COLLISION PROBABILITIES AMONG THE SATELLITES OF THE SECOND DNEPR LAUNCH

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ABSTRACT

The close approaches among the seven bodies (five payloads and two parts of the rocket third stage) injected into orbit during the second Dnepr launch are analysed. Due to the Dnepr vehicle peculiar way of releasing the payloads, they were inserted in very similar orbits, hence an interest has arisen in this near passage events case study. Having defined a 20×8×8 (along-track, radial, out-of-plane) km wide "encounter ellipsoid", the satellites orbits were propagated from the Two-Line Elements, resulting in 22 close encounters occurred from the second orbital month to March the 8th 2001. The features of such close approaches (distance, relative velocity components) are examined; however, as all the payloads are microsatellites, the collision probabilities are extremely small. A forecast of future encounters is also presented, in order to statistically evaluate the global collision probability for each satellite.

1 SCENARIO DESCRIPTION

On September the 26th 2000, the second launch of the Russian-Ukrainian "Dnepr" vehicle, [1], occurred. Five satellites were successfully put into orbit: two Italian (UNISAT and MEGSAT-1), one Malaysian (TIUNG-SAT-1) and a mini-constellation of two Saudi Arabian spacecraft (SAUDISAT-1A and 1B).

The Dnepr launcher is nothing but the SS-18 "Satan", that is the most powerful Soviet Intercontinental Ballistic Missile, suitably modified for commercial space launches. When inserting satellites into orbit higher than 350 km (as it is the September 2000 launch case), a very peculiar way of delivering the spacecraft (called "throttled-back" mode) is used : the third stage of the vehicle rotates (see Fig. 1) so that the satellites are in the back side of the stage and they can be delivered by simply being unlocked (by means of pyrotechnic devices) from the launcher: neither springs nor other devices are used to push the spacecraft[1]. On the contrary, as the upper stage (US) continues to be thrust, it goes away from the released satellite.

Such a delivery system, comes up from the military mission of the SS-18, as it would have guaranteed a good precision in addressing the atomic bombs to the targets.

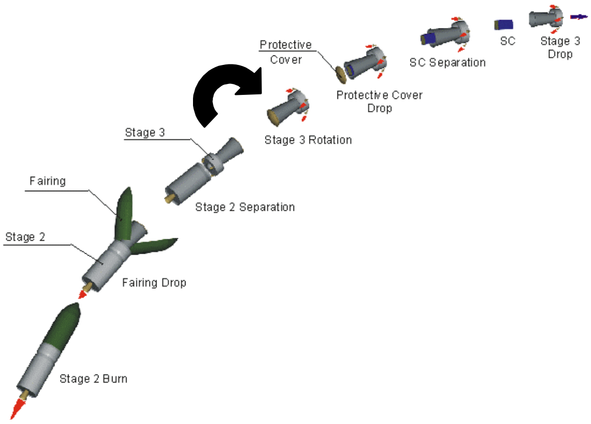

Fig. 1. Dnepr mission profile

The time distance between two successive deliveries is 1 s, while the thrust of the US is 0.5 *g*, [2]: this implies a release distance of only 2.5 m and a velocity difference of 5 m/s between two consecutively unlocked satellites.

Therefore, the five satellites were injected into very similar orbits (about 650 km high, almost circular, 64.5° inclined); of course also the launcher's third stage and the payload module cover are in similar orbits. As a consequence potentially dangerous close approaches may occur among these seven objects.

Such near passage events were analysed, and the relevant probabilities of collisions evaluated.

2 THE CLOSE APPROACHES INVESTIGATION

As the first purpose of the work is assessing the impact probability relevant to any single event, a direct method was employed, based on the numerical integration of the seven bodies' trajectories starting from the objects'

[1] Actually an exception in the second launch was constituted by Tiungsat-1 spacecraft, which was built with an own spring-based separation system.

