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Orbit design for launching INTEGRAL on the Proton/Block-DM launcher

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Abstract. This paper describes some aspects of the mission design determined by use of the Proton/Block-DM launch vehicle in the version used for injection onto a highly elliptical orbit of the international gamma-ray astrophysics laboratory INTEGRAL. Methods and results used for choosing an operational orbit for INTEGRAL are presented.

Key words. space vehicles – orbit evolution – launch window

1. Introduction

One of the most important components of the INTEGRAL project was a tool for delivering the scientific instruments mounted on board the spacecraft (SC) onto the orbit with parameters acceptable for the fulfillment of the planned observations. So the necessary attention was paid for choosing the proper launch vehicle (LV). As the best option the Russian LV with the symbolizing name Proton with the upper stage DM has been chosen (Proton LV and Launch Services User's Guide 1995). Criteria for such a decision were capability to launch the SC onto an optimal orbit and high enough level of reliability, what was demonstrated by Proton during more than three decades of launching operations (approximately 300 launches). The idea to use this rocket for launching INTEGRAL was considered by ESA as a very good argument in support of the INTEGRAL project at large.

The very important part of the mission design was the orbit optimization what is significantly determined by the LV characteristics. In our case the scheme of launching was dictated by the following characteristics: during the first phase of injection the SC with an upper stage is put onto the low nearly circular parking orbit with the use of three stages of Proton itself, then after the coast part of the trajectory the upper stage is fired for putting the SC onto a highly elliptical transfer orbit.

2. Requirements and constraints to the project operational orbit and launching scenario

The INTEGRAL project is related to the class of space missions which are to be designed in accordance with the following list of constraints and requirements:

- Maximum payload mass.
- Ballistic lifetime not less than 7–10 years.
- Minimization of the duration of the SC motion inside the radiation belts at the altitudes where damaging impact of particles. trapped in the belts is expected (i.e. at the heights lower than 9000 km).
- Maximum flight time outside the regions of possible influence of the radiation belts on measurements (i.e. at the altitudes higher than 40 000–60 000 km).
- Maximum time of flight in the coverage regions of the ground stations.
- Distance to the ground stations is to be limited by the radiolink possibilities taking into account a necessary bit rate.
- Minimum time of the flight in eclipse regions.

For the INTEGRAL-on-Proton case some additional constraints are to be added, some ones can be eased and some are to be specified more strictly (Janin 2001). The payload mass was specified to be 4100 kg. The perigee altitude is to be never lower than 7500 km during the operational lifetime of the SC (5.2 years in the extended version) and preferably higher than 9000 km. The maximum eclipse duration (cylindrical shadow) is set to be 1.7 hours. No eclipse is allowed after separation up to the first apogee passage. Because of the

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absence of possibility to store the scientific data on board the SC the full ground stations coverage over altitude 40 000 km is required. For critical operations such as the SC orbital maneuvers the visibility from at least two ground stations is demanded. With the coverage problem and operational convenience the demand to put the SC onto a geosynchronous orbit is connected, what means that the sideral orbital period is to be multiple of the star day ($23^{\mathrm{h}}56^{\mathrm{m}}4^{\mathrm{s}}$) to allow repetitive working shifts on ground and optimizing the station coverage pattern. In combination with the constraint on the maximum distance from ground station to the SC allowed by radiolink capabilities, equal 160 000 km, the previous demand means that the orbital period is to be not more than 3 days. That means that for satisfying the constraints connected with the radiation belts the sideral period is to be exactly 3 star days. Taking into account that the ground stations planned to be used for INTEGRAL (Redu and Goldstone) are situated in the Northern hemisphere, it is obvious that the apogee of the operational orbit is to be well above the equator, i.e. the equatorial declination of apogee is to be maximal. This declination is constrained from the launcher side because the orbit inclination is determined by coordinates of the launch site (Baikonur) and by restrictions on the areas where falling stages (and other separated parts of the LV) are allowed. In addition the injection trajectory is to be planar. Only an initial orbital inclination of 51.6° remained as viable option for the INTEGRAL-on-Proton launch.

