

# Launch Profiles Used by the Four-Stage Proton-K

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The four-stage Proton-K launch vehicle was first proposed for launching commercial satellites for western customers in the mid-1980s, but because of international politics the first commercial launch did not take place until 1996. This paper reviews the launches of the four-stage Proton-K, concentrating on the various in-orbit launch profiles which have been flown.

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## 1. Introduction

Nearly 35 years after its maiden flight in July 1965, the Proton launch vehicle is still the most powerful vehicle to be used operationally within the Soviet/CIS space programme. It was originally flown in the two-stage UR-500 "missile version" with a short second stage on four missions during 1965-1966, with one of the launches failing to reach orbit. The four-stage Proton-K was introduced in March 1967, carrying the Blok D fourth stage\*, while the first three-stage launch was in November 1968.

Russian literature refers to both the three- and four-stage variants of the vehicle as being the Proton-K (or UR-500K), and this is why for both *Worldwide Satellite Launches* and the derived "Satellite Digest" which appears in *Spaceflight* this writer introduced the designators "Proton-K (3)" and "Proton-K (4)" to differentiate between the two variants.

A detailed historical review of the Proton launch vehicle family has already been published recently [1], and therefore the details will not be repeated here. However, it will be noted that the first writer to show a reasonable reconstruction of the Proton launch vehicle was Piet Smolders [2], long before other western writers: one can only assume that Smolders has not previously received credit for being the first to show that the first stage included six "strap-ons" is because his work was not widely accessible in English. He did incorrectly show that there was a second stage central core on the vehi-

cle, but this was a mistake which many subsequent writers made (for example, see [3]).

In addition to looking at the Blok D and DM flights atop the Proton-K vehicle, the role of the Blok D within the L-3 manned lunar landing programme will be briefly reviewed.

## 2. Fourth Stages Used on the Proton-K

Two classes of fourth stages have flown atop the Proton-K: the Blok D for deep space missions and the Blok DM for Earth orbital missions. The Blok D took elements from the third stage of the GR-1 "global missile" and the Blok L fourth stage of the Molniya(-M) launch vehicle [4]. In a space role the Blok D was originally conceived as the fifth stage of the N-1/L-3 manned lunar launch vehicle, where the requirement was for the stage to be capable of multiple burns.

Table 1 provides a summary of the different Blok D and Blok DM stages which have flown over the years in the domestic space programme.

The designs of the Blok D and Blok DM families of stages had much in common with essentially the same propellant loads, tank diameters, etc. Table 2 provides a summary of the details which we have for these stages.

Before any details concerning the Blok D/DM were revealed in Soviet/Russian literature it had been possible to deduce some dry masses from publications by Valentin Glushko [5,6,7]. The origi-

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*This is an abridged version of the paper presented at the British Interplanetary Society's Soviet/CIS Symposium on June 5th, 1999.*

*\* It should be noted that the Russian spelling "Blok" is used here, rather than the Anglicised "Block".*

**TABLE 1:** Blok D and Blok DM Stages Used on the Proton-K.

| Version                               | Designator | Missions                                                                   |
|---------------------------------------|------------|----------------------------------------------------------------------------|
| Blok D Family - Deep Space Missions   |            |                                                                            |
| Blok D                                | 11S824     | Luna 15-24, Mars 2-7, Venera 9-10, Zond 4-8                                |
| Blok D-1                              | 11S824M    | Astron, Granat, VEGA 1-2, Venera 11-16                                     |
| Blok D-2                              | 11S824F    | Fobos 1-2, Mars 8 (aka Mars-96)                                            |
| Blok DM Family - Earth Orbit Missions |            |                                                                            |
| Blok DM                               | 11S86      | Geosynchronous orbit (1974-1990),                                          |
| Blok DM-2                             | 11S861     | GLONASS satellites, geosynchronous orbit (1986-date), Cosmos 1603 and 1656 |
| Blok DM-2M                            | 11S861-01  | Gals, Ekspress, Kupon, some Prognoz                                        |
| Blok DM-5                             | 17S40      | Cosmos 2344                                                                |

It should be noted that there was a period when both the Blok DM and the DM-2 were flying missions to geosynchronous orbit. The commercial fourth stages are discussed in section 7 of this paper.

nal versions of the Blok D had derived masses of about 1,800 kg while later versions were about 2,020 kg. In looking at the masses of the Blok D (and also the Blok DM) one has to be careful about what is being included. At launch the stage is encased in a hollow cylinder with a mass of ~800 kg, and there are two ullage motors (*SOZ - stabilizatsii i obespecheniya zagotovleniya*, stabilisation and launching provision) attached: these objects are noted further below.

The Blok D carries two main propellant tanks: a near-spherical (possibly an actual sphere) liquid oxygen tank and below that a toroidal kerosene tank. The original stage was powered by a single 11D58 engine designed within the Korolyov bureau, but later versions used an improved 11D58M engine.

The hollow cylinder which surrounds the fourth stage at launch is separated at about the time that the orbital injection burn takes place for Blok D missions and is discarded in orbit for Blok DM missions. It is not clear how the length of this shroud might vary with the length of the Blok D/DM, but for a standard Blok D it has a diameter of 3.7 metres and a length of 3.996 metres.

The ullage motors are used to provide a small forward acceleration to settle the propellant for the burns of the stage and are separated as the stage's main engine ignites for the final main burn.

There are differences in the mode of operating the Blok D and the Blok DM. The Blok D would receive its commands via the attached payload. In comparison, the Blok DM would generate its own

**TABLE 2:** Numerical Data for Blok D/DM Fourth Stages.

| Stage                 | Blok D        | Blok D        | Blok D        | Blok DM       |
|-----------------------|---------------|---------------|---------------|---------------|
| Source                | [8]           | [9]           | [10]          | [10]          |
| Fuel                  | Kerosene      | Kerosene      | Kerosene      | Kerosene*     |
| Oxidiser              | Liquid oxygen | Liquid oxygen | Liquid oxygen | Liquid oxygen |
| Length, metres        | 5.5           | 5.5           | 5.37          | 6.22          |
| Diameter, metres      | 3.7           | 3.7           | 3.70          | 3.70          |
| Dry mass, kg          | (1,800)       | (2,440)       | 2,000         | 2,140         |
| Total mass, kg        | 13,360**      | 17,300        | (17,000)      | (17,190)      |
| Propellant mass, kg   | 11,560**      | (14,860)      | 15,000        | 15,050***     |
| Fuel                  |               |               |               | 10,600        |
| Oxidiser              |               |               |               | 4,300         |
| Thrust, kN            | 85            | 85            | 85            | 85/88         |
| Specific impulse, sec | 346           | 350           | 352           | 352/361       |

Figures given in parentheses are not specifically quoted in the reference material.

\* Some versions used SYNTIN: for the thrust and specific impulse values the first is for kerosene and the second for SYNTIN.

\*\* These masses are at orbital injection: approximately 3,300 kg of propellant was used for the orbital injection manoeuvre.

\*\*\* As quoted in [10]: compared with the fuel and oxidiser masses, the total propellant mass is in error by 150 kg.

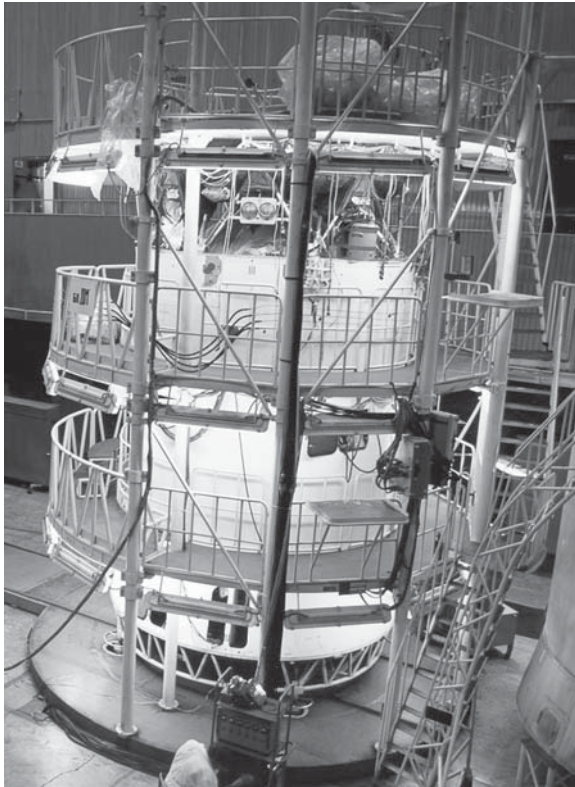


Fig. 1 Blok DM undergoing final assembly and testing at the RSC Energiya plant: the stage proper is hidden within the shroud, surrounded by access platforms.  
(Copyright, International Launch Services.)

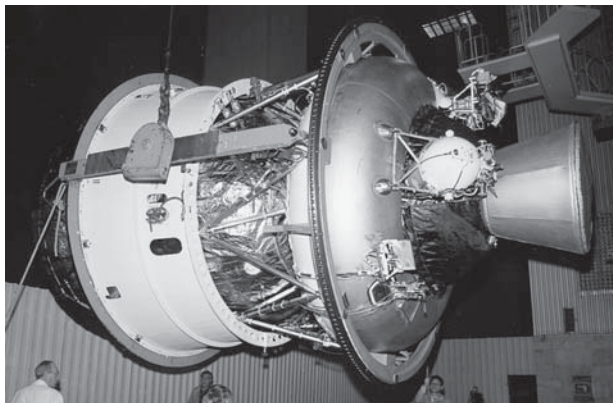


Fig. 2 A complete Blok DM stage before the cylindrical shroud which encases it at launch has been attached. The stage's control unit (not carried on Blok D flights) is in shadow on the top of the stage, seen at the left of this picture.  
(Copyright, International Launch Services.)

commands with the payload being passive until the time of separation from the fourth stage.