Proceedings of the 3rd European Conference on Space Debris, ESOC, Darmstadt, Germany, 19 - 21 March 2001
(ESA SP-473, August 2001)

first reliable Two-Line Elements (TLE) releases; of course, the orbit propagator continuously corrects the trajectories exploiting each further TLE update.

Obviously, due both to residual errors in the propagation and to initial condition (or TLEs') inaccuracies, it is not possible to forecast with absolute precision if a collision actually occurs; on the contrary, the probability of collision associated to a near passage event can always be assessed, (see, for example, [3] and [4]). We have defined a "safe ellipsoid" (or "encounter ellipsoid") around each spacecraft; when a passage of one of the seven objects occurs inside the safe ellipsoid of another one, we talk about a "close approach" (even referred to as "near passage event" or "encounter") and we evaluate the probability of impact associated to that event with the classical method hereafter shortly described. The safe ellipsoid proportions and dimension are related to the "expected errors" (variances) in the orbit propagation: the assumed *proportions* of both the "safe ellipsoid" and the "expected error ellipsoid" are 2.5×1×1 (along track, radial, out of plane) while the *dimensions* will be detailed in the following section 2.1.

2.1 Near Passage Events Forecasting

The bodies we are interested in are all catalogued (see Table 1) by the United Sates Space Command (USSPACECOM), [5]; the orbital data we have used are distributed by NASA. From [6] it is possible to deduce that the predicted characteristics of a close approach between two catalogued bodies (event time, minimum distance, relative position and approach direction etc.) vary very much as new TLE sets are available (the predicted minimum distance changes up to some tens of kilometres in the last two days before the encounter, [6]).

According to [7], the minimum distance prevision accuracy in a close approach between catalogued objects is "a few kilometres after a few days" (i.e. employing "a few days" old TLE set). In the same paper it is well underlined that a prevision based on TLEs propagation for Cerise satellite and catalogue object n. 18208, showed a 1.5 km close passage between such bodies at the epoch 24/7/96 09h:48min:02.3s (the employed TLEs were about 24 hours old). As it is well known, such encounter came out to be a collision.

Propagating the seven Dnepr launched objects from TLE sets and comparing the results with successive TLE releases, we usually experienced along-track position inaccuracies of the order of 1 km in 1 day of integration. Nevertheless, up to 1 order of magnitude higher error sometimes occur, due to either TLE inaccuracies or bad attitude simulation (the latter is an issue of concern particularly for object 26551, which is roughly a flat cylinder).

Table 1. The second Dnepr launch related objects

Object	Catal. n.	Previous Catal. n.	Mass (kg)	Charact. radius (cm)
Saudisat-1A	26545	26546 26547 26548	11	14
Megsat-1	26546	26547	56	30
Unisat	26547	26551	12	17
Tiungsat-1	26548	26546	50	25
Saudisat-1B	26549		11	14
Dnepr R/B	26550		5000[2]	200
Dnepr Debris	26551	26545	150[2]	75

From these considerations we can state:

1. a close approach whose along-track distance is smaller than 20 km can not be considered an absolutely safe event; for this reason we defined an encounter ellipsoid 20×8×8 km (along track, radial, out of plane) wide;

2. the expected errors affecting the minimum distance components are not univocally estimable; as a consequence, we carried out a collision probability parametric analysis using different sets of variances, spanning from 10×4×4 km to 1×0.4×0.4 km (as usual, respectively along track, radial and out of plane).

2.2 The Close Approaches Numerical Determination

The near passage events prediction was performed by a suitably developed propagator. The numerical integrator is a Runge-Kutta-Fehlberg; though this algorithm is capable of varying the step size (allowing quite large time intervals), we obviously needed small steps for estimating the events minimum relative distances: then a distance-related variable step size was implemented.

