INTERNATIONAL SPACE COMPANY KOSMOTRAS

DNEPR LV APPLICATION FOR SPACECRAFT INJECTION INTO HIGH ENERGY ORBITS

TECHNICAL EVALUATION

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JULY 2001

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INTRODUCTION

Spacecraft market analysis indicates that currently manufacturers of space hardware have an increased interest to launches of small spacecraft into high energy orbits, like:

- geostationary orbit;
- high elliptical orbits like Molniya
- trans-lunar trajectory.

The main concern of the customers is the price of launches into high energy orbits. Currently, expensive launchers are used for launches into these orbits, such as Proton, Ariane-4, -5, Molniya, Souyz-Fregat, Delta, Atlas, H-2A.

The performance characteristics make Dnepr the most powerful light class launcher – the weight of payload it is capable of delivering into a low earth parking orbit is up to 3,600 kg (for instance, Rokot LV can deliver 1,900 kg of payload and Kosmos LV – 1,400 kg into a similar orbit). At the same time, the price of a parking orbit launch by Dnepr is relatively low - $10 – 11M depending on the contract terms and conditions and complexity of payload adaptation.

All these make Dnepr commercially attractive for launches of small spacecraft into high energy orbits, provided that the spacecraft are equipped with additional boosters. And the most challenging task in terms of performance is launches into the geostationary orbit. This technical evaluation refers to launches of small spacecraft into the above-mentioned orbits using Dnepr launch vehicle.

This technical evaluation was prepared in pursuance of the decision of ISC Kosmotras Board of Directors dated May 29, 2001.

1. LAUNCHES OF SPACECRAFT INTO GEOSTATIONARY ORBIT

1.1 Selection and Justification of Mission Profile

Among all types of spacecraft, geostationary communications satellites are the most expensive to build, launch and operate. The cost of building a geostationary satellite can reach $500 M, and launching it into orbit can cost up to $100 M. Yet, this class of space systems outstrips all other means of practical space exploration in terms of commercial efficiency .

Modern space communications market is characterized by the appearance of a new class of spacecraft. These are small communications satellites weighing about 500 kg with 5 to 7 transponders. This market trend is caused by the fact that many users of communications services refuse from using big expensive satellites weighing 2,000 – 2,500 kg with 20 – 25 transponders. For many countries, the application of small and lower cost satellites is sufficient to ensure the complete coverage of their territory with communications network.

The appearance of small communications satellites makes it necessary to provide reasonably priced launch opportunities for them using light class launch vehicles. The following mission profiles to the geostationary orbit using light LVs are possible:

1. The launch vehicle delivers the stack consisting of the satellite and orbital module equipped with **electric thrusters** into a low earth parking orbit. These electric thrusters have a high specific impulse and ensure the transfer into the geostationary orbit within **5 – 6 months**.
2. **Lunar-assist maneuver** is used for geostationary orbit injection. After injection into a parking orbit, the acceleration to the Moon is provided by a **high thrust chemical engine**. The spacecraft trajectory should be calculated in such a way that the spacecraft approaches the Moon at the moment when the latter is in the plane of the Earth's equator. In this case, following the spacecraft flight around the Moon, the lunar gravitation will send the spacecraft back to Earth and change its orbit inclination to 0 degrees, i.e. the plane of the Earth's equator. Deceleration and injection into the geostationary orbit is provided by another chemical engine. Total time of injection into the final orbit is about **8 days**.

This technical evaluation refers to the **second mission profile** described above. Main advantages of this mission profile as compared to the first one, are as follows:
- short time of injection into the geostationary orbit (when the injection time is 5-6 months, this period of time is counted against the spacecraft life, and thus means less time of its actual operation in orbit);
- radiation safety (during the injection by means of electric thrusters, the spacecraft has to repeatedly pass through the Earth's radiation belts, which requires special protection for its on-board instrumentation).