All launch profiles of the Proton-K launch vehicle with an added fourth stage have involved at least two planned burns of that fourth stage to place the payloads into their planned final orbits: on a few occasions three manoeuvres have been seen. Prior to western commercial satellites starting to fly on the vehicle the Proton-K would fly a few standard mission profiles (generally one profile for each class



Fig. 3 A collection of Blok DM stages in their cylindrical aerodynamic casings, awaiting shipment from the RSC Energiya production facilities to Baikonur. The control units of the stages extend above the surrounding shrouds.  
(Copyright, International Launch Services.)

of mission), but with the advent of the commercial launches the vehicle has shown itself to be more versatile than western observers had expected.

### 3. Original Blok D Mission Profiles

When considered as part of the N-1/L-3 manned lunar landing programme, the Blok D would have acted as a fifth stage or service module (the distinction between a rocket stage and a spacecraft's service module becomes blurred when considering manned lunar missions: was the Apollo Service Module a fourth stage of the Saturn-5 or part of the spacecraft?), performing the initial lunar orbit injection and the descent to the lunar surface.

At launch, the L-3 complex comprised the manned "Heavy Soyuz" LOK (mass 9,850 kg), the "lunar module" LK (mass ~5,500 kg), a shroud covering the LK (mass ~500 kg) and the Blok D (dry mass ~2,000 kg, propellant mass ~14,900 kg, two "ullage motors" SOZ at 120 kg each), having a total mass of nearly 33 tonnes. In this reconstruction the "Zond" variant of the Blok D is assumed (as detailed in Table 2 and derived from [8]) with a dry mass of 2,000 kg rather than 1,800 kg to allow for additional structure to carry a payload heavier than the Zond.

The Blok D would perform the initial lunar orbit injection (LOI) to a ~110 km circular orbit, reducing the mass to 24,575 kg (using "exact arithmetic"): a second LOI burn would reduce periselene to 16 km,

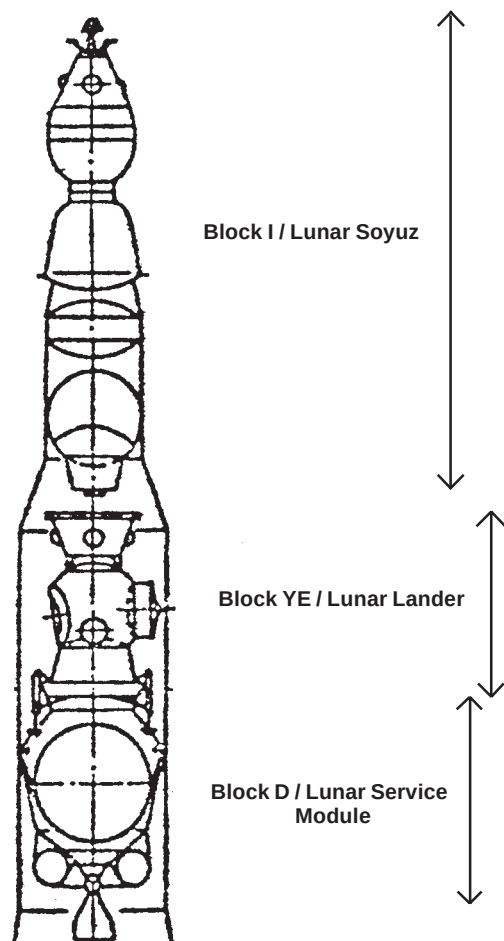


Fig. 4 A Russian sketch (from [11]) showing the L-3 manned lunar landing mission stack which would have carried the Blok D for lunar orbit injection and the lunar landing.

with the mass reducing to 24,395 kg. At this point a cosmonaut would transfer from the LOK to the LK via a hatch in the shroud surrounding the LK and the LOK and shroud would then separate. Close to periselene when at a velocity of 1,670 m/s the two ullage motors would briefly fire and be discarded just as the Blok D main engine ignites to essentially “kill” the orbital velocity and allow the combined Blok D/LK to drop towards the lunar surface. This would see the mass drop from 13,805 kg to 8,425 kg, leaving about 925 kg propellant in the Blok D for further burns during the descent. At an altitude of 1.5-2 km the LK would separate from the Blok D and perform a soft-landing on the Moon.

While the figures given above are approximate, they certainly show that the Blok D carried sufficient propellant for the lunar landing with a reasonable reserve for course corrections and additional manoeuvres during the descent to the lunar surface.

When the Proton-K vehicle started to fly with the Blok D as a fourth stage for the Zond (L-1) and third

generation Luna missions in 1967-1969 all western observers originally misunderstood the launch profile being used. It was thought that the three-stage Proton-K placed its own third stage into orbit which would then separate from the Blok D fourth stage/payload assembly, and that the Blok D would then perform a single manoeuvre to take the payload out of low Earth orbit (LEO) and place it onto a trans-lunar or trans-planetary trajectory (Astron and Granat remained in highly eccentric Earth orbits reaching out to 200,000 km, and they used the Blok D class stage rather than the DM because they used the standard Venera spacecraft “bus”).

In recent years Russian literature describing the launches of Zond and Luna missions [12,13] and the more recent Fobos and Mars 8 missions have shown that the above analysis is incorrect. In reality, all three stages of the Proton-K launcher are sub-orbital, with the Blok D performing a small burn to reach Earth orbit. As the stage prepares for its second burn two ullage motors are fired to settle the remaining propellant and as the main engine ignites these small motors are shut down and discarded in LEO. When the Blok D completes its burn both it and its payload are on either a trans-lunar, eccentric Earth orbit (apogee around 400,000 km after acceleration by the lunar gravitational field) or an escape trans-planetary trajectory.

It should be realised that the mass figures for the Blok D/L-1 assembly which are quoted in [8] relate to the time of Earth orbit injection, and thus exclude the propellant used for the Earth orbit injection burn. Assuming a fully-laden Blok D, the stage would be carrying 3,300 kg of propellant which would perform an injection burn of 550 m/s, and this is not included in the data quoted in [8].

The Fobos 1 and 2 missions in 1988 and Mars 8 in 1996 had slightly different launch profiles. In these instances the fully-fuelled spacecraft were heavier than the Proton-K/Blok D-2 combination and could accelerate to a trans-Mars trajectory. Therefore on these missions the launch profile called for the second Blok D-2 burn to leave the spacecraft in an eccentric Earth orbit (apogee ~130,500 km for Fobos 1): the spacecraft would then separate and use its own Fregat propulsion module to complete a small manoeuvre taking the spacecraft out towards Mars. This profile worked for the two Fobos missions but failed for the Mars 8 mission: a communications problem between the spacecraft and its Blok D-2 prevented the second ignition from taking place, although the on-board automatic sequencer ensured that the spacecraft separated from the Blok D-2 at

the planned time after launch and then performed its own small “trans-Mars” manoeuvre (which in reality simply raised apogee to around 1,500 km) using the Fregat module.

#### 4. Using the Blok DM to Reach Geosynchronous Orbit

The standard launch profile for payloads intended to reach geosynchronous orbit (GEO) was introduced with Russia’s first geosynchronous launch - Cosmos 637 in March 1974 - and it is still the standard for domestic GEO launches.

Since the payloads carried to GEO are far lighter than the normal planetary probe (typically ~2 tonnes compared with ~4.5-5.5 tonnes), the Proton-K launch vehicle can use its third stage for orbital injection, with the Blok DM being fully fuelled for its planned manoeuvres to GEO.

Table 3 presents the orbital data for a typical Russian launch to GEO: Raduga 31, launched in February 1994. After reaching orbit the Blok DM (DM-2 version in this instance) and its attached payload separate from the third stage soon after orbital injection. A hollow cylindrical casing which surrounds the Blok DM is discarded and the stage performs attitude control and thermal roll manoeuvres in preparation for its first main engine burn which comes at the first pass through the ascending node of the orbit (equator crossing from south to north), around an hour after launch.

TABLE 3: Orbital Data for Raduga 31 Launch.

| Object               | Incl<br>o | Period<br>min | Perigee<br>km | Apogee<br>km |
|----------------------|-----------|---------------|---------------|--------------|
| Raduga 31            | 1.51      | 1,471.77      | 36,450        | 36,514       |
| Proton-K third stage | 51.65     | 88.36         | 184           | 202          |
| Fourth stage casing  | 51.65     | 88.38         | 188           | 201          |
| Fourth stage (DM-2)  | 1.51      | 1,467.79      | 36,296        | 36,513       |
| Ullage motor (1)     | 47.38     | 646.56        | 277           | 36,504       |
| Ullage motor (2)     | 47.08     | 648.55        | 362           | 36,521       |

These orbital data are taken from [14].

Once the first burn has been completed the fourth stage/payload are put into a roll to even out heating during the ascent to geosynchronous altitude. The geosynchronous transfer orbit (GTO) is rarely tracked but the discarded SOZs are left in orbits with an inclination typically close to 47.5° which approximates the theoretical inclination that permits the minimum total velocity change when transferring from a 51.6° LEO to a ~1.5° GEO using a two-impulse manoeuvre. However, since the SOZs are discarded after the second Blok DM burn has

started, they are no longer in the original GTO, and it is probable that the GTO has an inclination close to 48.5-49° to minimise the total Blok DM velocity change.

The coast to apogee takes around five-and-a-half hours and at the first pass through the apogee alti-

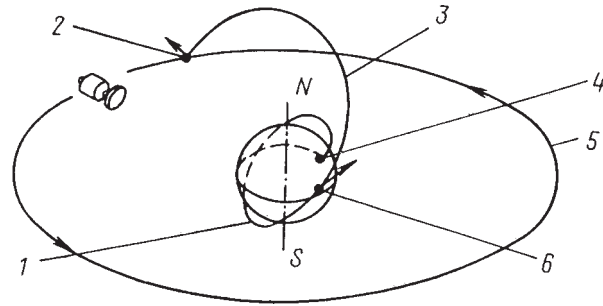


Fig. 5 A Russian illustration (from [15] with the events not numbered in chronological order) showing the standard launch profile used by the Proton-K/Blok DM to place a satellite into geosynchronous orbit.