There are also constraints connected to the launching scenario. Proton/Block-DM has the capability to deliver the 4000 kg payload onto the highly elliptical 3 days period orbit with the perigee altitude 40 000 km. But this option demanded some modifications of the Block-DM due to the longer than used before coast phase from the perigee to the apogee, where the last (from 3 in this case) ignition of the main engine of the upper stage was to be done with the subsequent separation of the SC. The standard scenario for the launch supposes two ignitions of the upper stage's main engine. The three stages of Proton deliver the orbital unit onto a suborbital trajectory, i.e. onto an orbit with the perigee under the Earth surface. Then the first ignition of the upper stage's main engine follows almost immediately after separation of the orbital unit (after 5 min of operation of the auxiliary engine unit) transferring the orbital unit onto the low Earth orbit. Such approach maximizes the payload mass. After the coast phase the procedure of the second ignition of the main engine is to be fulfilled in the region of the planned perigee to inject the SC onto a highly elliptical orbit.

Nevertheless an alternative injection scenario was accepted. The principle criteria for this choise were 1). enhancement of the reliability of the launch and 2). prolongation of the time that the SC generally spends at high altitudes (above 40 000 km). The excessive launching capability of the Proton/Block-DM has been exchanged onto raising the reliability level: only one ignition of the Block-DM engine was planned for putting the SC from the low parking orbit onto the transfer orbit with the apogee height 154 000 km and the perigee height 685 km. Three stages of Proton were to deliver the orbital unit onto the 192 × 690 km parking orbit. During this phase of the launch operations the visibility from Russian ground stations is supported constantly. But for the upper stage operation there were no possibility to receive telemetry information because of absense of the necessary ground stations in the southern hemisphere. So the Rocket and Space Corporation Energia with support of Rosaviacosmos and ESA have organized the installation of mobile station in Argentina. The optimal location for telemetry receiving have been chosen covering he total time of upper stage main engine burn. Separation of the SC from the upper stage is to be performed in the visibility zone of the ESA (Redu) and Russian (Schelkovo) ground stations. After that the drift phase of the injection procedure was to begin when the orbit drifts to the optimum position with respect to the ground stations planned for telemetry and control. The launching operations are illustrated by Fig. 1.

One week after separation the perigee raise maneuvers were planned to begin with the use of the SC own engines, which apply velocity impulses in the apogee region. Four perigee raise maneuvers were planned. After this the fifth maneuver, rather small, was planned for the apogee height raise in order to reach a geosynchronous orbital period and thus to stop the orbit drift with respect to the Earth surface. Distribution of the impulses of the maneuvers was planned in such a way in order to to achieve the required initial phasing of the orbit with respect to the ground stations on the rotating Earth. During the described maneuvers the SC engines thrust is to be directed approximately along the velocity vector which in case of INTEGRAL is the velocity vector in the apogee. During these operations solar panels are to be directed towards the Sun, so the new constraint arises: the solar aspect angle is to be inside the given limits. In our case it means that the angle between the velocity vector in the apogee and the direction to the Sun is to be in these limits (from 50 to 130 degrees).

3. Orbit choice and launch windows

Orbits with such a high apogee as in our case are under sufficient influence of the Sun and Moon gravity forces so their parameters evolve very quickly. This evolution can be described approximately by the following equations (Eliasberg 1965), which give secular variation of the SC orbital elements per orbit averaged for one orbital revolution of a perturbing body:

$$
\begin{aligned}
\overline{\delta a} &= 0, \\
\overline{\delta e} &= \frac{15}{4}\pi \frac{\mu_1}{\mu_0}\left(\frac{a}{r_1}\right)^3 e\sqrt{1-e^2}\sin^2 i \sin 2\omega, \\
\overline{\delta \Omega} &= -\frac{3}{2}\pi \frac{\mu_1}{\mu_0}\left(\frac{a}{r_1}\right)^3 \frac{\cos i}{\sqrt{1-e^2}}\left(1-e^2+5e^2\sin^2\omega\right), \\
\overline{\delta i} &= -\frac{15}{8}\pi \frac{\mu_1}{\mu_0}\left(\frac{a}{r_1}\right)^3 \frac{e^2}{\sqrt{1-e^2}}\sin 2i \sin 2\omega, \\
\overline{\delta \omega} &= \frac{3}{2}\pi \frac{\mu_1}{\mu_0}\left(\frac{a}{r_1}\right)^3 \frac{1}{\sqrt{1-e^2}} \\
&\quad \times\left[5\cos^2 i\sin^2\omega+\left(1-e^2\right)\left(2-5\sin^2\omega\right)\right], \\
\overline{\delta h_{\mathrm{P}}} &= -\frac{15}{4}\pi \frac{\mu_1}{\mu_0}\left(\frac{a}{r_1}\right)^3 ae\sqrt{1-e^2}\sin^2 i \sin 2\omega.
\end{aligned}
\qquad (1)
$$

