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THE REPLENISHMENT OF LEO SMALL SATELLITE CONSTELLATIONS

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ABSTRACT

LEO systems, composed of small satellites with masses of up to a few hundred kilograms each, used for the purposes of navigation, communication or remote sensing have been considered and sometimes realised for the past 50 years. At present, following the successful establishment of the SSTL Disaster Monitoring Constellation (DMC) many LEO remote sensing small satellite systems are being developed.

The most economic deployment of such constellations is usually considered to be best carried out several satellites at a time using launchers such as Rockot and Dnepr. For example, the RapidEye system (of five satellites) is planned to be launched by Dnepr in 2007. However, it is expected that the replenishment of the constellations with fresh satellites will be done piecemeal, making the use of these mid-range small launchers uneconomic. An additional problem, particularly with co-ordinated remote sensing systems such as the DMC is that the new satellites will have to be inserted into the constellations with high accuracy as well as economically and on time.

In the paper an assessment is made of the range of launchers which are (or could be in the future) economical enough to be considered for use in launching the satellites of remote sensing satellites constellations either singly or in pairs. CST experience gained in the brokering and managing of the launches of the DMC and RapidEye constellations will be employed and applied to the present day situation as well as to that which might exist in the future, 5 years from now.

Introduction

The task of replenishing artificial satellites actually arose when these satellites began to be used for applied missions of a long-term nature. When constellations of these satellites were deployed for various purposes, this task became a still more of an actual problem since the absence of even a single functioning satellite could disturb the running of a whole constellation.

Initially, this need to urgently replace a constellation's satellite which had either failed or had expired its lifetime arose mostly for military-relevant constellations since their operation was concerned with a threat to national security, especially during pre-war periods or, moreover, during war time. However, certain civil-purpose orbital systems which have been created during recent times raise the same problem. They are, for example, the Earth remote sensing (ERS) systems which are intended for natural or man-caused disaster monitoring.

These space systems are concerned with closely following the processes of a crisis and a disturbance of their operation due to an absence, even temporary, of one or a few of the satellites in their constellations would lead to undesirable consequences which would be no less important than for military-relevant space systems. Therefore, the need of quick replenishment is evident for these systems.

The current space systems of this type are based on small satellites, each of which has a mass of no more than one ton. These satellites are being deployed in low-Earth orbits (LEOs) due to the specifics of their operational function (Earth observation from space). These features provide an opportunity to launch the corresponding satellites either in clusters by using small class launch vehicles, or possibly as piggy-backs in the missions of heavier class launch vehicles with a significant saving of launch expenditures for each satellite.

Examples of these systems in which CST is engaged include the SSTL Disaster Monitoring Constellation (DMC) which has been deployed using Cosmos small launch vehicles and both piggy-back and cluster methods. (For additions to this system other launch solutions will have to be found as Cosmos stocks are now depleted.) Another example would be the RapidEye system of five satellites which is planned to be launched as a cluster by the Dnepr launch vehicle in 2007.

However, while such constellations can be deployed using launchers large enough for several satellites at a time, these methods are not suitable for the launch of a single small satellite at a time for the replenishment of these constellations. Those small class of launch vehicles, which are being used for the launches of these satellites in clusters are evidently too expensive for the injections of single satellites in dedicated launches while the long times that are required for the collection of a group of other satellites for a rideshare cluster launch or for the search of a suitable launch for a piggy-back injection could not meet the requirement of an in-time launch for the urgent replenishment of the constellation.

Fig. 1. The 'Falcon-1' U.S. launch vehicle during its first launch.

Therefore, solving this problem requires using that small class of launch vehicles which have payload capabilities near to the mass of the satellite to be launched (in order to reduce the launch price down to a minimum) and have the capability of quick response (in order to provide the in-time launch). Besides, the launch price of the required launch vehicle has to be as low as possible in comparison with its competitors.

The 'Quick response' term means that the time of the launch vehicle's pre-launch preparation after a request has not to exceed the time of the pre-launch preparation of the satellite to be launched. Besides, these requirements could be supplemented by the requirement to provide several launches for a few satellites consecutively during a short period of time for the case of a few of the constellation satellites failing in orbit almost simultaneously, or for some rapid augmentation of the system.

Actually, these requirements are the same as those for the 'Responsive Access' concept which is currently being discussed, assessed and even developed for realization. An assessment of this concept from the point of view of its preceding realization in the former Soviet Union (FSU) and of current Russian launch vehicles suitable for using the concept is discussed in /1/. (This presented some of the findings of a study that CST had undertaken earlier this year for the British National Space Centre (BNSC) which, as well as other studies investigating the concept of recoverable satellites for strategic constellations where the satellite cost predominates, was in turn stimulated by a study of the market for launchers allowing responsive access to space that CST had completed in December 2005 for NASA/DARPA /5/.)