1.2 Justification and Selection of Propulsion Unit

Two options should be considered when selecting a propulsion unit for payload injection into the geostationary orbit using the lunar-assist maneuver:

- liquid propulsion unit (amyl + heptyl)
- solid propulsion unit

Liquid propulsion unit has a higher specific impulse (330 sec. as compared to 290 sec. of the solid propulsion unit), but the weight of the solid propulsion unit structure is less than that of the liquid one. In addition to that, the use of the solid propulsion unit makes it possible to separate the burned motor after the acceleration to the Moon is complete, while the deceleration burn to get to the geostationary orbit could be performed by another solid propulsion unit. Such operation can be easily conducted by using a solid propulsion unit, while it can not be always done effectively by using a liquid one. However, it is still necessary to make calculations to compare both types of the propulsion units.

The comparison should be made in terms of the payload mass (M_{pl}) being delivered to the trans-lunar trajectory, since this part of the mission requires most of the performance. Values of ideal velocity for flight into the geostationary orbit are as follows:

- acceleration to the Moon….3,160 m/sec.
- deceleration after circumlunar flight…1,175 m/sec.

The mass of the payload delivered to the trans-lunar trajectory will be equal to:

$M_{pl} = M_{mm} – M_p – M_{pu}$, where: (1)

M_{mm} – initial mass of mission module starting from a low earth parking orbit to the Moon

M_p – mass of the propellant required for acceleration

M_{pu} – mass of the propulsion unit.

Using the Ziolkovsky formula, it is possible to calculate the mass of the propellant required for acceleration:

$M_p = M_{mm} [1 – \exp (- \frac{Vid}{gPsp})]$, where (2)

V_{id} – ideal velocity of acceleration

P_{sp} – specific impulse of the rocket motor

g – acceleration of gravity

The mass of liquid propulsion unit is calculated by the following formula:

$M_{lpu} = a\, M_p + 0.05\, M_p + M_{lrm}$, where (3)

a – ratio of propellant tank mass to propellant mass

M_{lrm} – mass of liquid rocket motor.

Based on formulas (2) and (3) above, the formula (1) for liquid propulsion unit will look as follows:

$$M_{pl} = M_{mm} \{ \exp (- \frac{Vid}{gPsp}) - [1 – \exp (- \frac{Vid}{gPsp})] [a + 0.05] \} - M_{lrm} \quad (4)$$

The mass of solid propulsion unit is calculated by the following formula:

$M_{spu} = M_p$ (1/ß – 1), where (5)

ß - ratio of mass of propellant to the total loaded mass.

Based on formulas (2) and (5) above, the formula (1) for solid propulsion unit will look as follows:

$$M_{pl} = M_{mm} \{ 1 - 1/ß [1 – \exp (- \frac{Vid}{gPsp})] \} \quad (6)$$

The constants used in formulas (4) and (6) above have the following values:

M_{mm} = 3,600 kg – initial mass of the mission module delivered by the Dnepr launch vehicle into the low earth parking orbit
V_{id} = 3,160 m/sec. – ideal velocity of acceleration to the Moon
P_{sp} = 330 sec. – specific impulse of liquid rocket motor
P_{sp} = 290 sec. – specific impulse of solid rocket motor
g = 9.81 m/sec.^{2}
a = 0.20 (statistical data of the Russian propulsion units indicates a = 0.18 – 0.25)
ß = 0.92 (US Thiokol's catalog indicates ß = 0.92 – 0.94)

The results of the calculations conducted indicate that the mass of the payload being delivered to the Moon from a low earth parking orbit is:

- **710 kg, if a liquid propulsion unit is used; and**
- **1,065 kg, if a solid propulsion unit is used.**

Therefore, the use of a solid motor gives **a 33% increase in the payload mass**. That is why, all subsequent calculations were based on the use of solid motors.

US Thiokol's STAR solid motors are appropriate for acceleration of payload from a low earth parking orbit to a high energy orbit. It should noted that Thiokol's STAR motors will not be a part of the Dnepr launch vehicle as additional stage, but will be incorporated into the mission module. Therefore, STAR motors will be supplied to the spacecraft authority under a separated contract and then the fully integrated mission module will be shipped to Russia as a single flight unit to be launched into parking orbit.