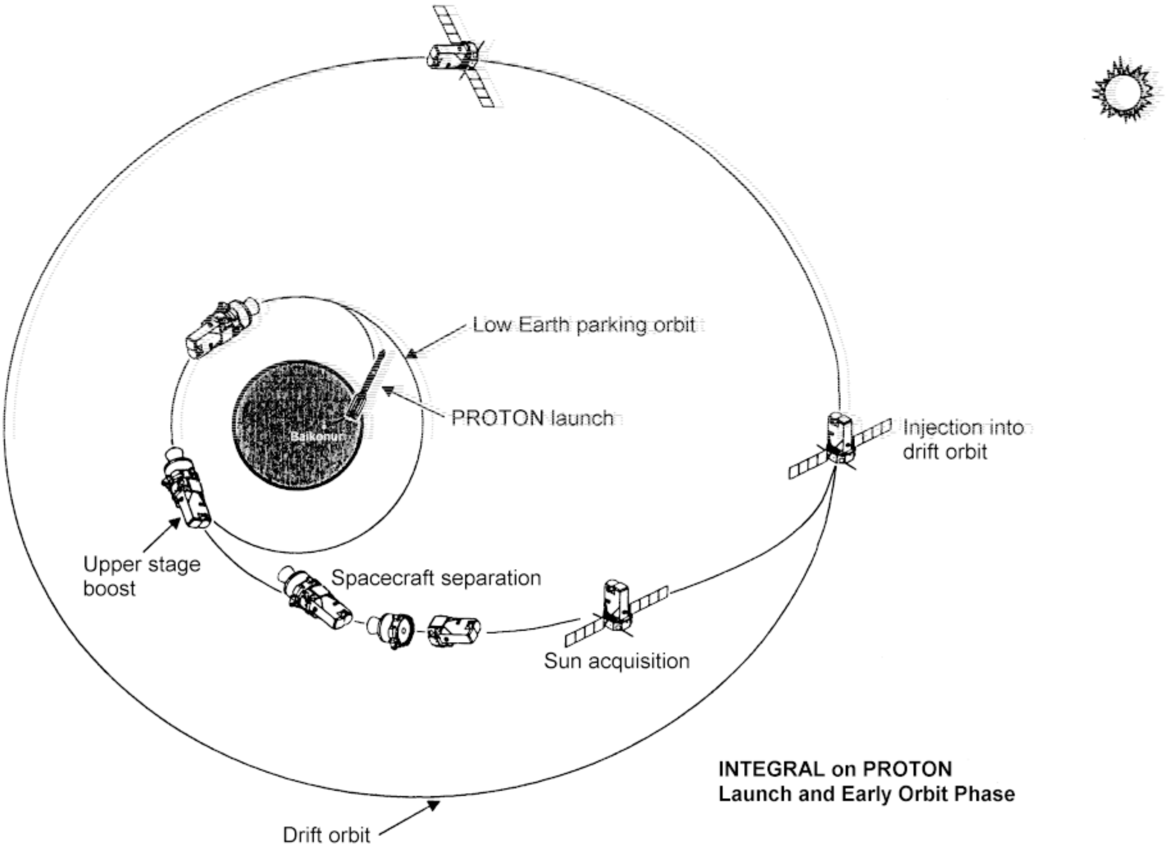

Fig. 1. The INTEGRAL-on-Proton launch and early orbit phase.

Here $a, e, \Omega, i, \omega, h_{\mathrm{P}}$ are the osculating semimajor axis, eccentricity, ascending node longitude, inclination, perigee argument, height of the perigee with respect to the perturbing body orbit plane (in our case it is close to the ecliptic plane), μ_0 is the Earth gravitational constant, μ_1 is the perturbing body gravitational constant (the Moon and Sun respectively in our case), r_1 is the distance to the perturbing body.