Key (re-written for this paper): 1. Initial parking orbit, 2. Second ignition of the Blok DM and subsequent separation of the satellite, 3. Geosynchronous transfer orbit, 4. Launch from Baikonur, 5. Geosynchronous orbit, 6. First ignition of Blok DM.

tude (which is over a descending node of the orbit, passing north to south over the equator) the ullage motors briefly fire and are discarded just as the Blok DM main engine fires for a second time. This second manoeuvre reduced the orbital inclination to around 1.5° and circularises the orbit at around 36,000-36,500 km. After the second burn of the Blok DM the satellite performs a small separation manoeuvre, and then the fourth stage itself performs a separation manoeuvre to ensure that the two objects do not collide. Following the separation manoeuvre the Blok DM performs its final operations which include the venting of unused propellants. As a result, the Blok DM and the payload are always tracked in slightly different orbits.

When the Russians issued their first marketing literature for the four-stage Proton-K they noted that the vehicle would place its payload into an orbit with a period of  $1,436 \pm 20$  minutes [15]. Inexperienced western writers without any real knowledge of the Russian space programme outside the available marketing literature took this as the accuracy of orbital injection and thus claimed that the Proton-K was not a particularly accurate launcher. In reality this variation of orbital periods represents the standard range of geosynchronous drift orbit (GDO) periods used within the domestic programme. After the GDO injection, the satellite would drift around the GEO band, and when the required longitude was reached it would perform a small orbital “tweak”

to enter a “stationary” orbit with a period of 1,436 minutes.

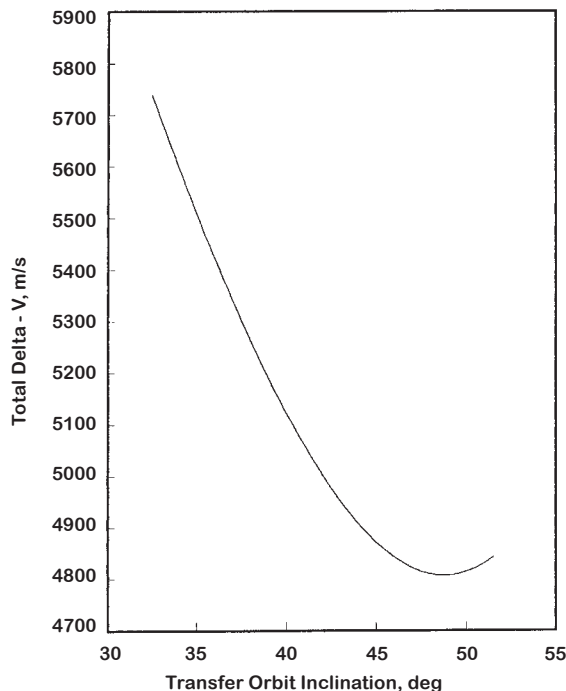


Fig. 6 This graph is a plot showing the total velocity required to transfer from an initial 51.6°, 185-220 km orbit to a 1.5°, 36,000 km circular geosynchronous drift orbit via a 215-36,000 km transfer orbit as a function of the transfer orbit inclination. It is assumed that two manoeuvres are performed, one at the perigee of the transfer orbit and one at the apogee. It is clear that there is a distinct minimum total velocity change, this coming when the orbital inclination is 48.8°. Typically Proton-K launches use a transfer orbit close to 47.5°, not quite the value for the minimum velocity change although the difference is small.  
(Copyright, Phillip S. Clark, 1999)

It was noted above that the GTO inclination is close to the one which gives the minimum total velocity change for the Blok DM, and this is brought out in fig. 6. Taking the initial parking orbit as 51.6°, 185-220 km, the GTO as 215-36,000 km and the GDO as 1.5°, 36,000 km circular, then the minimum velocity change comes when the GTO inclination is 48.81°: this gives the perigee burn as 2,497 m/s and the apogee burn as 2,307 m/s, a total change of 4,804 m/s.

Control of a satellite’s orbital inclination while operating in GEO is expensive in terms of propellant and until the introduction of the Gals and Ekspress satellites the Russians chose to use a “passive” control. The early Russian launches used inclinations close to 0.2°, but as the operational lifetimes increased, so did the initial orbital inclinations, and since the mid-1980s most satellites have had initial orbital inclinations close to

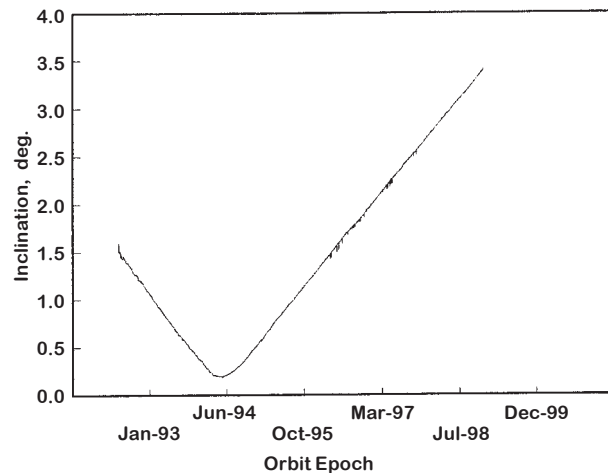


Fig. 7 As an example of the “passive inclination control” used on the majority of Russian geosynchronous orbit satellites, the data for Gorizont 26 is shown here from launch in mid-1992 through to the end of 1998. The satellite performed no inclination control manoeuvres, but the Russian choice of geosynchronous orbit injection parameters meant that natural perturbations to the orbit would reduce the inclination from an initial 1.5° to a minimum of less than 0.2° in May 1994, from which time the inclination has risen again.  
(Copyright, Phillip S. Clark, 1999.)

1.5°. This initial inclination is high by western standards, but the Russians choose the GEO parameters so that natural orbital perturbations due to primarily luni-solar effects would automatically reduce the inclination to about 0.2° over a few years, after which time the inclination would start to increase once more. After about 4-5 years the inclination would have returned to 1.5° and although it would continue to increase, the Russians expected that the satellite would have either failed on-station or been boosted into a retirement orbit before the inclination increased too far above this value.

## 5. Varying the Standard Launch Profile

Since the standard launch profile used by the Russians operates “like clockwork” with all major manoeuvres and orbital parameters fixed, the result is that the orbital injection is over  $91.6 \pm 1.25^\circ \text{E}$ . If a satellite is to be located east of the injection location then the GDO period will be less than 1,435.8 minutes (the Earth’s rotation period and thus the geostationary orbital period): for locations to the west of  $\sim 90^\circ \text{E}$  the orbital period is significantly in excess of 1,435.8 minutes.

Four Cosmos satellites (all part of the Prognoz early warning system) have used a slight modification of the standard launch technique: Cosmos 1940 (1988), Cosmos 2155 (1991), Cosmos 2209 (1992) and Cosmos 2345 (1997). On these four missions

the Blok DM2/satellite assembly remained in LEO for four additional circuits before the Blok DM-2 fired for the first time: the second burn took place as normal after half a circuit of the GTO. As a result the injection longitude for these flights was close to 0° E. This reduced the time required for the satellites to reach their planned operating location over 336° E.

Two things are interesting concerning this variation of launch profile. First, an additional circuit in LEO would have shifted the injection point by a further 22.5°, permitting injection over 337.5° E - far closer to the operational longitudes. Possibly the Russians did not take this approach since it would have permitted little time for trajectory measurements and refinements of the orbit between GDO injection and the satellites' planned longitude being reached ?

Secondly, other Russian payloads have been launched to longitudes similar to these Prognos satellites (eg, Raduga to 335° E, Luch/Cosmos to 346° E, Cosmos/Potok to 346.5° E and Gorizont to 349° E) and although these could have benefited from the same launch profile they have all used only the unmodified original profile with orbital injection close to 90° E.

## 6. Launches of Glonass and TSELINA-2 Satellites

The launch technique of Cosmos satellites in the GLONASS network have used a profile which parallels the standard launches to GEO. The original launches started at 51.6° and via an intermediate GTO the Blok DM-2 would perform two manoeuvres (one in low Earth orbit, one at the apogee of the GTO, the latter discarding the ullage motors) before deploying three Cosmos satellites into a near-circular 19,100 km orbit inclined at 64.8°.

This profile was used for the first six launches in the GLONASS programme. Starting with the launch of Cosmos 1778-1780 the parking orbit used an inclination of 64.8°, ensuring that all of the manoeuvres were co-planar (see Table 4).

A new launch profile was seen for the launches of two *Tselina-2* test payloads (in the guise of Cosmos 1603 and Cosmos 1656) in 1984-5. On each mission, after launch the usual two objects were tracked in a parking orbit (Proton-K third stage and the fourth stage casing). At the first pass through the descending node of the orbit the Blok DM-2 ignited for the first time, placing the assembly into a 51.6°, 190-835 km orbit. As the assem-

TABLE 4: Orbital Data for Two GLONASS Launches.

| Object                      | Incl<br>o | Period<br>min | Perigee<br>km | Apogee<br>km | AoP<br>o |
|-----------------------------|-----------|---------------|---------------|--------------|----------|
| 1 - Original Launch Profile |           |               |               |              |          |
| Cosmos 1593                 | 64.79     | 675.72        | 19,088        | 19,171       | 210      |
| Cosmos 1594                 | 64.75     | 677.22        | 19,138        | 19,197       | 175      |
| Cosmos 1595                 | 64.68     | 681.50        | 19,189        | 19,361       | 73       |
| Proton-K third stage        | 51.63     | 88.23         | 183           | 191          | 292      |
| Fourth stage casing         | 51.62     | 88.32         | 185           | 197          | 78       |
| Fourth stage (DM-2)         | 64.76     | 675.93        | 19,124        | 19,146       | 22       |
| Ullage motor (1)            | 52.11     | 340.21        | 386           | 19,146       | 0        |
| Ullage motor (2)            | 51.99     | 340.58        | 406           | 19,147       | 0        |
| 2 - Modified Launch Profile |           |               |               |              |          |
| Cosmos 2362                 | 64.83     | 675.57        | 19,115        | 19,137       | 210      |
| Cosmos 2363                 | 64.83     | 674.49        | 19,083        | 19,114       | 299      |
| Cosmos 2364                 | 64.75     | 675.54        | 19,118        | 19,132       | 93       |
| Proton-K third stage        | 64.85     | 87.45         | 138           | 159          | 284      |
| Fourth stage casing         | 64.84     | 87.57         | 142           | 167          | 343      |
| Fourth stage (DM-2)         | 64.81     | 674.77        | 19,084        | 19,127       | 288      |
| Ullage motor (1)            | 64.78     | 340.11        | 393           | 19,131       | 297      |
| Ullage motor (2)            | 64.85     | 340.15        | 392           | 19,134       | 297      |
| Debris (1)                  | 64.84     | 90.69         | 155           | 462          | 87       |
| Debris (2)                  | 64.68     | 89.51         | 148           | 352          | 67       |
| Debris (3)                  | 65.04     | 89.28         | 144           | 334          | 66       |
| Debris (4) *                | 64.8      | 89.4          | 142           | 341          | -        |

These orbital data are based upon the Two-Line Orbital Elements: the Cosmos 2362-2364 data are from *Worldwide Satellite Launches, 1998*.