The most likely choices

The world's inventory of small class launch vehicles which have payload capabilities of less than one ton is very limited. Taking into consideration that this type of launch vehicle from the so-called 'third space-world countries' (for example, the Israeli 'Shavit' or Japanese J1) are not generally or easily commercially available, the number of the launch vehicles to be examined for their suitability for constellation replenishment becomes still narrower. Actually, they are only U.S. and FSU launchers.

A selection of these launch vehicles by the criterion of corresponding payload capability (no more than one ton) gives the following results:

U.S. launchers:
Pegasus XL
Minotaur
Falcon-1

FSU launchers:
Start
Shtil

This short list is in need of certain corrections and supplements. First of all, the U.S. Minotaur has to be excluded from the list since it is not available for the launches of foreign satellites on a commercial basis due to a use of the Minuteman III missile's stage in its composition. Secondly, this list can be supplemented with those launch systems which are being currently developed and would be put into operation during nearest 2-3 years.

Actually, the 'Falcon-1' (Figure 1) is attributed to this last category since after one unsuccessful flight, it is not yet fully put into operation. Other U.S. advanced small launch vehicles and space transportation systems which are being developed for a realization of the 'responsive access' concept cannot yet be examined for their application to the discussed task– they either are intended for national military-relevant missions, or have a doubtful probability of realization.

A single FSU launch system which is currently in development and is suitable for the examined task is the air-launched 'Ishim' (Figure 2) which was ordered by Kazakhstan in Russia and is planned to be operational beginning from 2008 /2, 3/.

Fig. 2. A model of the 'Ishim' Kazakhstan launch system's MiG-31I carrier aircraft with the suspended launch vehicle.

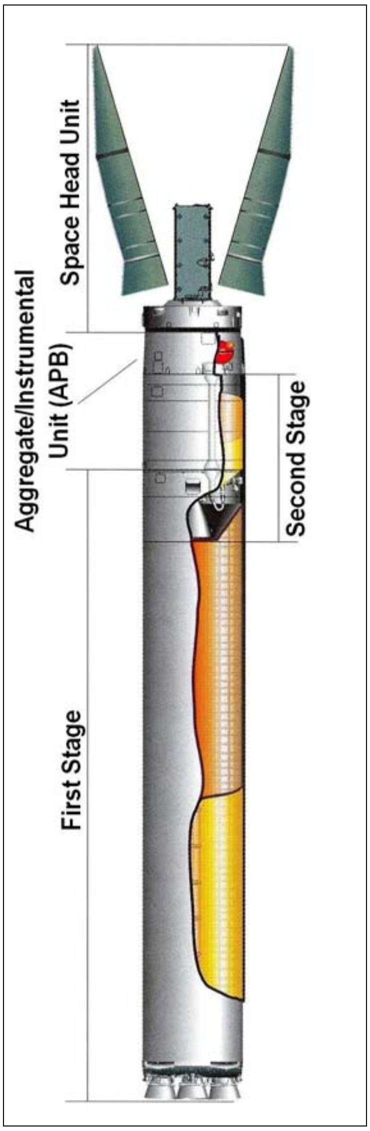

Fig. 3. The 'Strela' launch vehicle.

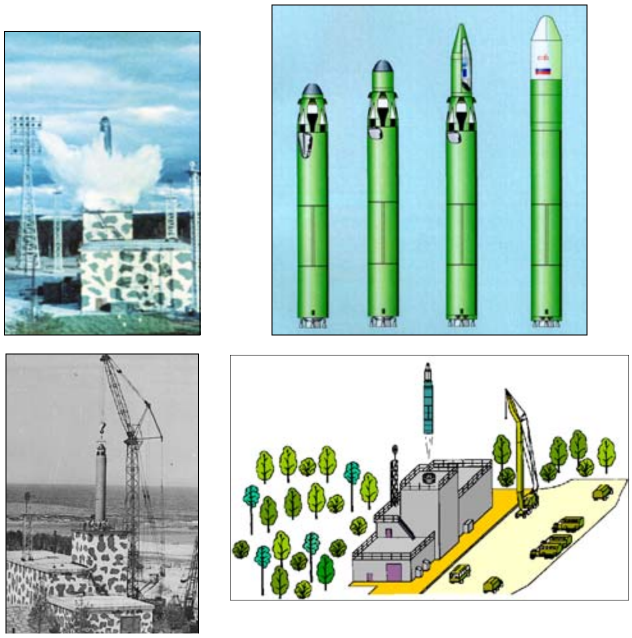

Fig. 4. Nenoksa test range - Ground-based launch complex in Nenoksa (NSK-37) and (top right) the 'Shtil' family of launch vehicles converted from the SS-N-23 (RSM-54) SLBM, from left to right: 'Shtil-1', 'Shtil-2.1', 'Shtil-2', 'Shtil-3'.