1.3 Flight Configuration

This technical evaluation is based on the application of Dnepr launch vehicle and two solid motors like US Thiokol's STAR motors. The following documents were used to prepare the evaluation:

- Dnepr LV performance curves contained in the Dnepr User's Guide;
- baseline trajectory data supplied by Central Scientific and Research Institute of Machine Building (TSNIIMASH), Moscow, Russia;
- Thiokol's STAR Motor official catalog; and
- characteristics of on-board systems and units of some Russian spacecraft.

Flight configuration to the geostationary orbit is composed of the following elements:

- Dnepr LV in its basic configuration that has been in operation since the British UoSAT-12 launch in 1999;
- STAR-48A solid motor;
- STAR-27 solid motor; and
- Orbital module (new item).

The trajectory scheme is shown in Fig. 1-1. General view of the mission module consisting of STAR-48A, STAR-27, orbital module and payload (spacecraft) is shown in Figure 1.2. The geostationary orbit injection sequence is shown in Figure 1.3.

Lunar-assist maneuver is applied for payload injection into the geostationary orbit. The unique feature of this mission profile is the use of Moon gravity to change the orbit inclination from 50.5^0 (low earth parking orbit inclination) to 0^0. The spacecraft should approach the Moon at the particular moment of time, when the Moon is within the plane of the Earth's equator, which occurs twice a month. This mission profile is a common knowledge and US Hughes corporation was forced to actually test it in 1998 due to unsuccessful injection of Asiasat-3 satellite into the geostationary orbit. Originally, the traditional mission profile to the geostationary orbit was planned, which envisaged active maneuvers for injection into the final orbit. However, the Proton LV failed to deliver payload into the required geostationary transfer orbit. By means of firing the STAR motor, the satellite was transferred to a circumlunar trajectory, and then to a near-geostationary orbit.

It should be noted that the lunar gravitation parameters have been precisely calculated and verified during many lunar missions. Vast experience of lunar flight trajectory calculations is possessed by Russian companies: Lavochkin Association, Institute of Applied Mathematics of the Russian Academy of Sciences and Central Scientific and Research Institute of Machine Building (TSNIIMASH). Multiple orbital maneuvers within the lunar gravitation field at various altitudes have been performed. Therefore, calculations of the trajectory to the geostationary orbit using the lunar-assist maneuver will not be a problem.

Parameters of injection into the geostationary orbit using the lunar-assist maneuver are as follows:

- parking orbit inclination………………………………………………………….50.5^0
- minimum circumlunar flight altitude (in lunar radii)…………………………….3.92
- lunar transfer time…………………………………………………………4.92 days
- total injection time…………………………………………………………7.8 days
- value of ideal velocity:
    - acceleration to the Moon……………………………………………….3,160 m/sec
    - deceleration after circumlunar flight……………………………………1,175 m/sec
    - trajectory correction during the mission ……………………………….100 m/sec.