\* Although this object (1998-077M) was catalogued by USSPACECOM, no Two-Line Orbital Elements were issued for it: the orbital data are from the Goddard Space Flight Center's Action Report.

TABLE 5: Orbital Data for Cosmos 1656 Launch.

| Object               | Incl<br>o | Period<br>min | Perigee<br>km | Apogee<br>km | AoP<br>o |
|----------------------|-----------|---------------|---------------|--------------|----------|
| Cosmos 1656          | 71.11     | 101.58        | 807           | 861          | 207      |
| Proton-K third stage | 51.62     | 88.37         | 188           | 200          | 155      |
| Fourth stage casing  | 51.60     | 88.45         | 185           | 211          | 131      |
| Fourth stage (DM-2)  | 71.11     | 101.57        | 806           | 860          | 209      |
| Ullage motor (1)     | 66.59     | 101.62        | 812           | 858          | 206      |
| Ullage motor (2)     | 66.58     | 101.39        | 791           | 858          | 217      |

These orbital data are derived from the Two-Line Orbital Elements.

bly passed through the ascending node the Blok DM-2 ignited for a second time, raising the orbit to 815-855 km, inclined at 66.6°. A third manoeuvre took place as the ullage motors fired and were separated, changing the orbit to 71°, 850 km. This manoeuvre took place over the northern Plesetsk cosmodrome, and as a non-equatorial orbital plane change it was extremely expensive in terms of propellant. This writer was one of the first to decipher the deployment profile of the satellite [16].

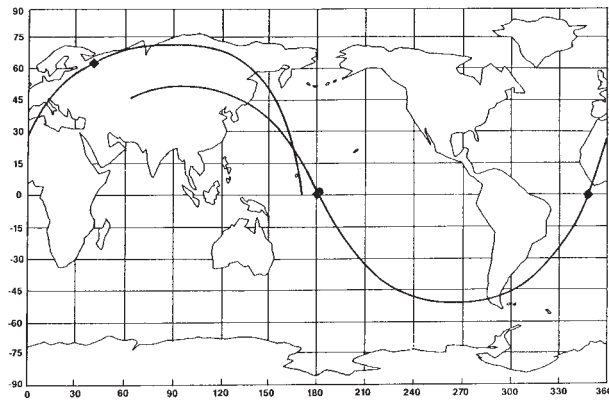


Fig. 8 Location of the three manoeuvres performed by Cosmos 1603 and the subsequent Cosmos 1656.  
(Reproduced from figure 37 of *The Soviet Year in Space*, 1984 with permission)

This launch profile was only seen on these two missions, with subsequent *Tselina-2* satellites being launched directly to 71°, 850 km orbits using the Zenit-2 launch vehicle. However, until recently this profile has been the only one to have seen a member of the Blok DM family perform three orbital manoeuvres.

## 7. Blok DM Variants for Commercial Launches

The Russians have indicated new designators for Blok DM stages which have been used to launch the commercial missions, and a new series of fourth stage designators was introduced by the Russians

[17]. The fourth stage was apparently being tailored for specific clients:

- (1) DM1 Lockheed Martin satellites (derived from the domestic DM-2 stage);
- (2) DM2 for the Motorola Iridium satellites;
- (3) DM3 for Hughes satellites (based upon the domestic Blok DM-2M);
- (4) DM4 for Space Systems/Loral satellites.

The fourth stage used by the domestic Cosmos 2344 photoreconnaissance satellite was described as a Blok DM-5, and this appears to be the DM2 but without the special Khrunichev-built Iridium multiple payload carrier/dispenser.

The Russians have indicated that the commercial fourth stages differ in the payload interfaces and also the flight control software. In addition the commercial Blok DM missions have not had any ullage motors tracked in an intermediate GTO: since the ullage motors are required to settle propellant just before the main engine ignites it is likely that they are simply not separated for commercial missions, possibly as a safety measure.

## 8. Commercial Launches to Geosynchronous Orbit

Table 6 provides a complete listing of the Proton-K flights which have been used for launches of western commercial satellites (through to the end of June 1999). The three launches of Iridium satellites are discussed in section 10 of this paper.

These commercial launches have introduced a new launch profile for the Proton-K with its Blok DM family of fourth stages. In most cases the first burn of the Blok DM variant is co-planar with the initial parking orbit at 51.6°. All of the first burns of the commercial fourth stages have taken place during the first pass through the ascending node of the LEO.

**TABLE 6:** List of Commercial Proton-K Launches.

| Launch Date | Satellite    | Mass kg | Manufacturer | Model    | Customer            |
|-------------|--------------|---------|--------------|----------|---------------------|
| 1996 Apr 8  | Astra 1F     | 3,010   | Hughes       | HS-601   | SES                 |
| Sep 6       | INMARSAT-3 2 | 1,144   | LM           | S-4000   | INMARSAT            |
| 1997 May 24 | Telstar 5    | 3,650   | SS/Loral     | FS-1300  | Loral Skynet        |
| Jun 18      | 7 x Iridium  | 7 x 657 | Motorola     | Iridium  | Iridium Inc         |
| Aug 27      | PAS 5        | 3,720   | Hughes       | HS-601HP | PanAmSat Corp       |
| Sep 14      | 7 x Iridium  | 7 x 667 | Motorola     | Iridium  | Iridium Inc         |
| Dec 2       | Astra 1G     | 3,300   | Hughes       | HS-601HP | SES                 |
| Dec 24      | AsiaSat 3    | 3,410   | Hughes       | HS-601HP | AsiaSat             |
| 1998 Apr 7  | 7 x Iridium  | 7 x 667 | Motorola     | Iridium  | Iridium Inc         |
| May 7       | EchoStar 4   | 3,478   | LM           | S-7000   | EchoStar Comms Corp |
| Aug 30      | Astra 2A     | 3,635   | Hughes       | HS-601HP | SES                 |
| Nov 4       | PAS 8        | 3,800   | SS/Loral     | FS-1300  | PanAmSat Corp       |
| 1999 Feb 15 | Telstar 6    | 3,763   | SS/Loral     | FS-1300  | Loral Skynet        |
| Mar 21      | AsiaSat 3S   | 3,465   | Hughes       | HS-601HP | AsiaSat             |
| May 19      | Nimiq 1      | 3,646   | LM           | A-2100AX | Telesat             |
| Jun 18      | Astra 1H     | 3,728   | Hughes       | HS-601HP | SES                 |

Lockheed Martin is abbreviated to LM: in their satellite models “S” stands for “Series”. SES is Société Européenne des Satellites.

Western commercial satellites tend to be heavier than the Russian payloads, and thus the fourth stage cannot reach the GDO - there simply is not the propellant to do so. Therefore, the orbits used on the commercial missions are a compromise.

The standard launch profile for commercial launches calls for the first burn of the fourth stage from the LEO of 51.6°, 185-220 km to the GTO at around 51.6°, 215-36,000 km to total 2,460 m/s. The second burn of the fourth stage is fixed in terms of total magnitude by the amount of remaining propellant and the mass of the satellite, but that orbital change can be split between changing the orbital plane and the perigee altitude.

Reference to Table 7 shows how the orbital incli-

nation and perigee for the fourth stage in the GDO have varied from one mission to the next. After the final fourth stage burn the satellite has to use its own propulsion system to reach geosynchronous altitude.

When Telstar 5 flew the standard commercial launch profile it was highlighted as being “unusual” [18], although it was essentially the same profile which had been used for Astra 1F more than a year earlier. Although the Astra 1F GTO of 51.6°, ~220-36,000 km had not been tracked by USSPACECOM, the use of this orbit has been confirmed by SES [19], and is in fact the standard one used for commercial Proton-K launches to GEO.