It is also possible to add the Russian 'Strela' small launch vehicle (Figure 3) which was converted from the SS-19 ICBM with minimum changes. Although the 'Strela' has a payload capability which is more than 1 ton, it would be suitable for the examined task since its announced modest launch price allows it to compete with launch vehicles of lower payload capability.

The modest price is a consequence of the FSU system of conversion – the basic ICBMs can be purchased from the Russian militaries at very low prices since these missiles are sold from the number of those for which the guaranteed lifetimes are near to expiration. The same consideration also applies to the sea-launched 'Shtil' launch vehicles (Figure 4) which are based, with minimum up-gradings, on the Russian RSM-54 SLBM and, partially, to the 'Start' launch vehicles (Figure 5) which are based on the 'Topol' ICBM. (In contrast with the U.S. converted launch vehicles, the Russian small launch vehicles which are converted from ballistic missiles with a use of their hardware do not have any limitations on their supply for foreign missions on a commercial basis). The list now becomes:

U.S. launchers:
Pegasus XL
Falcon-1
FSU launchers:
Start
Shtil
Strela
Ishim

Fig. 5. The Russian 'Start' (left) and 'Start-1' launch vehicles and the 'Topol' missile from which they are derived.

Cost, Availability and Utility

An assessment of the chosen launch vehicles by the criterion of cost, i.e. by a comparison of launch prices, can shorten the list. Of course, the necessity to replenish in-time a constellation which has to urgently perform a certain important mission would force the operators to spend additional monies. However, if this could be avoided by the use of another, cheaper launch vehicle, this will be done, especially if the launch price of the competing launcher is greatly less. The 'Pegasus XL' with its launch price at the level of at least US$ 14-15 mln. is significantly more expensive than the other chosen launch vehicles which all have launch prices of less than US$ 10 mln. For this reason, the 'Pegasus' will be declined for further assessment, although its use for urgent replenishment can not be excluded.

Another criterion that has to be considered is the capability to provide an urgent launch within a minimum time, after a request, at any time. This requirement implies that a certain stock of already manufactured launchers has to be stored in conditions which should enable their urgent pre-launch preparation including mating with the satellite to be launched. (For a simplification of the present assessment, it is assumed that the preceding mutual integration of the satellite with the launcher at the level of the mission planning, interface agreement, etc. has been completed beforehand, after which the launcher was chosen to be contracted for the probable replenishments of a certain space system's constellation.)

The assessed launch vehicles i.e. the U.S. 'Falcon-1', Russian 'Start', 'Strela' and 'Shtil' and the Kazakhstan 'Ishim' use all the known concepts of launch. Thus, the 'Falcon-1' is launched from a surface launch facility, the 'Strela' is silo-launched, the 'Start' uses a mobile land-based launch device, the 'Shtil' is launched from a submarine's launching tube and the 'Ishim' is an air-launch system. A use of the basic missiles' launch facilities (devices) by the FSU converted launch vehicles provides certain advantages in regard of an urgent launch on request but has certain shortcomings in other regards. Thus, for example, the silo-based 'Strela' can be prepared for a launch during a very short time, however, the next launch for the following replenishment of a few of these satellites can only be provided from the same silo after no less than two weeks. (Of course, multiple silos could be used.)

Also, a weak position in this regard belongs to the submarine-based 'Shtil', since its launches are at present bound to training cruises of Russian Navy's submarines and these launches are partially considered to be training launches of the basic SLBMs. This allows the significant saving of expenditures for launch provision but does not allow the necessary flexibility in the launch schedule. Due to this, the 'Shtil' in its current options, which are well described in /4/, cannot yet provide in-time launches for urgent constellation replenishment and has to be omitted for the moment from the list of the launch vehicles to be composed in this paper.