The J_2 secular effects and the air drag were the only perturbations taken into account: the errors described in the paragraph 2.1 overcame the inaccuracies due to disregarding other perturbations. Moreover, the air drag model was an extremely simple, passive, specifically developed one, which takes into account the density dependence on the altitude only; such a model allows a

[2] Deduced from orbital decay.

relatively fast numerical integration. A check and possibly a tuning of the model – by means of a sample satellite orbit propagation – is needed in order to take account of the solar activity in the period to be examined; as a sample spacecraft the UNISAT[3] microsatellite was used, because its shape and mass are precisely known.

2.3 Collision Probability Evaluation

Once the results of the numerical propagation are available, it is possible to carry out the probability of collision associated to any single event using very classical methods.

The input data for this evaluation are: the relative position coordinates of the "impacting" body with respect to the "target" one[4] at the passage epoch; the error estimates on the same coordinates; the encounter "collision radius", defined as $r_c = r_1 + r_2$, where, of course, r_1 and r_2 are the bodies' characteristic radii (here defined as average). Obviously, a collision occurs when the minimum distance between two objects is lower than their "collision radius".

To take account of the uncertainties, the encounter position is modelled as a three-dimensional multivariate gaussian random variable, whose components (scalar variables) are supposed to be statistically independent (that is, their joint probability density function is the product of the marginal density functions, [8]); we denote with $\vec{d}_{\min} \equiv [d_t \quad d_h \quad d_r]^T$ (components respectively along-track (t), out of plane (h) and radial (r)) such minimum distance random vector. Of course, the average values of the three scalar variables are the minimum distance components found out by the numerical integration and indicated with $\vec{m}_d \equiv [m_t \quad m_h \quad m_r]^T$. The (vector) variance is equal to the (vector) error which the propagation is supposed to be affected by.

The joint probability density function is

$$f_{\vec{d}} = \frac{e^{-\frac{1}{2}\left[\left(\vec{d}_{\min} - \vec{m}_d\right)^T \mathbf{C}^{-1}\left(\vec{d}_{\min} - \vec{m}_d\right)\right]}}{(2p)^{3/2}|\mathbf{C}|^{1/2}}$$

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[3] UNISAT is the first satellite designed and manufactured by the GAUSS (Gruppo di Astrodinamica dell'Università degli Studi di Roma "La Sapienza").

[4] The near passing bodies can be defined as "target" or "impacting" as the safe volume is not spherical, but rather depending on the "target" motion. In principle, an event could come out to be a "close approach" for one only of the satellites.

where **C** is the covariance matrix:

$$\mathbf{C} = \begin{bmatrix} \mathrm{E}\left[(d_t - m_t)^2\right] & 0 & 0 \\ 0 & \mathrm{E}\left[(d_f - m_f)^2\right] & 0 \\ 0 & 0 & \mathrm{E}\left[(d_r - m_r)^2\right] \end{bmatrix}$$

with E[ ] being the expected value operator; the major diagonal terms are the variances (s^2_i , i = t, h, r) relevant to the $\vec{d}_{\min}$ individual components, whereas the off-diagonal terms are the variances (E[($d_i - m_i$) ($d_j - m_j$)] i, j = t, h, r, i ≠ j), null as we hypothesised the $\vec{d}_{\min}$ scalar components to be statistically independent random variables, [8].

The collision probability is easily estimable as

$$p_c = \int_{-r_c}^{r_c}\int_{-r_c}^{r_c}\int_{-r_c}^{r_c} f_{\vec{d}}\, dd_t\, dd_r\, dd_h$$

3 RESULTS

Up to March the 8th 2001, 22 passages between the seven bodies have occurred, with reference to the 20×8×8 km wide "encounter ellipsoid". In Fig. 2 the number of events for each satellite is reported; of course their sum is 44, as each event is an encounter for two objects. The number of conjunctions with a distance lower than 10 and 5 km is also visualised.