It is clear from the given formulae that the perigee height rises if the value of the perigee argument ω lies inside the limits $270° < \omega < 360°$ or $90° < \omega < 180°$. The fastest perigee raise takes place if $\omega = 135°$ or $\omega = 315°$ and $i = 90°$ (all these values are with respect to the ecliptic plane). For our case the apogee is to be in the Northern hemisphere, so the acceptable value for the perigee argument is 315°. With the fixed inclination $i = 51.6°$ with respect to the equator, the highest inclination to ecliptic we receive if the right ascension of the ascending node (RAAN) is equal to 180°, then we receive $i = 75.1°$.

With such a choice one can receive the fastest raise of the perigee height only in the initial point. As it can be shown choosing the initial ω of about 322° it is possible to fasten raise of the perigee height up to achieving a circular orbit (Eismont et al. 2003). But with this choice only two requirements are met: the long ballistic lifetime of the SC and the fast leaving of the altitudes with the radiation belts impact. The other requirements of INTEGRAL such as the maximum allowed duration of the eclipse, the ground station coverage are not satisfied. Optimization of the orbit choice may be reached by optimal balancing of the demanded parameters. As acceptable compromise the argument of perigee equal to 300° with respect to the equator has been chosen. Despite this value does not correspond the maximum possible declination of the apogee direction it allows ones to receive the full ground stations coverage planned for INTEGRAL for the SC flight over heights 40 000 km.

At the same time it gives the possibilities to choose acceptable perigee argument with respect to the ecliptic plane just by proper choice of the right ascension of the ascending node. It is easy to show that for the orbit inclination to equator 51.6° the maximum difference between the perigee arguments with respect to equator and ecliptic planes is 30.5°, i.e. for 300° of the perigee argument to equator by choosing the RAAN value one can receive the perigee argument to ecliptic from 269.5° to 330.5°. It gives the broad enough interval for choosing this key parameter. For Proton right ascension of the ascending node is rigidly connected to the time of its liftoff. The choice of the liftoff time fixes the the ascending node position. position and vice versa: acceptable in framework of the existing constraints the values of RAAN are transformed in the interval of possible liftoff times, i.e. the launch window depending on the day of the year. As it was shown despite rather strong constraints for the accepted equatorial perigee argument equal to 300° the launch windows are open during