However, it should be noted that plans for the further development of the 'Shtil' family foresee the provision of launches from a surface launch site or from an especially allotted submarine. If these plans will be realized, the 'Shtil' will be significantly more suitable for the task of constellation replenishment and although its launch price will undoubtedly grow, it should still be competitive. Thus, the final list for comparison is

U.S. launchers:
Falcon-1

FSU launchers:
Start
Strela
Ishim

Comparative rating

The remaining four launch vehicles can be compared and rated using characteristics which reflect the above-mentioned criteria. The first of these criteria, payload capability, can be defined more precisely. As was shown in /5/, the optimum payload capability for a small launch vehicle to be used for the ‘launch-on-request’ of small satellites is 800 kg. The ‘Falcon-1’ corresponds to this value and the ‘Start-1’ almost corresponds as well, while the ‘Strela’ is somewhat oversized by this index. At the same time, the ‘Ishim’ has a maximum payload capability of 160 kg. This is significantly less than the defined optimum value but is suitable for a majority of the current small satellites which form the constellations to be replenished.

Launch price is another important parameter. Since this price for each launch system would be altered depending on the mass of payload to be launched even in dedicated launches, it is reasonable to compare the assessed launchers, not just by their unit launch price which is under 10 million US dollars (and possibly 3 million for Ishim), but by specific launch prices (i.e. the price per 1 kg) which can be calculated proceeding from the launcher’s maximum payload value.

The indices which are concerned with the capabilities to provide an urgent launch on request have to be compared for the assessed launchers as well as those which show the launchers’ capabilities to quickly provide the next launch for the replenishment of a few satellites in the case of necessity.

One more important index is the available range of orbit inclinations. This index is defined by the method of launch and it is bound closely with the capability of the launch vehicle to be launched from foreign territories. This capability is stipulated both by the provision of a broader range of orbit inclinations and by the requirement of the launch customer to shorten the time for the satellite pre-launch preparation by the elimination of the satellite delivery to a launch spot.

The results of the comparison of the chosen launch vehicles are summarized in Table 1.

Table 1

COMPARISON OF THE CHOSEN LAUNCH VEHICLES FOR THEIR PROBABLE USE FOR THE REPLENISHMENT OF SMALL SATELLITE CONSTELLATIONS

Requirement or parameter, feature	**Launch systems (ranking position by every the item)**				**Notes**
	‘Strela’	***‘Start-1’***	***‘Ishim’***	***‘Falcon-1’***	
1. Capability to provide an urgent launch on response	Within no more than 1 hour (1-2)	Within no more than 1 hour (1-2)	Within no more than 2-3 hours (3)	Within no more than 3-5 hours (4)	-
2. Capability to provide the launches from customers’ territories	Absent (4)	Provides with low expenditures (2)	Provides with minimum expenditures (1)	Can provide with certain expenditures* (3)	*In the case of a quickly-mounted launch facility use
3. Range of realized orbit inclinations	Fixed, defined by the launch silo location (4)	Broad (2)	Most broad (1)	Broad* (3)	*In the case of a quickly-mounted launch facility use
4. Capability to provide urgently a following launch (launches)	Low, within a week*, but alternative silos exist (2)	Very high, within a few of hours (1)	Sufficiently high, within a day (3-4)	Sufficiently high, within a day (3-4)	*Would be enhanced by the use of a few launch silos
5. Payload capability’s correspondence to optimum (most probable) value	Oversized by three times (3-4)	Corresponds (1-2)	Less by two times* (3-4)	Corresponds (1-2)	*Nevertheless, corresponds to the expected mass of a certain number of the satellites to be launched
6. Launch price, US$ millions	7-9*	7-9*	2.5-3*	6-8*	*Supposed value, not ranked
7. Readiness	Now (1-2)	Now (1-2)	2 years (3-4)	1 year (3-4)	
Total ranking position	***3***	***1***	***2***	***4***	-

Conclusions

As one can see, the currently operated Russian "Start-1' is a most suitable launch vehicle for a replenishment of small satellite constellations. However, it could be in serious competition with the U.S. 'Falcon-1' (for heavier small satellites) and the Kazakhstan-owned 'Ishim' (for the 100-kg category of satellites) if the developers of these launch vehicles could decrease their launch prices, as they are currently promising. This list of potential competitors could also contain the Russian 'Shtil' options once they are not bound with the necessity to be launched during the training cruises of the Russian Navy's submarines. Indeed, the final choice for constellation operators may be between 'Shtil' and 'Ishim'. We shall have to wait and see.

It is important to underline that the launches of small satellites for an urgent replenishment of constellations by the assessed method of dedicated launches will be significantly more expensive than launches by the cluster or piggy-back launch methods which are being mostly used for the deployment of these constellations. However, the task to maintain the full-scale operation of these constellations for an implementation of their important missions would justify the enhanced launch expenditures since the provision of in-time urgent replenishment can be carried out only by the method of dedicated launches.

As is shown above, the capability to realize these launches is currently in existence and it will be expanded in the nearest future. CST continues to be ready to provide interested customers with the necessary services to enable the arrangement of the required launches.

References

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