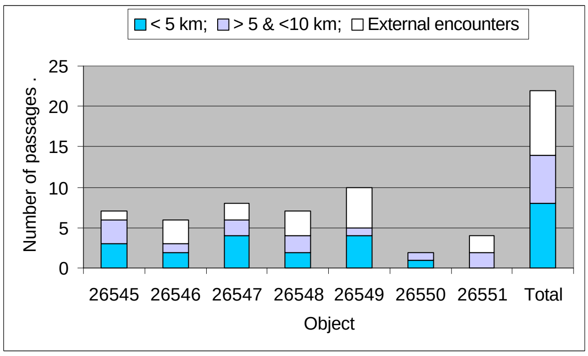

Fig. 2. Number of close approaches

The nearest passage event (see Fig. 3) took place at Modified Julian Date 2000 (MJD2000) 419.7, involving the spacecraft Unisat and Saudisat-1B; the minimum calculated distance was 1,28 km.

To this encounter is *not* associated the greatest collision probability (see Fig. 4) as this parameter strongly depends on the event collision radius.

The maximum collision probability ($0.32 \cdot 10^{-10}$) approach is the one between Tiungsat and the Dnepr rocket body dated MJD2000 317.8. The two objects passed 2.3 km apart from each other (of course, according the numerical simulation).

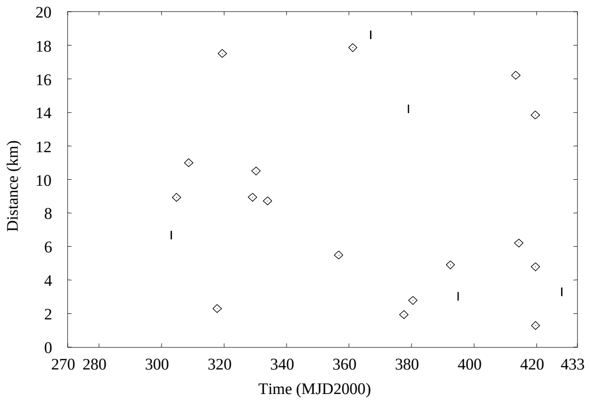

Fig. 3. Minimum approach distances

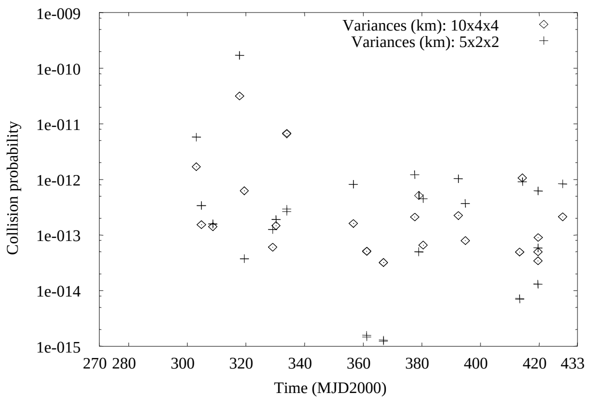

Fig. 4. Probability of collision

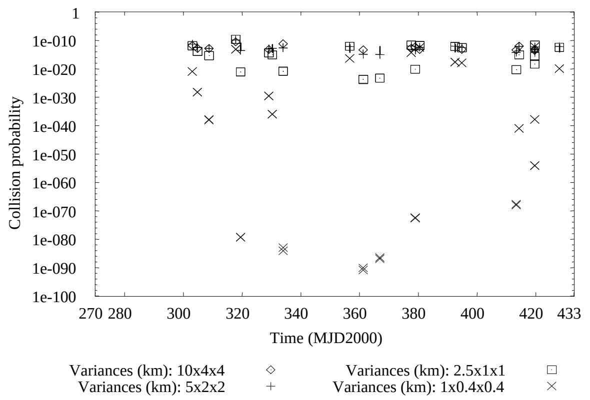

Fig. 5. Probability of collision (more variances)

However, from the Fig. 4 it is apparent that the probability of collision associated to the encounters are not very high. This is not unexpected as the collision radii are very small if compared both with the variances and with the minimum distance components average values. As a consequence, we also deduce that the total impact probability for any of the Dnepr-launched objects and even the global probability of collision relative to all the near passage events – happened among the seven bodies until MJD2000 433 – have been extremely small.

