these requirements can be met by the method of dedicated launch only. Therefore, this value of the K_1 criterion is equal to zero or near to it, the dedicated launch method should be chosen. If the criterion's value is equal to zero or near to it, the piggy-back launch method should be chosen without doubts since this method, especially when primary missions are being provided by heavy launch vehicles, would provide lowest launch prices but without meeting requirements for defined launch time and some restricted requirements for orbit parameters.

Intermediate values of the $K1$ criterion require additional explanation. Thus, if the time of launch has certain limitations but the range of these limitations is a sufficiently broad one (for instance, the launch should be carried out during some defined year) or certain requirements for the satellite orbit are in existence nevertheless (for example, if this orbit has to have a high inclination), the value of the corresponding influencing factor, either F_t or F_o would be equal to 0.5 and the K_1 criterion will be around 0.5 as well. This level of the criterion's value shows that both the rideshare and piggy-back launch methods would be used.

On a basis of the statistic data preliminary analysis, it is possible to assume that the values of the K_1 criterion in the range of 0-0.2 corresponds to a necessity to use the dedicated launch method, the range of 0.2-0.5 shows a preference of rideshare launch method, the 0.5-0.8 gives approximately equal chances for both the rideshare and piggy-back launch methods use and, lastly, when this range is exceeded, the piggy-back launch method has evident advantages.

The choice of launch vehicle class is based on more empiric considerations. It is evident that the small class's launch vehicles are suitable for dedicated launches of small satellites while heavy class's launchers are preferable for those piggy-back launches for which the K_1 criterion is near to 1 (due to lowest specific launch prices that are being provided by this class's launchers). Equally, the small class's launchers can provide in the best manner rideshare launches of small satellites since clusters of these satellites (that are mostly micro-satellites) have total masses that do not exceed small launchers' payload capabilities. However, when the choice between a rideshare launch by a small class's launcher and a launch as a piggy-back by a medium/heavy launcher has to be done for the small satellite mission with the K_1 criterion's value in the rang of 0.5-0.8, it is necessary to take into account an influence of additional factors.

The first of these factors reflects the necessity to provide a defined sort of orbit that cannot be actually serviced in primary launches of heavy class's launchers. Indeed, as this is marked above, these launch vehicles almost cannot inject the piggy-backs into polar orbits and sun-synchronous orbits (SSOs) since an overwhelming majority of their primary missions are requiring other orbits with low inclinations. So, the corresponding influencing factor F_{so} for an especially required sort of orbit will have the value either of zero, if this special sort's orbit is required, or of 1, if this orbit is not required.

The second factor has to take into account the sub-class of the small satellite itself. Indeed, it is reasonable to launch nano-satellites as piggy-backs on any class's launchers since it would be difficult to collect a set of other small satellites around a single nano-satellite for a rideshare launch. So, the corresponding influencing factor F_{sc} has the value of 1 for the nano-sub-class's satellites, the value in the range of 0.8-0.3 for micro-satellites that have masses from somewhat more than 10 kg to 100 kg accordingly and 0.3-0 for small satellites with masses from somewhat more than 100 kg to around 300 kg accordingly I(launches of small satellites that have masses more than 300 kg would be provided preferably by the dedicated method).

The K_2 criterion for the choice between a rideshare launch by a small class's launcher and a launch as a piggy-back by a heavy launcher can be calculated by the following formula:

$$K_2 = F_{so} F_{sc}$$

One can see that the criterion is equal to zero when only the small class's launcher shall be used for a launch of the assessed small satellite by the rideshare method and it is equal to 1 for a launch of nano-satellite as a piggy-back by a heavy launch vehicle.

The intermediate values of the K_2 criterion between 0 and 1 can be estimated by their approximation to the marginal values: the value equal to 0.5 means that both the launch methods have approximately equal chances, the values lower show to a preference for the rideshare launch method while the values higher give this preference to the piggy-back launch method.