Letter to the Editor

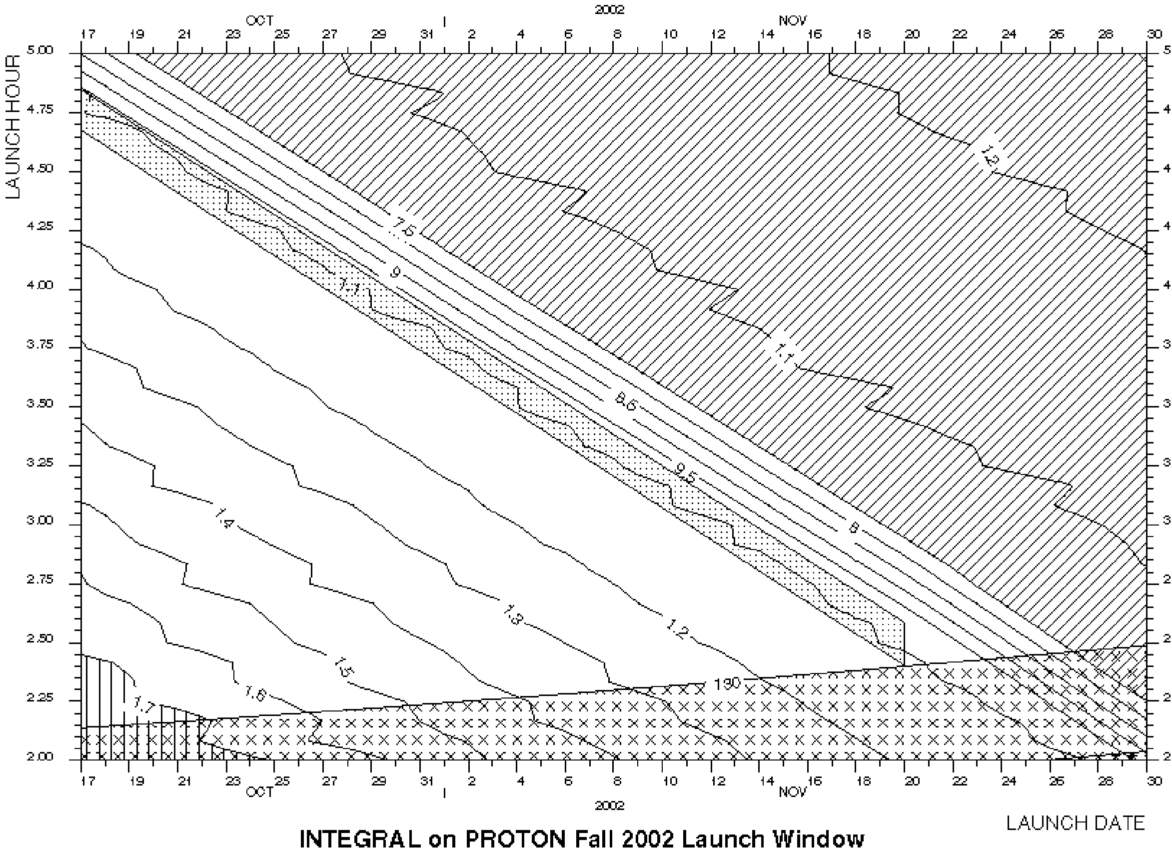

Fig. 2. Overall launch window for INTEGRAL. Shading shows the areas of parameters forbidden due to (×) the solar aspect outside (50°, 130°) 7, 13 days after the lift-off, (/) the minimum height less than 7500 km, (|) the maximum eclipse duration larger than 1.7 h (countours of constant level are given also for 1.5 and 1.3 h), (\) the eclipse 10 min after the injection (dashed countours of constant level), dotted area is 10 min launch window determined by launcher.

343 days (94%) per year for the 1.7 hours maximum allowed eclipse duration, and during 166 days (45%) for the 1.3 hours eclipse.

Figure 2 shows window evolution around the actual INTEGRAL launch date on October 17, 2002 approved as the nominal date for the launch of INTEGRAL on Proton. The nominal time for the launch was chosen to be 4 hour 41 min UTC as giving possibility to keep the duration of eclipses less than 1.1 hours and the ballistic lifetime well higher than demanded figure, and the perigee altitude high enough (higher than 10 000 km during 7.5 years). Duration when the SC is above 60 000 km is 84% of the flight time and it is fully covered by Redu and Goldstone. The chosen time of the launch corresponds RAAN equal to 104.9, and this value was planned to be approximately kept during possible changes of the launch date by keeping the actual launch window in the region shown as dotted area in Fig. 2. Such approach was determined by strategy of the Proton launch delay: postponing is possible only by multiple of one day; 10 min width of the planned windows allows to keep the same onboard flight program of Block-DM during 3 days still sustaining the attitude of the orbital block unit in required limits with respect to the Sun direction. Also during these three days the liftoff time is kept constant, for the following 3 days the liftoff time is to be decreased by 12 min 5 s, what allows one to stay inside the 10 min launch window for Proton.

4. Orbit evolution

Figure 3 presents the perigee height as a function of time since October 13, 2002, $8^{\mathrm{h}}13^{\mathrm{m}}20^{\mathrm{s}}$ UTC. It increases up to 12 450 km (in November 2006) what is followed by the same decrease of the apogee altitude (Janin 2002). The inclination increases constantly and reaches 87° at the end of the extended mission. The RAAN decreases regularly by 80° during the mission and the argument of perigee stays relatively constant around 300° during 2.5 years with the subsequent decrease to 275°.

It should be mentioned that comparatively small variation of the perigee argument and perigee height means the comfortably low eclipse duration and good ground station coverage what confirms the chosen initial orbit parameters as a successful compromise between required demands and constraints to the orbit.