In Fig. 5 are reported the probabilities of collision relevant to the same conjunctions considering two more smaller variances combinations (in addiction to the two already used for Fig. 4 results). Observing the smaller variances cases, we infer that there are not significant increases of the impact probability for the closest approaches, whereas, as predictable, an enormous reduction characterises the further passes.

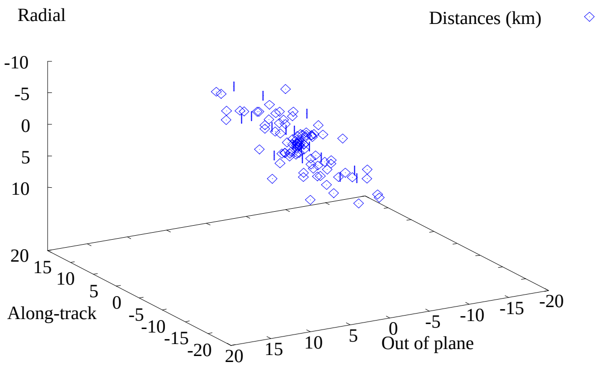

Fig. 6. Near passage positions 3D distribution

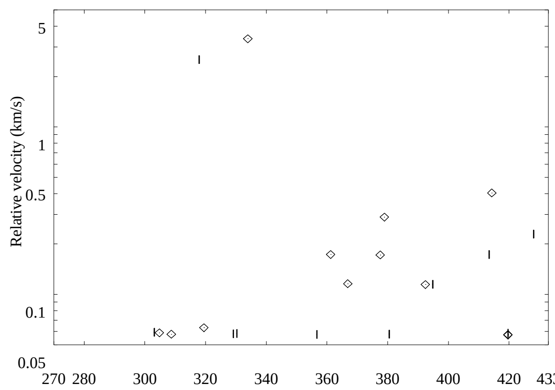

Fig. 7. Encounter relative velocities

In Fig. 6 are illustrated the relative minimum distance positions; it is apparent that the greatest component is often the along-track one; this is due to the very similar velocity vectors that cause the encounters to be characterised by pretty small relative velocity (see Fig. 7 and Fig. 8): this, in turn, let the small orbital plane differences to assume a key role in the fly-by, resulting in great along-track minimum distances.

We point out that the greatest relative velocities are relevant to the near passes involving the Dnepr upper stage or, secondarily, the payload module cover ("Dnepr debris"): as a matter of fact these are the objects having the more dissimilar orbits with respect to the other Dnepr launch related bodies. More in detail, the relative velocities in the close approaches between two payloads, come out to rarely reach 0.2 km/s.

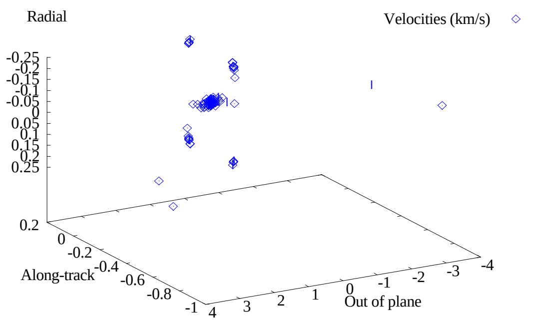

Fig. 8. Encounter relative velocity components

4 FUTURE ORBIT EVOLUTION

It is apparent that a well calibrated prediction must be based on recent orbit estimates; nevertheless, an evaluation of the seven bodies' future orbital evolution – and of the relevant global impact probabilities – is provided; we underline the absolutely *not deterministic*, but rather statistical value of the results hereafter presented: none of the forecasted close-approaches is guaranteed to occur at all.