As an aside, when SES confirmed the Astra 1F

**TABLE 7:** Comparison of Actual and Theoretical Separation Orbits.

| Satellite  | Actual Incl ° | Actual Perigee km | Actual Satellite ΔV m/s | Modelled Incl ° | Modelled Perigee km | Modelled Satellite ΔV m/s |
|------------|---------------|-------------------|-------------------------|-----------------|---------------------|---------------------------|
| Astra 1F   | 6.95          | 11,966            | 750                     | 9.15            | 13,750              | 750                       |
| Telstar 5  | 17.60         | 6,459             | 1,240                   | 17.79           | 6,650               | 1,245                     |
| PAS 5      | 14.61         | 8,434             | 1,080                   | 14.76           | 8,500               | 1,085                     |
| Astra 1G   | 12.35         | 10,161            | 950                     | 12.43           | 10,200              | 960                       |
| EchoStar 4 | 15.44         | 8,197             | 1,120                   | 15.53           | 8,100               | 1,125                     |
| Astra 2A   | 15.62         | 7,799             | 1,125                   | 15.73           | 7,850               | 1,135                     |
| PAS 8      | 17.29         | 6,783             | 1,220                   | 17.47           | 6,850               | 1,230                     |
| Telstar 6  | 17.37         | 6,638             | 1,230                   | 17.71           | 6,750               | 1,240                     |
| AsiaSat 3S | 13.11         | 9,513             | 995                     | 13.20           | 9,550               | 1,005                     |
| Nimiq 1    | 16.48         | 7,015             | 1,195                   | 16.62           | 7,100               | 1,190                     |
| Astra 1H   | 16.37         | 7,341             | 1,175                   | 16.50           | 7,400               | 1,175                     |

**NOTE:** The “Actual” orbital data refer to the inclination and perigee of the separation orbit as tracked by USSPACECOM and reported in *Worldwide Satellite Launches, 1996-1997* [20], *Worldwide Satellite Launches, 1998* [21] and the monthly issues of *Worldwide Satellite Launches, 1999* [22]. The “Modelled” data are the results of searching for the theoretical minimum satellite velocity and extracting the corresponding pair of orbital inclination and perigee altitude for the separation orbit.

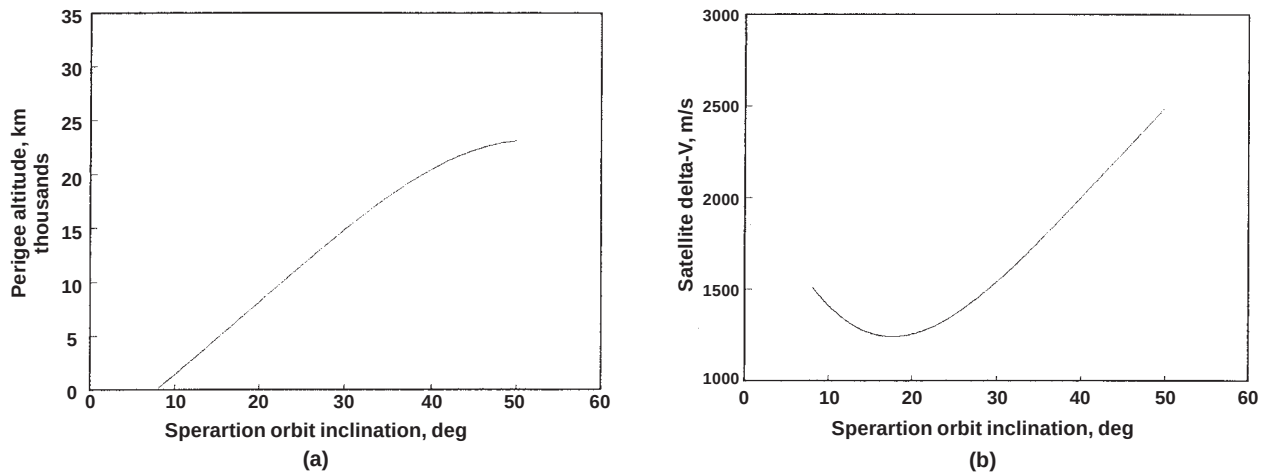


Fig. 9 These two graphs investigate properties of the orbit in which Telstar 5 separated from the Blok DM4 fourth stage. Since the initial transfer orbit is a standard one, the propellant mass of the fourth stage is fixed and the mass of the payload is fixed, the velocity change to the orbit where the fourth stage and payload separate is also fixed. Figure 9(a) shows how this fixed velocity results the separation orbit's perigee altitude is a function of the orbit's inclination. Given the range of inclinations (and thus perigee altitudes), Figure 9(b) shows how the velocity change required to reach a geosynchronous orbit varies with the separation orbit inclination. There is a clear minimum velocity at an inclination of  $\sim 17.5^\circ$  (corresponding perigee  $\sim 6,700$  km), and these were the values used for the Telstar 5 separation orbit as detailed in Table 7. (Copyright, Phillip S. Clark, 1999)

orbital data it was noted in their fax that “the Proton launch vehicle with the Blok DM has provided orbit accuracy better than any previous launch vehicle used by SES” [19].

The separation orbit parameters are carefully chosen for most missions. Depending upon the propellant available, at one extreme it is possible to change the orbital inclination to one close to  $0^\circ$  but have very little effect on the perigee altitude, at the other the orbital inclination is changed very little but the perigee could be raised to one approaching geosynchronous altitude. This is brought out in fig. 9(a) which shows the variation in perigee altitude as a function of orbital inclination for the values of the second Blok DM burns for the Telstar 5 launch.

Although fig. 9(a) itself does not reveal anything special about the combination of inclinations and perigees chosen for the Telstar 5 mission, a further plot showing the satellite velocity changes required to reach a GEO as a function of the separation orbit inclinations - see fig. 9(b) - clearly shows that the inclinations (and thus the corresponding perigee altitudes) were chosen to correspond with the minimum velocity changes required by the satellite.

For Telstar 5, the minimum satellite manoeuvre of 1,245 m/s corresponds to an inclination close to  $17.8^\circ$  and a perigee of  $\sim 6,650$  km which compare well with the actual figures in Table 8 of 1,240 m/s,  $17.6^\circ$  and 6,549 km respectively.

The launch profile described above has been used for most commercial Proton-K launches to GEO with the first exception being INMARSAT-3 2: with a launch mass of 1,144 kg, this satellite was light enough for the Proton-K to place directly into a GDO like Russian domestic payloads. Having said this, the GTO was at the “commercial”  $51.6^\circ$  rather than  $\sim 47.5^\circ$  seen in the domestic programme.

The launch of Nimiq 1 in May 1999 showed a variation in the commercial launch profile. After launch to a standard parking orbit, the Blok DM1 performed orbital plane changes with both burns, rather than just on the second burn. The first burn to place the stage and satellite into GTO shifted the inclination to  $48.55^\circ$ , thus mimicking the standard launch profile for domestic launches.

Table 7 compares the actual separation orbit inclination and perigee, as well as the satellite velocity change, together with the theoretical values which give the minimum satellite velocity change. It will be noted that apart from the light Astra 1F (INMARSAT-3 2 is excluded from this analysis), the actual and modelled data are in good agreement.

Of course, the launch mass of the satellite has a direct effect on the velocity change which can be performed by the fourth stage: whatever the stage's propellant mass, the total velocity change is fixed by the satellite's mass. Figures 10(a) and 10(b) show the masses of the commercial satellites launched to GEO by the Blok DM stages, together with straight line “least squares” plots.

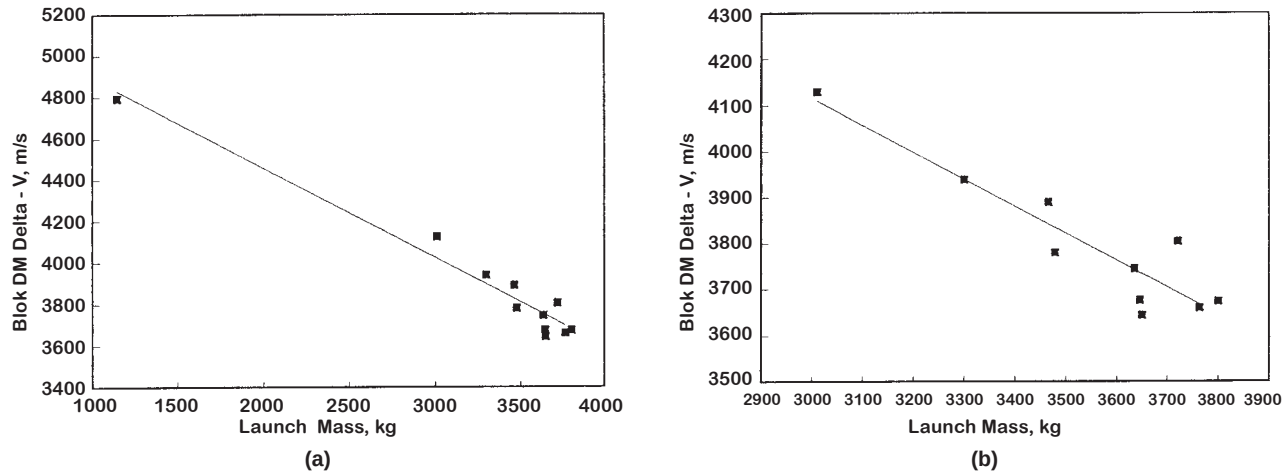


Fig. 10 Two graphs showing the total velocity change performed by a commercial Blok DM stage as a function of the satellite launch mass, with "least squares" trend lines shown for each graph. Included in (a) INMARSAT-3 2 (top left of the graph) must be considered anomalous because the mass was 50% or less of the maximum mass which the four-stage Proton-K can place into geosynchronous orbit. The satellite is therefore omitted in (b), which shows the variation in data about the least squares trend. (Copyright, Phillip S. Clark, 1999)

When all of the satellites are considered - Fig. 10(a) - the least squares relationship has a correlation coefficient of 0.98, but this includes INMARSAT-3 2 which had a launch mass some 45-50% below the typical mass of a Russian domestic payload launched to GEO: therefore on this mission the Blok DM1 need only be carrying a partial propellant load.

Excluding INMARSAT-2 3 from the analysis - fig. 10(b) - the correlation coefficient is not quite as good, 0.92 and the scale of this plot shows that there is some spread about the least squares line, probably suggesting that for some missions the full propellant load was not carried on all of these launches either.

Following launch aboard a four-stage Proton-K, the satellite requires a smaller velocity change to

reach a GDO than if it had been launched by a western launch vehicle. This is something which is brought out in Table 8.