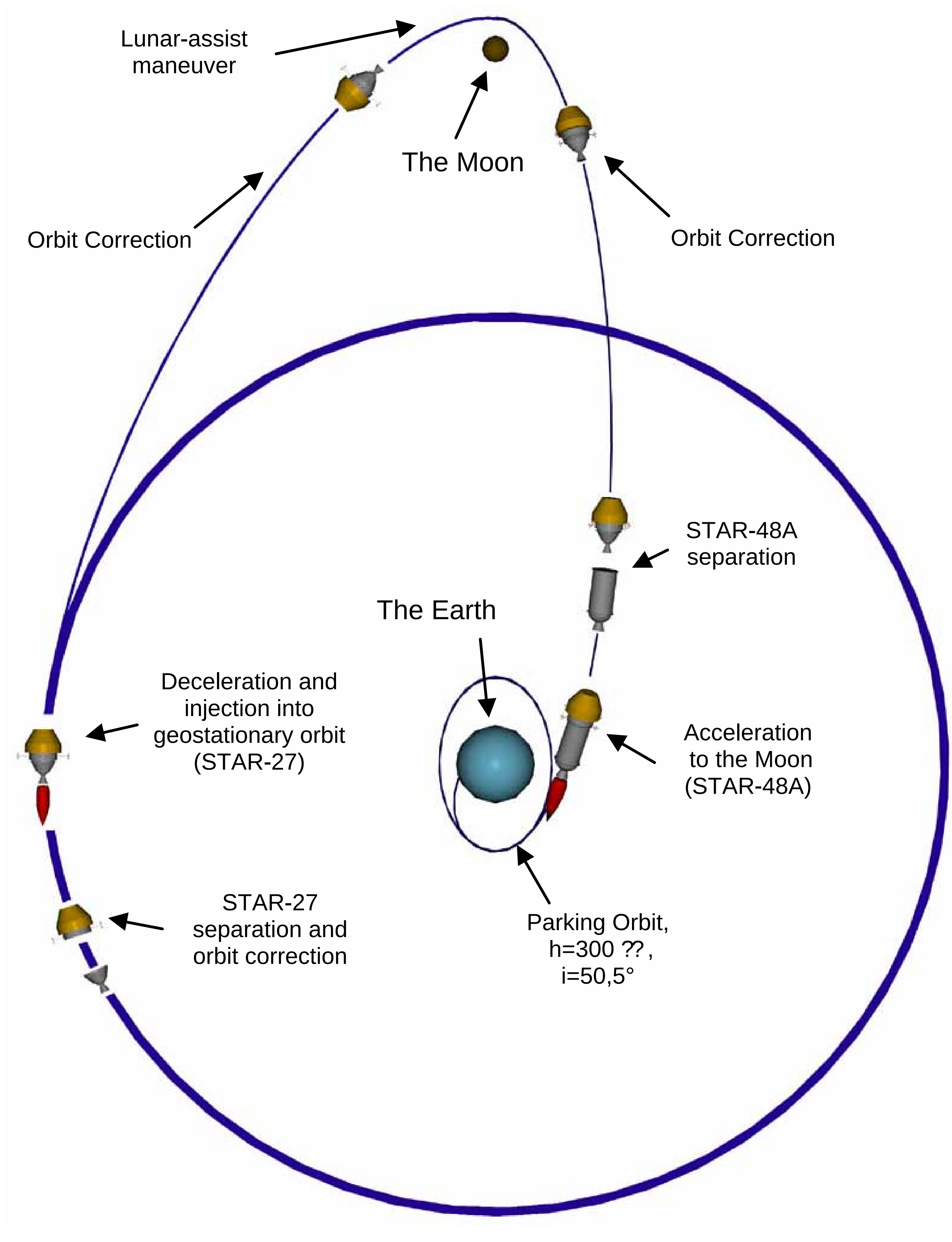

Fig. 1-1. Trajectory scheme

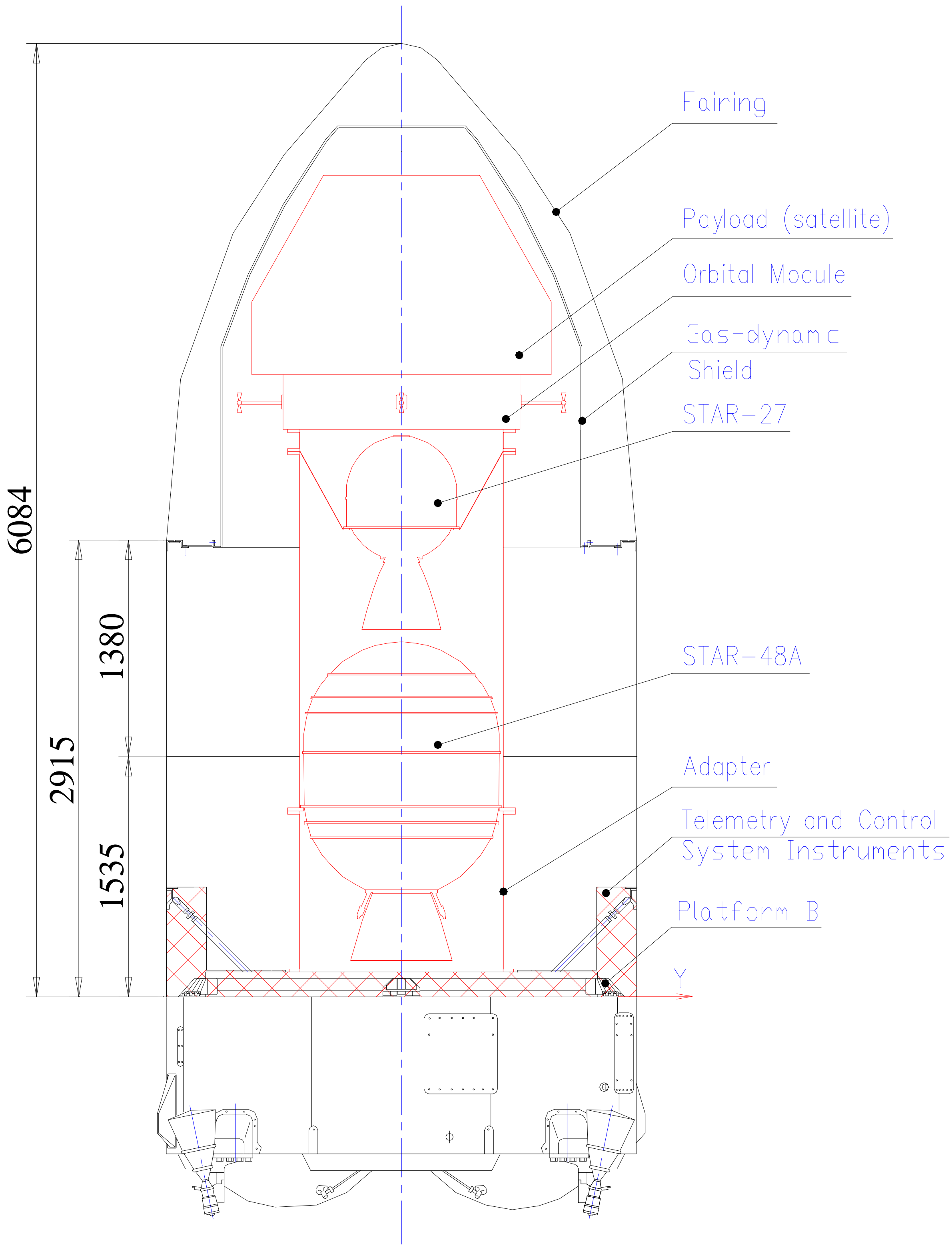

Figure 1.2. General View of Mission Module for Injection into Geostationary Orbit