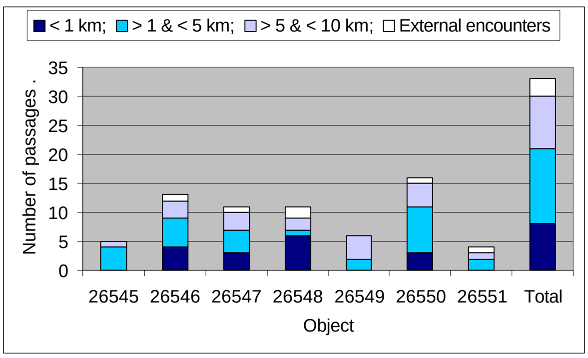

Fig. 9. Number of future close approaches

A one year long orbital propagation of the seven satellites orbit has been carried out from March the 9th 2001 midnight (MJD2000 433). 33 near passage events have been predicted, as showed in Fig. 9. What is impressive is the high number of very close approaches foreseen: 8 passes would take place with a minimum distance lower than 1 km. Even if, as we said, each of these encounters might not happen at all, the probability of so close passages, seems to be definitely not negligible.

The diagram in Fig. 10 is useful to have an idea of the statistical distribution of the events minimum distances; from such information it is deduced the importance to continue monitoring the orbital evolution of the seven bodies.

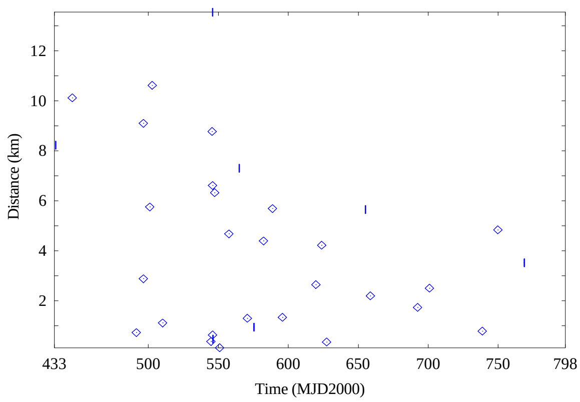

Fig. 10. Minimum future approach distances

Table 2. Global collision probabilities over one year

Object	Catal. n.	1 year global collision probability
Saudisat-1A	26545	9.64E-11
Megsat-1	26546	6.15E-10
Unisat	26547	2.91E-10
Tiungsat-1	26548	8.66E-10
Saudisat-1B	26549	8.44E-11
Dnepr rocket body	26550	2.28E-09
Dnepr Debris	26551	4.22E-10
Total		**2.33E-09**

While it does not make sense to talk about the impact probability associated to one single future event, it may be interesting the total probability of collision for each of the objects: we can expect such a value not to be affected by great errors. Therefore, in Table 2 the global collision probabilities over a one year time span, carried out with 5×2×2 km variances, are reported; we remember that such small variances are not related to the effective assessment of a single event impact probability, but rather are used to deduce an "average" behaviour: we want to have a though rough evaluation of the results we would face if we really were able to predict the approaches with such small errors.

Furthermore, an overall probability of impact among any two of the seven bodies is reported in Table 2.

As it is apparent, the highest impact probability is relative to the Dnepr third stage: this is not unexpected, as its dimensions are by far the greatest; moreover, the global collision probability for all the bodies is only slightly greater than that relevant to the Dnepr upper stage. The values, however, are not a matter of concern.

5 DNEPR LAUNCHED PAYLOADS GENERAL SAFETY CONCLUSIONS

The near passage events occurred, in the first 5.5 months of orbital life, to the seven objects inserted into orbit by the second Dnepr launch, have been examined; as the orbits are quite similar, the 22 encounters are characterised by small relative velocities; some potentially dangerous passages have happened, even if the relevant impact probabilities were not high.

A simulation relative to one future orbital year has also been carried out; the results show that the collision probabilities are pretty low, even if very close approaches may take place.

The peculiar satellite delivering system of the Dnepr vehicle, does not seem to compromise the payloads' general orbital safety; however, the orbital evolution of the September 2000 Dnepr launched bodies will be monitored during the next months.

6 REFERENCES

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