Table 8 shows the GTOs and the GEOs for payloads in the same series as those listed in Table 6, but for launches on western vehicles - primarily Ariane-4 variants and the Atlas-2A(S) vehicles. Both of these vehicles - and also the Delta-2 (7925 variant) - use a different launch technique compared with Proton-K. The Russian vehicle has a fourth stage which manoeuvres out of GTO and for domestic launches will place payloads into a GDO, following which the payload only has to perform small manoeuvres. The western (and also Chinese) launch vehicles will only place the payloads into GTO and then the satellite itself has to manoeuvre to a GEO. This means a significant increase in the satellite mass to carry the propellant for the major apogee burn.

TABLE 8: Western Launches of Selected Commercial Payloads.

| Satellite    | Launch Vehicle | Launch Mass kg | Transfer Orbit |            |           | Satellite $\Delta V$ m/s | Geosynchronous Orbit |            |           |
|--------------|----------------|----------------|----------------|------------|-----------|--------------------------|----------------------|------------|-----------|
|              |                |                | Incl o         | Perigee km | Apogee km |                          | Incl o               | Perigee km | Apogee km |
| Astra 1E     | Ariane-42L     | 3,010          | 4.14           | 502        | 35,844    | 1,450                    | 0.10                 | 35,705     | 35,879    |
| PAS 3R       | Ariane-44L     | 2,918          | 6.92           | 256        | 36,959    | 1,410                    | 0.03                 | 35,666     | 35,886    |
| INMARSAT-3 1 | Atlas-2A       | 2,064          | 21.85          | 1,019      | 35,577    | 1,600                    | 2.67                 | 35,758     | 35,811    |
| INMARSAT-3 4 | Ariane-44L     | 1,999          | 7.02           | 207        | 35,795    | 1,500                    | 0.27                 | 35,770     | 35,806    |
| Telstar 401  | Atlas-2AS      | 3,375          | 23.87          | 190        | 35,800    | 1,738                    | 0.05                 | 35,784     | 35,791    |
| Telstar 402R | Ariane-42R     | 3,410          | 7.10           | 259        | 36,546    | 1,436                    | 0.20                 | 35,754     | 35,830    |
| Thor 2       | Delta-2 (7925) | 1,467          | 19.72          | 1,314      | 36,471    | 1,536                    | 0.05                 | 35,781     | 35,794    |

Where possible representative US and Ariane launches have been chosen for satellites owned by the same first four companies which have used the Proton-K vehicle. Astra and PAS have only used Ariane launches: Thor 2 is chosen to represent the Delta-2 launch vehicle since no company has yet used both Proton-K and a Delta-2. Orbital data are from appropriate issues of *Worldwide Satellite Launches*: delta-V ( $\Delta V$ ) (manoeuvres) are calculated based upon an "instantaneous" orbit change over the equator, and thus might be slightly in error, but the same method has been used to calculate manoeuvres for the Proton-K launches.

Since Ariane launches are from the near-equatorial launch site of Kourou the GTO inclination is 7° or less (lower inclinations require a dog-leg manoeuvre during the ascent to orbit) - and changing inclination is an expensive manoeuvre: US launches from Cape Canaveral start with a minimum inclination of 28.5°, although in-flight dog-leg manoeuvres and/or in-orbit plane changes can reduce the GTO inclination to some extent. Table 8 shows that for an Ariane launch one can expect that the satellite will have to perform an apogee burn of around 1,400-1,450 m/s, while for US launches (depending upon the GTO inclination) the corresponding burn is 1,600 m/s or more.

A comparison with Table 7 shows that launching via Proton-K involves the satellite performing a velocity change of 1,230 m/s or less. Indeed, in the case of the INMARSAT-3 2 launch the satellite was so light that Proton-K was able to place the satellite virtually into a GDO, just as it does with domestic launches (although the GTO was at 51.6°, unlike domestic launches).

The advantage that launching with the Proton-K vehicle brings is that a smaller apogee burn is required for injection into a GDO, and this can translate to a lower launch mass of the satellite. If the satellite has a unified propellant system (using the same propellant for both the apogee burn and for in-orbit station-keeping and other manoeuvres), then by launching with a full propellant load - or even with more "spare" propellant than a western launcher would permit - will allow more station-keeping manoeuvres to be conducted and thus extends the useful life of a satellite on-station.

## 9. Using Super-Synchronous Orbits

As of June 1999 the Proton-K has not used super-synchronous orbits for launching payloads to geosynchronous altitudes. The use of super-synchronous orbits calls for the launch vehicle to "overperform" in that the payload is launched into a GTO which has apogee in excess of the geosynchronous altitude. The reason to use these orbits is that the magnitude of the orbital plane change manoeuvre is proportional to the velocity at the time of the manoeuvre, a lower velocity means a decrease in the plane change manoeuvre - and the way to reduce the orbital velocity is to manoeuvre at a higher altitude.

Some Chinese and western launches have used the super-synchronous launch technique, although

normally the GTO apogee is within the range 40,000-45,000 km. The most extreme super-synchronous launch which has taken place to date is that of Orion 1 in 1994 aboard an Atlas-2A, with a mass of 2,340 kg, Orion 1 was much lighter than the maximum payload limit of the Atlas-2A to GTO, and thus advantage was taken of this by using a super-synchronous transfer orbit of 25.5°, 402-120,000 km. After separating from the Centaur second stage, Orion 1 then manoeuvred into GEO. The velocity changes performed by the satellite amounted to about 1,515 m/s: if the Atlas-2A had used a standard 25.5°, 400-36,000 km GTO then the satellite would have had to perform manoeuvres totalling around 1,760 m/s to reach GEO.

Although the Proton-K has not used a super-synchronous launch profile yet, there is no reason why it cannot. Of course there are many possibilities in terms of trade-off with the payload mass and its effect on the manoeuvres which can be performed by the Proton-K fourth stage and then the remaining manoeuvres to be performed by the satellite itself.

Using the figures previously noted, domestic launches (using a plane change at each of the two fourth stage burns) have a velocity requirement of 4,815 m/s (2,545 + 2,270 m/s), and this translates into a maximum payload mass of around 2.5 tonnes. A possible Proton-K launch would start with a super-synchronous transfer inclination of 51.6° and perform a single plane change at the first apogee burn of the fourth stage (second burn of the stage), raising perigee to geosynchronous altitude: when passing through this altitude the fourth stage would perform a further burn to circularise the orbit at geosynchronous altitude. Thus a Blok DM (variant) stage could directly inject a payload into a GDO using a super-synchronous orbit and three burns of the rocket stage: the satellite would only need to perform minor manoeuvres to reach its operational orbital location.

Figure 11 shows a plot, illustrating the total Blok DM manoeuvre requirement for super-synchronous apogee altitudes within the range 40,000-200,000 km, and the requirement drops from an initial 4,800 m/s to about 4,600 m/s - the latter figure being around 200 m/s less than the standard domestic launch requires. This could be translated into a heavier satellite with more station-keeping propellant than could be launched using other techniques.

## 10. Launching Iridium Satellites

On June 6, 1997 the launch of Cosmos 2344 - a new

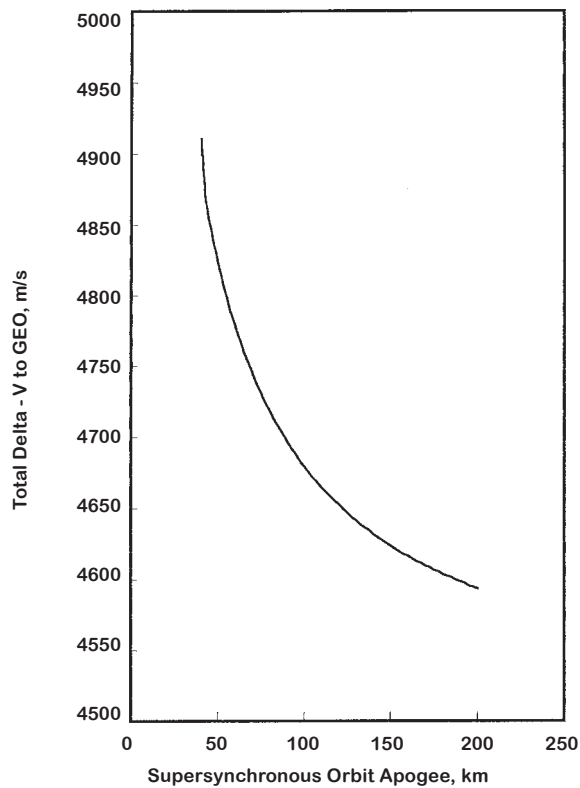


Fig. 11 Graph showing the total velocity change to reach geosynchronous orbit when a super-synchronous transfer orbit (with apogees of 40,000-200,000 km) is used. Although the four-stage Proton-K has yet to use this flight profile, if used it would permit a saving of up to 200 m/s which would permit heavier satellites to be placed into geosynchronous orbit. (Copyright, Phillip S. Clark, 1999)

class of optical reconnaissance platform - is reported to have introduced the new Blok DM-5 fourth stage to the Proton-K. This launch involved a new launch profile. Starting off in a 64.8°, 140-170 km parking orbit, the Blok DM-5 manoeuvred first to a 64.5°, 200-2,490 km transfer orbit and then to a 63.4°, 1,510-2,745 km orbit where the satellite separated. This orbit had never been used before.

The first commercial launch of a group of Iridium satellites using a Proton-K vehicle came on June

18, 1997: while the United States Delta-2 (7920) launch vehicle could only carry 5 Iridium satellites on each mission, the greater lifting power of the Proton-K with a Blok DM2 fourth stage allows for seven satellites to be carried at once. As previously noted, a modification of the Blok DM-5 fourth stage was used for the Iridium launches.

The first of the three contracted launches of Iridium satellites aboard a Proton-K (orbital data are given in Table 9) used another new launch profile. After launch into LEO at an inclination of approximately 73°, the Proton-K third stage and fourth stage shroud were separated and decayed from orbit before being catalogued (most probably the non-cataloguing of these pieces on the first launch was because USSPACECOM was not ready to follow the new profile). The first Blok DM2 burn placed the stage and its satellites into a transfer orbit reaching out to ~516 km (planned apogee) and the second burn circularised the orbit at this altitude but shifted the orbital inclination to approximately 86.4°: it was into this orbit that the seven Iridium satellites were deployed.