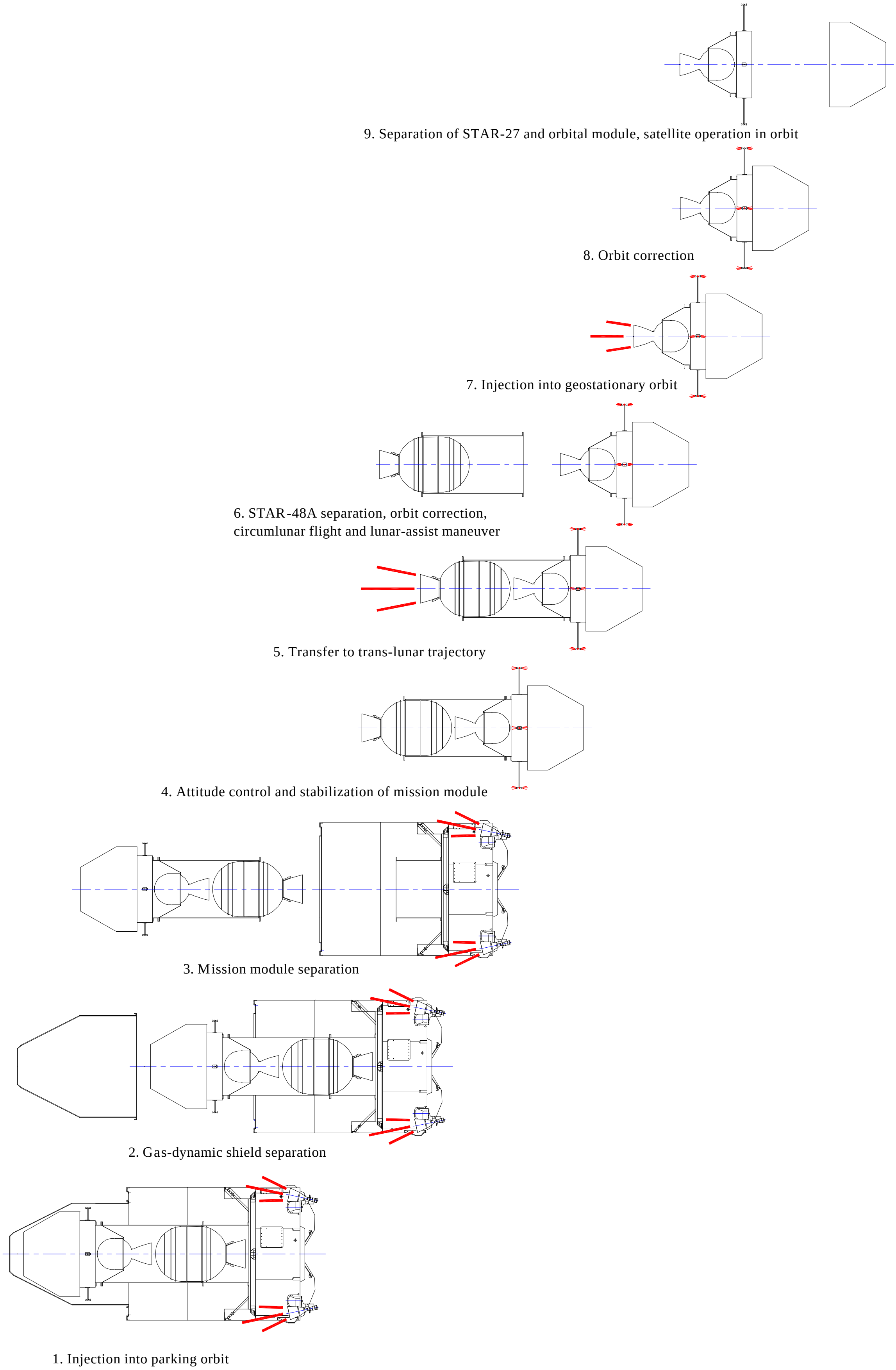

Figure 1.3. Sequence of Operations during Injection into Geostationary Orbit

1.4 Trajectory Calculations

Injection into a 300 km circular parking orbit inclined 50.5^0 is performed by Dnepr-1 LV. Deployed in this orbit is a mission module consisting of the spacecraft, orbital module, STAR-48A and STAR-27 motors.

The first (acceleration) impulse for transfer from the parking orbit to the trans-lunar trajectory is applied by firing the STAR-48A motor. The STAR motor data given below is taken from the official Thiokol Catalog.

STAR-48A characteristics are as follows:

- total loaded weight…………………………………………………………..2580 kg
- propellant weight……………………………………………………………2430 kg
- propellant weight/total loaded weight ratio…………………………………..0.941
- total inert weight (without propellant)………………………………………...150 kg
- specific impulse……………………………………………………………….289.9 sec.

Ideal velocity of acceleration to the Moon is 3,160 m/sec. Final/initial mass ratio is 0.33. The initial mass of the payload injected by Dnepr LV into the 300 km low earth parking orbit is assumed as 3,600 kg. The final mass after the acceleration burn is 1,190 kg. The mass of the burnt propellant is 2,430 kg. After the acceleration to the Moon and STAR-48A motor separation, the flight is continued by the STAR-27/orbital module/spacecraft stack, the total mass of which is 3,600 – 2,580 – 20 – 30 = 970 kg (an adapter between two solid motors weighing 20 kg is separated along with the STAR-48A motor; the weight of the orbital module propellant required for stabilization during the STAR-48A motor burn is 30 kg).

Following the circumlunar flight with lunar-assist maneuver and change of orbit inclination from 50.5^0 to 0^0, the deceleration burn is performed in order to transfer to 36,000 km geostationary orbit. The deceleration impulse is applied by firing the STAR-27 motor.