The K_2 criterion does not take into account the case when nano- and micro-satellites would be launched as piggy-backs by the medium class's launch vehicles in their low-orbital primary missions. These missions would provide sometimes injections of their payloads, both primary and secondary ones, into SSOs and polar orbits, therefore, the F_{so} factor has not a sense for them. However, these missions are sufficiently rare ones and, if the opportunity to use one of them for a piggy-back launch of some small satellite will take place with meeting the main particular requirements for the small satellite mission, this opportunity should be used since, as for piggy-back launches by heavy class's launchers, the piggy-back launches by medium class's launch vehicles are also providing lowest specific launch prices.

The choice of concrete launch vehicle does not require a use of any criterion. There are a few of simple principles only: for dedicated launches, the small launch vehicle would be chosen by its payload capability that should be near to the mass of the small satellite to be launched (if the requirement of the "responsible access" is in existence for the mission, the chosen launcher should provide this capability, of course); the small launcher for a rideshare launch should be chosen proceeding from the total mass of the satellites that will be gathered for this launch; the primary mission for a piggy-back launch is being chosen from the number of this sort's available missions by the principle of its maximum approximation to the desirable parameters of the small satellite mission (term of launch, orbit, etc.). Of course, the pricing indices for various small launchers that are approximately identically suitable for the small satellite launch should be taken into account as well as availability of these launchers (the "availability" means a capability to use the launcher for launches of foreign payloads, it is stipulated mostly by political considerations, see [1] for more details).

With this approach to a choice of launch method, launcher's class and concrete launcher for any small satellite and its mission, it is possible to lead to minimum the difficulties that should be overcome during solving the problem of small satellite launch, especially, for those small satellite manufacturers that have not a significant state support for their activity. Of course, the proposed method of launch arrangement optimisation is not a guarantee of the launch problem solving in all the cases but it shows that a provision of access to the space for small satellite manufacturers is not an insurmountable hurdle in a majority of the cases. The already gained multi-year experience of numerous small satellite builders confirms this assertion [6].

CONCLUSIONS

1. The increasing share of small satellites being developed and launched creates a challenge to find affordable launches matching their operational requirements. This has the potential to limit some commercial and civil missions from being implemented, despite the satellite technology being affordable and mature.

2. Basing on results of statistic analysis, the approach to a choice of the launch method, launch vehicle's class and concrete launcher for a small satellite mission is proposed and recommendations on this approach realization are given.

3. By considering the numbers of small satellites launched annually, it is clear that the problem of launch is not insurmountable, and is solved in the majority of cases.

4. It is shown that the problem of small satellite launch is not an insurmountable hurdle and that this problem would be solved in a majority of the cases.

5. It is recommended that the small satellite community continue to persuade the organisations procuring dedicated launches in accepting secondary passengers to make most effective use of the launcher capacity. The smallsat community will need to demonstrate a certain degree of benefit to the primes, and individual organisations may need to work with a broker or aggregator to help secure specific slots.

6. It is recommended that those seeking a shared launch consider working with organisations with suitable experience. Launch providers prefer to have only a single contractual interface, and there are many political, export and logistical hurdles to overcome, especially when considering international launch options.

REFERENCES

1. The Impact on the Small Satellite Market from the Introduction of a Low-cost US Small Launch Vehicle, CST Report, 2005
2. Responsive Access to Space for European Microsatellites, G. Webb, J. Paffett, Paper ID 2359 of 59th International Astronautical Congress, 2008
3. Affordable Access to Space Using a Russian Launch Vehicle, D.Lorenzini et al, SSC03-III-1, Proceedings of the 17th Annual AIAA/USU Conference on Small Satellites, Logan Utah, Aug 2003
4. Launching Small Satellites in Russia, the Present Situation and Some Future Directions, G. Webb, O. Sokolov, Paper ID 2357 of 59th International Astronautical Congress, 2008

5. 20 Years Experience Using Low-cost Launch Opportunities for 20 Small Missions, Meerman et al, IAC-02-IAA.11.5.V7.01 - IAF 2002, Toulouse, October 2002
6. Affordable Access to Space - Getting There, A.Currie et al, SSC03-III-7, Proceedings of the 17th Annual AIAA/USU Conference on Small Satellites, Logan Utah, Aug 2003
7. "Tight budgets could create new openings for secondary payloads", Space News, 9th March 2009.