Once the satellite deployment was done the Blok DM2 performed a third manoeuvre to de-orbit itself. This ensured that the Iridium orbital regime will not become cluttered with discarded rocket stages. When Iridium launches use the Delta-2 (7920) vehicle the Delta-2 second stage performs a post-deployment burn to take it out of the Iridium orbital regime, and the Chinese-launched Smart Dispenser (carried on the CZ-2C as a third stage when launching pairs of Iridium satellites) performs a manoeuvre to reduce perigee, thus bringing the stage down from the deployment orbit.

Since the Proton-K third and fourth stages and the fourth stage shroud are not in orbit for long, they have not always been tracked by

TABLE 9: Orbital Data for Iridium Satellite Launches Using the Proton-K.

| Launch Date | Parking Orbit<br>(Third Stage and<br>Fourth Stage Casing) |         |        | Transfer Orbit<br>(Blok DM2 Fourth Stage) |         |        | Separation Orbit<br>(Blok DM2 Fourth Stage) |         |        | Satellite  | Deployment Orbit<br>(Satellite) |         |        |
|-------------|-----------------------------------------------------------|---------|--------|-------------------------------------------|---------|--------|---------------------------------------------|---------|--------|------------|---------------------------------|---------|--------|
|             | Incl                                                      | Perigee | Apogee | Incl                                      | Perigee | Apogee | Incl                                        | Perigee | Apogee |            | Incl                            | Perigee | Apogee |
|             | o                                                         | km      | km     | o                                         | km      | km     | o                                           | km      | km     |            | o                               | km      | km     |
| 1997 Jun 18 | ~72.6                                                     | ~170    | ~170   | ~72.6                                     | ~170    | ~516   | ~86.4                                       | ~516    | ~516   | Iridium 14 | 86.35                           | 501     | 523    |
| 1997 Sep 14 | 72.58                                                     | 124     | 143    | ~72.6                                     | ~170    | ~516   | ~86.6                                       | ~516    | ~516   | Iridium 29 | 86.63                           | 505     | 523    |
| 1998 Apr 7  | ~72.6                                                     | ~170    | ~170   | ~72.6                                     | ~170    | ~516   | ~86.4                                       | ~516    | ~516   | Iridium 62 | 86.66                           | 500     | 522    |

These orbital data are taken from entries in [20] and [21]. Actual orbital data are shown from the first satellite in each cluster (which are identified using the numbers assigned by USSPACECOM when they were launched) and the parking orbit for the second cluster of satellites: all other orbital data are estimated. The three clusters carried the following satellites (in the order of International Designator): Iridium 14, 12, 10, 9, 13, 16 and 11 (June 1997), Iridium 29, 32, 33, 27, 28, 30 and 31 (September 1997) and Iridium 62, 63, 64, 65, 66, 67 and 68 (April 1998).

USSPACECOM. None of the three was catalogued on the first Proton-K launch of Iridium satellites. On the second launch only the third stage was tracked and on the third launch none of the three was tracked.

Something which has not been widely described is that the Iridium satellites have come in three versions [23]:-

- (1) Version 1 - mass 657 kg: light battery packs, full propellant load;
- (2) Version 2 - mass 667 kg: heavy battery packs, full propellant load;
- (3) Version 3 - mass 662 kg: heavy battery pack, propellant mass reduced by 5 kg.

The first cluster of Iridium satellites to be launched aboard the Proton-K used the first version of Iridium satellites while the second and third clusters to fly on the Proton-K used the second version. It will be noted from Table 9 that the first Proton-K launch placed the satellites into orbits with inclinations close to  $86.4^\circ$  which is the inclination used for the operational satellites (although the operational altitude is 775-780 km) - the same inclination had been used for the first two Iridium launches using the Delta-2 (7920) vehicle. Starting with the launches of the fourth (aboard a Delta-2) and fifth (aboard Proton-K) clusters, launches would be made into deployment orbits at  $\sim 86.6^\circ$ : it seems likely that this was extra "insurance" that the Iridium deployment orbit would not become congested if some launches failed.

## 11. Using Proton-K to Reach Sun-synchronous Orbits

In the future, a modification of the Iridium launch profile could be used by the Proton-K for launching payloads to Sun-synchronous orbits. Although a detailed launch profile has not been published for such launches, based upon the Iridium profile a Proton-K could place a fully-fuelled Blok DM (class) fourth stage and payloads into a  $73^\circ$  LEO. The fourth stage would perform one burn (presumably over the equator) to a (co-planar ?) orbit with an apogee at the planned altitude and when passing through that apogee (over the equator) a second burn could circularise that orbit, at the same time performing an orbital plane change to  $97-99^\circ$ . The Russians have suggested launches to  $97^\circ/400$  km,  $98^\circ/600$  km and  $99^\circ/900$  km orbits (in truly Sun-synchronous orbits the altitude is a function of the inclination), and this suggests payload

masses of 2.5 tonnes or more.

## 12. Fourth Stage Flight Records

Although this paper is concerned with the operations of the fourth stages flown on the Proton-K missions, as an aside the launch record of the original two-stage UR-500 missile version and the three-stage Proton-K will be included here. Table 10 provides a year-by-year summary of the launches of each launch vehicle and fourth stage variant.

The period 1967-1969 for the Proton-K/Blok D combinations is perhaps the worst that any launch vehicle worldwide has experienced. In this period there were 18 launches: of these 8 were failures of the three stages of the Proton-K and 4 were failures of the Blok D either before reaching parking orbit or when trying to leave parking orbit - resulting in only 6 successful launches (Cosmos 146 in 1967, Zonds 4-6 in 1968 and Luna 15 and Zond 7 in 1969).

Table 11 provides a summary of the launch record of the UR-500 and Proton-K vehicles, the latter with and without a fourth stage. Failures in the Table are split between those involving the three stages of the Proton-K and those of the fourth stages.

Omissions from this listing are:-

- (1) In early 1967 a Proton-K/Blok D vehicle was tested on the pad prior to the Cosmos 146 launch: this appears to have been a facilities test vehicle rather than a flight vehicle;
- (2) In July 1968 the launch of the Proton-K/Blok D was scrapped after the Blok D exploded before launch;
- (3) The launch failure of a dual Cosmos mission aboard a Proton-K has been rumoured for early 1979 (dates in January and April are reported), but this seems to be some kind of duplication of the failure in August 1977 of a dual Cosmos mission.

When considering the number of Proton-K launches (with or without a fourth stage) during the late-1970s through to the early-1990s it should be remembered that in "American terms" this was equivalent to launching ten or more Saturn-1B vehicles a year.

Table 11 carries two sets of data for the three-stage Proton-K: where the lower three stages of a launch with a fourth stage successfully flew then this is considered to be a Proton-K success, while a failure of one of these lower stages on a four-stage launch is considered to be a Proton-K failure. Using

**TABLE 10:** Annual Launch Record of the Proton Launch Vehicle.

| Version    | 1965 | 1966 | 1967 | 1968 | 1969 | Total |
|------------|------|------|------|------|------|-------|
| UR-500     | 2    | 2    |      |      |      | 4     |
| Proton-K/D |      |      | 4    | 4    | 10   | 18    |
| Proton-K   |      |      |      | 1    |      | 1     |
| Total      | 2    | 2    | 4    | 5    | 10   | 23    |

| Version      | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | Total |
|--------------|------|------|------|------|------|------|------|------|------|------|-------|
| Proton-K/D   | 5    | 5    | 1    | 5    | 2    | 3    | 1    |      |      |      | 22    |
| Proton-K     | 1    | 1    | 1    | 2    | 2    | 2    | 2    | 3    | 1    | 1    | 14    |
| Proton-K/DM  |      |      |      |      | 2    | 2    | 2    | 2    | 5    | 5    | 18    |
| Proton-K/D-1 |      |      |      |      |      |      |      |      | 2    |      | 2     |
| Total        | 6    | 6    | 2    | 7    | 6    | 5    | 5    | 5    | 8    | 6    | 56    |

| Version       | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | Total |
|---------------|------|------|------|------|------|------|------|------|------|------|-------|
| Proton-K      |      | 1    | 1    | 1    |      | 1    | 2    | 2    |      | 1    | 9     |
| Proton-K/DM   | 5    | 4    | 8    | 6    | 8    | 5    | 6    | 3    | 1    |      | 46    |
| Proton-K/D-1  |      | 2    |      | 3    | 2    |      |      |      |      | 1    | 8     |
| Proton-K/DM-2 |      |      | 1    | 2    | 3    | 4    | 1    | 8    | 10   | 9    | 38    |
| Proton-K/D-2  |      |      |      |      |      |      |      |      | 2    |      | 2     |
| Total         | 5    | 7    | 10   | 12   | 13   | 10   | 9    | 13   | 13   | 11   | 103   |

| Version        | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | Total |
|----------------|------|------|------|------|------|------|------|------|------|------|-------|
| Proton-K       | 1    | 1    |      |      |      | 1    | 1    |      | 1    |      | 5     |
| Proton-K/DM-2  | 10   | 8    | 8    | 6    | 11   | 6    | 3    | 1    | 1    | 1    | 55    |
| Proton-K/D-2   |      |      |      |      | 1    |      |      |      |      |      | 1     |
| Proton-K/DM-2M |      |      |      |      | 2    |      | 1    | 1    | 1    |      | 5     |
| Proton-K/DM3   |      |      |      |      |      |      | 1    | 3    | 1    | 2    | 7     |
| Proton-K/DM1   |      |      |      |      |      |      | 1    |      | 1    | 1    | 3     |
| Proton-K/DM4   |      |      |      |      |      |      |      | 1    | 1    | 1    | 3     |
| Proton-K/DM-5  |      |      |      |      |      |      |      | 1    |      |      | 1     |
| Proton-K/DM2   |      |      |      |      |      |      |      | 2    | 1    |      | 3     |
| Total          | 11   | 9    | 8    | 6    | 13   | 7    | 8    | 9    | 7    | 5    | 81    |

This table simply lists the number of launches of each Proton variant in each year, irrespective of the number failures: the versions are listed in the order of their first flights. One launch in August 1970 was intended as a sub-orbital test of the Proton-K, but was a failure. Figures are correct through to Astra 1H, launched in June 1999.