STAR-27 characteristics are as follows:

- total loaded weight……………………………………………………….356 kg
- propellant weight…………………………………………………………333 kg
- propellant weight/total loaded weight ratio……………………………….0.924
- total inert weight (without propellant)……………………………………27 kg
- specific impulse……………………………………………………………..288 sec.

The deceleration velocity, which ensures the transfer to geostationary orbit, is 1,175 m/sec. Final/initial mass ratio is 0.66. The weight of the STAR-27/orbital module/spacecraft stack prior to deceleration is 970 – 20 = 950 kg (20 kg of the orbital module propellant will be used for trajectory correction during trans-lunar flight and flight from the Moon to the geostationary orbit). Following the propellant burnout and STAR-27 motor separation, the mass of the orbital module/spacecraft stack will be 950 – 356 – 15 – 5 = 574 kg (15 kg of propellant will be used for stabilization during STAR-27 motor burn; STAR-27/orbital module adapter weighing 5 kg is separated along with the STAR-27 motor).

Of 574 kg, the weight of the orbital module is 74 kg (see section 1.4 below) and the weight of the spacecraft deployed at the geostationary orbit is **500 kg**.

1.5 Orbital Module

The orbital module is designed for performing orbital operations while on trans-lunar trajectory and return flight to the geostationary orbit. The orbital module propulsion unit provides attitude control and stabilization of the entire STAR-48A/STAR/27/orbital module/spacecraft stack.

Given below are the orbital module on-board systems and units and their weight data:

?	On-board systems and units	Weight, kg
1	Attitude control and stabilization system	25
2	Propulsion unit	20
3	Structure	10
4	On-board cables	3
5	Thermal insulation	2
6	Propellant tank pressurization helium	1
7	Weight margin	10
	Total weight of orbital module without propellant	**71**
8	Propellant	**75 (*)**
	Total weight of orbital module with propellant	**135**
	(*) 75 kg of propellant is used for the following:	
	• stabilization during STAR-48A motor burn	**30**
	• trajectory correction during trans-lunar flight	**10**
	• trajectory correction during return flight to the geostationary orbit	**10**
	• stabilization during STAR-27 motor burn	**15**
	• correction of geostationary orbit parameters	
	• residual propellant	

(*) 75 kg of propellant is used for the following:
- stabilization during STAR-48A motor burn……………………………..30 kg
- trajectory correction during trans-lunar flight ……………………………10 kg
- trajectory correction during return flight to the geostationary orbit……..10 kg
- stabilization during STAR-27 motor burn……………………………….15 kg
- correction of geostationary orbit parameters………………………………7 kg
- residual propellant………………………………………………………..3 kg

The characteristics of the orbital module propulsion unit are as follows:

- propellant ……………………………………….…Nitrogen tetroxide + UDMH
- thrust, pitch and yaw control thrusters……………………………………50 N
- thrust, roll control thrusters………………………………………………25 N
- specific thrust of thrusters………………………………………………..290 sec
- number of thrusters….pitch and yaw control………………………………..…8
  roll control……………………………………………………4

Propellant tanks are spherical, equipped with a displacing membrane. Propellant displacement is performed by supplying helium from a separate vessel. Four thrusters are used for each channel – yaw, pitch and roll.

It is assumed that the orbital module on-board equipment will be fabricated up to the Western space technology standards. For comparison, the Table below contains some basic data on orbital module attitude control and stabilization system developed by the Russian companies.

#	Systems and Units	Mass	Developed by
1.1	On-board computer with input-output unit	10.7 kg	NPO “Nauchniy Center”, Zelenograd, Moscow Region
1.2	Gyroscope	10.0 kg	NIIPM (“Rotor”), Moscow
1.3	Angular rate sensor	2.5 kg	NIIPM (“Rotor”), Moscow
	Solar orientation sensors “333K”, 2 pieces	3.3 kg	Central Design Bureau “Geophizika”, Moscow
	Earth orientation sensors “342K”, 2 pieces	3.0 kg	Central Design Bureau “Geophizika”, Moscow
1.4	Power amplifier unit, power distribution unit, cable network	5.5 kg	
	Total mass	35.0 kg	

Orbital module does not have a radio receiver/transmitter, telemetry system, antenna-feeder unit and a power supply system. The satellite is assumed to be equipped with these systems. Attitude control and stabilization of the orbital module may be partly performed by the spacecraft control system. Upon spacecraft injection into the geostationary orbit, the orbital module propulsion unit is used for final orbit corrections, and then it is separated from the spacecraft. Another option may be considered, when after the injection, the orbital module is not separated and is used for regular orbit corrections.