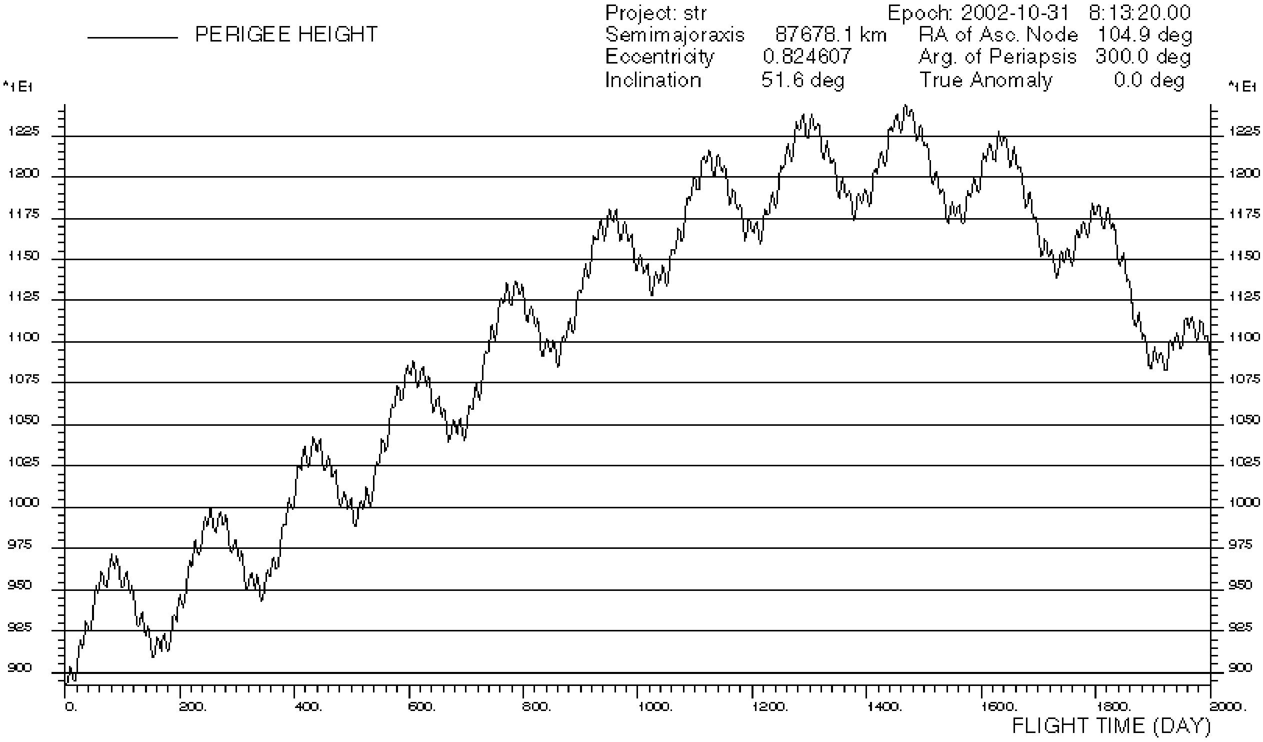

Fig. 3. Perigee height evolution for INTEGRAL.

5. Execution of the launching scenario

After the successful launch on Proton/Block-DM on October 17, 2002 INTEGRAL has been put on its transfer orbit with excellent accuracy; deviation from nominal orbit parameters were well inside the agreed limits. For example, deviation in the perigee height was 1.6 km, in the apogee height was 185 km what is 8 times better than the required figures. Then according to the planned scenario of the SC injection onto an operational orbit after the drift phase the perigee raise maneuvers were executed by the INTEGRAL own engine unit.

The finalizing maneuver raised the apogee height to 153 697 km and the perigee height to 9028 km and as a result INTEGRAL was put on its operational high elliptic orbit what took place on October 31, 2002 at $7^{\mathrm{h}}37^{\mathrm{m}}34^{\mathrm{s}}$ UTC. Processing the tracking data received by Redu, Goldstone and Perth ground stations confirmed the injection of INTEGRAL on its operational orbit with the required accuracy. Revisiting Fig. 3 and having the results of trajectory tracking data processing one can see that the measured (i.e. calculated from the actual tracking data) perigee heights are very close to the predicted ones. For example for the last available measured value referred to September 4 the difference between the measured and predicted perigee heigts is less than 50 km.

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