**TABLE 11:** Proton-K Launch Record.

| Version                                                         | Launches | Proton-K Failures | Stage 4 Failures | Successes | Success Rate, % |
|-----------------------------------------------------------------|----------|-------------------|------------------|-----------|-----------------|
| <i>Two-Stage UR-500 (missile variant)</i>                       |          |                   |                  |           |                 |
| UR-500                                                          | 4        | 1                 | 3                |           | 75              |
| <i>Three-Stage Proton-K</i>                                     |          |                   |                  |           |                 |
| Proton-K                                                        | 29       | 4                 |                  | 25        | 86              |
| Proton-K *                                                      | 261      | 21                |                  | 240       | 92              |
| <i>Proton-K/Blok D Family (deep space launches)</i>             |          |                   |                  |           |                 |
| Proton-K/D                                                      | 40       | 9                 | 5                | 26        | 84              |
| Proton-K/D-1                                                    | 10       | -                 | -                | 10        | 100             |
| Proton-K/D-2                                                    | 3        | -                 | -                | 3         | 100             |
| Overall                                                         | 53       | 9                 | 5                | 39        | 89              |
| <i>Proton-K/Blok DM Family (Earth orbit launches, domestic)</i> |          |                   |                  |           |                 |
| Proton-K/DM                                                     | 64       | 5                 | 1                | 58        | 98              |
| Proton-K/DM-2                                                   | 93       | 3                 | 4                | 86        | 96              |
| Proton-K/DM-2M                                                  | 5        | -                 | -                | 5         | 100             |
| Proton-K/DM-5                                                   | 1        | -                 | -                | 1         | 100             |
| Overall                                                         | 163      | 8                 | 5                | 150       | 97              |
| <i>Commercial Proton-K/DM Family (Earth orbit launches)</i>     |          |                   |                  |           |                 |
| Proton-K/DM1                                                    | 3        | -                 | -                | 3         | 100             |
| Proton-K/DM2                                                    | 3        | -                 | -                | 3         | 100             |
| Proton-K/DM3                                                    | 7        | -                 | 1                | 6         | 86              |
| Proton-K/DM4                                                    | 3        | -                 | -                | 3         | 100             |
| Overall                                                         | 16       | -                 | 1                | 15        | 94              |
| All Blok DM                                                     | 179      | 8                 | 6                | 165       | 96              |

\* The second set of data for three-stage Proton-K launches includes flights of the four-stage vehicle, classifying a three-stage success as a successful launch of the first three stages. For the four-stage variants the percentage success rate is for the fourth stage only, and therefore excludes failures of the first three stage. These figures are correct through to Astra 1H launched in June 1999.

these criteria gives a better reliability record for the Proton-K than does considering the three-stage launches alone.

The launch record of the Blok D family is not as good as the Blok DM family - although it should be noted that (as noted above) four of the Blok D failures were during the “black” period of 1967-1969. If this period is ignored then there were 22 launches of the Proton-K/Blok D vehicle, one failed to reach orbit and there was one Blok D failure: of the 21 Blok Ds which had a chance to fire (ie, ignoring failures of the first three stages) there were 20 successes, giving a success rate of 95%.

In considering failures involving the Blok D family, one has to remember that it is the spacecraft which is issuing commands to the fourth stage, and thus a spacecraft failure would automatically mean that the fourth stage would fail to operate: such missions where this happened were:-

- (1) Cosmos 419 (Blok D);
- (2) Mars 8 (aka Mars-96, Blok D-2).

In the case of Mars 8 a definitive cause for the failure has not been revealed, and it is possible that it was the Blok D-2 at fault rather than the spacecraft.

In Table 11 these two missions are not classified as fourth stage failures.

Turning to the Blok DM family, used primarily for launches of either GLONASS navigation satellites to 19,200 km orbits or GEO satellites, this has an excellent flight record with all three versions with more than one launch having a success rate greater than 95%. In 1999 both the Blok DM-2 and Blok DM-2M variants were still operational: it is possible that the flight of the Blok DM-5 in 1997 might be a “one off” since it has been reported that Cosmos 2344 was one of a kind.

There has only been one failure in the commercial Blok DM programme - when the second ignition of the Blok DM3 carrying AsiaSat 3 led to the partial disintegration of the rocket stage. Due to the low number of launches this one failure reduced the success rate of the Blok DM3 to 86%.

### 13. Introduction to Briz-M

While this paper is primarily reviewing the Blok D and DM families of Proton-K fourth stages, the new Briz-M fourth stage will be noted here.

The three-stage Proton-K launch vehicle was developed by the Chelomei design bureau (OKB-52, now Khrunichev) while the family of Blok D and DM fourth stages were developed within the Korolyov bureau (OKB-1, now Energiya). To convert the Proton-K to an “all-Khrunichev” vehicle, a new Khrunichev fourth stage has long been intended. As far back as the late 1960s there were studies to replace the Blok D with a new fourth stage using the RD-301 liquid fluorine (oxidiser) and liquid ammonia (fuel) engine [24]. The major problem was the extremely high toxicity of the propellants. Work was undertaken at one of the two Proton launch pads then in use in support of this new fourth stage, but it became clear that the leakages of propellant were extremely difficult to prevent, and therefore the new fourth stage was abandoned.

TABLE 12: Numerical Data for Briz-M Fourth Stage.

|                       |                    |
|-----------------------|--------------------|
| Fuel                  | UDMH               |
| Oxidiser              | nitrogen tetroxide |
| Length, metres        | 2.61               |
| Diameter, metres      | 4.0                |
| Dry mass, kg          | 2,370              |
| Propellant mass, kg   | 19,800             |
| Thrust, kN            | 19.6               |
| Specific impulse, sec | 325.5              |

Briz-M data are taken from [25].

For some years it has been planned to introduce Khrunichev’s Briz-M (“breeze”) fourth stage to the Proton-K, finally making it an all-Khrunichev vehicle. The original Briz-K propulsion module made its orbital debut on the maiden flight of the Rokot launch vehicle (December 26, 1994), but Briz-M is a much more powerful rocket stage. Details of the Briz-M are given in Table 12.

The much delayed maiden flight of a Proton-K with a Briz-M fourth stage - carrying a Raduga satellite - was originally planned for May 1999 but rescheduled to June and then July because of technical problems. The launch finally came on July 5th but a second stage malfunction prevented orbital injection from taking place. Briz-M did not get the chance to fire.

When fully-laden with propellant, Briz-M with its payload is too heavy for the three-stage Proton-K to put into orbit. Therefore, Briz-M will perform a small burn to place itself into the initial parking orbit, with the three stages of the Proton-K being suborbital: this recalls the launch profile for the Blok D family when used for deep space launches. Once in orbit, at least two further Briz-M burns will be required to reach the planned geosynchronous drift orbit.

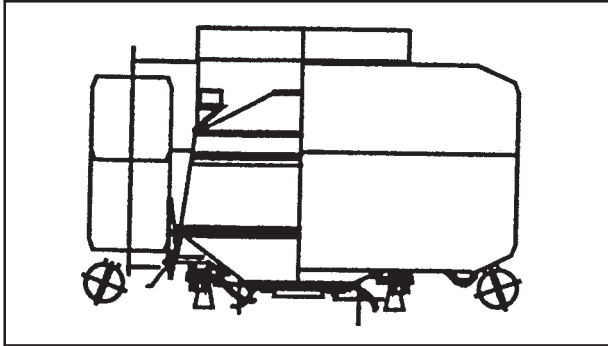


Fig. 12 Drawing of Briz-M which is planned to supplement and then replace the Blok DM fourth stages on Proton. The first launch with a Briz-M failed in July 1999 due a lower stage malfunction. (Copyright, International Launch Services.)

## 14. Conclusion

In addition to the launches noted above, on March 28, 1999 the maiden flight of the Zenit-3SL carried a Blok DM-SL as a third stage and successfully placed a test payload into GTO. Thus, the Blok DM family became the first upper stage to be flown on two different FSU launch vehicles. The standard launch profile for the Zenit-3SL is for the Blok DM-SL to place itself into a low parking orbit with its payload and after a short coast re-ignite to enter an equatorial GTO. Should the mission require it the Blok DM-SL can perform a third burn to enter a GDO, as happens on launches within the Russian domestic space programme.

It had been proposed that the Blok DM class stage would have played a role in the Energiya launch vehicle's programme. The Retro-Correction Stage planned for non-Buran Energiya launches was simply a Blok DM under another name. It would have been used as the "kick stage" to place heavy payloads into low Earth orbits and also as a spacecraft service module for lunar and planetary missions [26].

Over the last few years the demonstrated launch profiles of the Proton-K launch vehicle with its various Blok DM fourth stages have increased in number, and thus shown that the vehicle is more flexible than previously demonstrated. In the future we might see other new profiles introduced for super-synchronous transfers orbits being used as routes to GEO or launches to Sun-synchronous orbits, thus extended the Proton-K's capability even further.

The variation in launch profiles to GEO means that when launched on a Proton-K the satellites themselves have to perform smaller manoeuvres compared with western launches to reach their operational orbits. In turn this means that a larger mass can be launched to GEO using the Proton-K, and that increased mass can be translated into either an increase in station-keeping propellant or an increase in the useful payload mass (or a combination of both of these).

When the planned Proton-KM/Proton-M launch vehicles are introduced using more powerful upper stages one can expect even more variety in the launch profiles used by the vehicle.

## 15. Acknowledgements

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This paper started life in 1994 as a magazine article, but the magazine delayed publication for so long that Russian revelations overtook the article's analysis and it was therefore withdrawn at the author's request. A revised version of the 1994 article was published as follows:-

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