The orbital module may also be used as multi-purpose module for various orbital operations. If a scientific or commercial payload is placed on this module, it will become an independent small spacecraft.

2. LAUNCHES OF SPACECRAFT INTO HIGH ELLIPTICAL ORBITS

World's space market analysis indicates that a number of customers have an interest to launches into high elliptical orbits like Molniya with the apogee altitude of 40,000 or 71,000 km. The orbit inclination should be 63.5^0, since it allows to constantly maintain the position over the main axis of the elliptical orbit, i.e. the orbit apogee "hangs" on the same geographical latitude, which is important for communications or remote sensing.

Dnepr launch vehicle can be used for the injection of spacecraft equipped with solid motors (US Thikol's STAR-48? motors) into such orbits. The mission profile will be as follows:

- Dnepr LV delivers a mission module into a 500 km parking orbit inclined 63.5^0. The mission module consists of a spacecraft, orbital module and solid motor.
- By firing the solid motor at the perigee and thus applying acceleration, the spacecraft will be transferred into a high elliptical orbit.

The results of trajectory calculations are given in a Table below:

Characteristic	Value of Characteristic	
	Orbit 500 ? 40,000 km	Orbit 500 ? 71,000 km
Initial mass delivered to a low earth parking orbit, kg	3,430	3,220
Velocity impulse required for transfer from parking to high elliptical orbit, m/sec.	2,500	2,780
Final/initial mass ratio after acceleration impulse was applied	0.415	0.376
Mass of loaded STAR-48? motor, kg	2,130	2,130
Mass of STAR-48? propellant, kg	2,010	2,010
STAR-48? propellant weight/total loaded weight ratio	0.942	0.942
Mass of orbital module including 17 kg of propellant for stabilization, kg	110	110
Mass of STAR motor/orbital module adapter, kg	40	40
Payload mass, kg	**1150**	**940**

3. LAUNCHES OF SPACECRAFT INTO TRANS-LUNAR TRAJECTORY

Currently, there is an increased interest to launches of unmanned spacecraft to the Moon. These missions are both of scientific, and commercial nature.

Dnepr launch vehicle is capable of delivering a combination of spacecraft and STAR-48A motor into the trans-lunar trajectory. The mission profile will be similar to the first part of the mission profile described in section 1 hereof (launches into geostationary orbit). The mass of the spacecraft being delivered to the Moon is **970 kg**.

CONCLUSION

1. Market analysis indicates that at present, there is an increased interest of spacecraft manufacturers to launches of small spacecraft into high energy orbits – geostationary, high elliptical and trans-lunar trajectory.

2. Dnepr launch vehicle has the best performance for low earth parking orbit injection among other launchers of the light class – 3,600 kg (for instance, Rokot LV can deliver 1,900 kg of payload and Kosmos LV – 1,400 kg into a similar orbit). Therefore, Dnepr can be used for spacecraft injection into high energy orbits:

- **500 kg** of payload into the geostationary orbit;
- **1150 or 940** kg of payload into high elliptical orbit like Molniya inclined 63.5^0 with perigee altitude of 500 km and apogee altitude of 40,000 or 71,000 respectively;
- **970 kg** of payload into the trans-lunar trajectory.

3. US Thiokol's STAR solid motors are appropriate for acceleration of payload from a low earth parking orbit to a high energy orbit. It should noted that Thiokol's STAR motors will not be a part of the Dnepr launch vehicle as additional stage, but will be incorporated into the mission module. Therefore, STAR motors will be supplied to the spacecraft authority under a separated contract and then the fully integrated mission module will be shipped to Russia as a single flight unit to be launched into parking orbit.

4. This technical evaluation was prepared in pursuance of the decision of ISC Kosmotras Board of Directors dated May 29, 2001.