PREPARATION AND IMPLEMENTATION OF THE MIR FLIGHT CONTROL IN THE FINAL PHASE

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The problem to stop the operations with the Mir orbital complex and to investigate options for its safe deorbit arose seriously at the end of 1997 – beginning of 1998 due to some objective technical and economic reasons. The requirement to perform the deorbit in a controlled and 'civilized' way became one of the basic requirements, because the uncontrolled Mir reentry and fall out of its unburned fragments (especially in populated areas) could lead to a catastrophic situation.

The task was so complicated, that it took three years of preliminary studies and various modifications to start its practical implementation. This seems strange at first sight, considering the great experience of manned and unmanned vehicles returns to the Earth. But in the latter case the reentry was planned beforehand and the vehicles were equipped with the appropriate systems, at first engines, and had sufficient propellant reserves to deorbit. For the Mir complex this task had even not been considered (all hopes were connected with the reusable Buran system), and it was unexpected in some respect, also taking into account the lack of experience for the controlled deorbit of very heavy complex structures.

Many options of the Mir deorbit were considered, including the use of additional vehicles, in particular the Shuttle orbiter, but none of them gave a reliable solution without extended preliminary studies and numerous complex modifications. Therefore it was decided to rely only on the Mir capabilities.

In this case practically the only way to accomplish the task of a 'civilized' Mir deorbit and splash down in a selected oceanic area with a minimum propellant expenditure is a combined two-stage scenario:

- during the first stage, which is a passive flight, Mir is transferred to a lower pre-reentry orbit by exploiting the natural aerodynamic drag;
- during the second stage a reentry orbit is obtained in an active way (using the engines of the orbital complex), on which the final deboost impulse is applied to the station to transfer it to a reentry trajectory passing through the selected impact area.

To start investigating this scenario it was necessary to take into account the actual Mir capabilities.

1. Only the engines of the Progress M cargo vehicle could be used to execute deboost impulses. The main engine (SKD) thrust is ~300 kg and the maximum time of continuous burn may not exceed 300 s; the effective thrust of 8 control engines (DPO) is ~100 kg with a maximum time of continuous burn not greater than 400 s. The total deboost impulse with a simultaneous SKD+8DPO burn could be at the most 10 m/s of the station velocity.

The possible propellant onboard Mir is sufficient for a velocity change of not more than 18 m/s. It is evident that it was impossible to accomplish the task with the required reliability, and hence first of all it was necessary to determine the necessary conditions to execute the deorbit practically and to identify additional activities. To do this the following simplest, so-called one-impulse deorbit scenario was considered (Fig. 1). The Mir altitude naturally decreases to a level below 200 km and then the final deorbit is executed with one deboost impulse on the final orbit.

It should be mentioned that there are 3 successive orbits each day, from which it is possible to perform the descent in the selected area of the Pacific Ocean (daily orbits 1,2,3*).

The analysis shows that the practical implementation of this scenario is impossible for many reasons:

- The probability for the station to go into the required reentry orbits after the passive (aerodynamic) braking is very low (especially taking into account the short satellite lifetime at these altitudes);
- possible atmosphere variations could lead to an early and uncontrolled station reentry;
- the propellant amount required for the deorbit exceeds substantially the available onboard resources;
- the propellant amount required to maintain the station attitude for a long time and to stabilize it during the deboost burn at low altitudes is very high and comparable with the propellant required to execute the deboost burn itself;
- no reserve day of deorbit.

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* The 1st daily orbit is the 1st orbit of the day with the ascending node longitude west of 20° East

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The problem of Mir flight at low altitudes should be specially mentioned. Specialists were concerned about this problem till the last day due to the lack of data on the possible Mir behavior at flight altitudes below 200 km. The problem of the Mir attitude control and stabilization could be easily solved if Mir had a rigid enough structure, since the attitude control moments exceeded possible disturbing forces. But Mir is far from a rigid structure, it has a complex configuration with many solar panels where the joint behavior is difficult to predict. Finally practically all specialists concluded about the danger and even impossibility of the assured Mir attitude control at altitudes below 150 km. As a result a very important requirement was set forth to minimize the possible Mir flight at altitudes below 200 km and execution of the dynamic operations at altitudes above 200 km with relatively small perturbing moments.

Note another fact uncovered during the one-impulse scenario analysis. It turned out that in the course of the passive deceleration the maximum orbit altitude will be located above the selected splash down area. This is the unpleasant (but true) fact, since additional propellant resources equivalent to 4-5 m/s of deboost velocity are required.

The use of the two-impulse scenario presented in Fig. 2 also does not lead to a solution of the formulated problem. Its difference from the one-impulse scenario is in a preliminary shaping of the reentry orbit by the first impulse ΔV=8-9 m/s in order to provide the deorbit opportunity on the daily orbit 1, 2 or 3 and form an orbit geometry with the perigee above the impact area of fragments.

Nevertheless the conducted studies allowed to formulate various directions of research and technical work in order to provide necessary conditions for the accomplishment of the formulated task. A great volume of work was accomplished during the next years. The main activities were the following:

- development, ground and flight testing of a new modified Progress M1 tanker, delivering more than 2000 kg of propellant to the station;
- development and testing of a principally new mode of a simultaneous SKD and DPO burn;
- development and testing of rendezvous modes using small DPO engines instead of SKD;
- modification of the SKD main engine and DPO to increase the time of continuous burn (900 s instead of nominal 300 s and 2000 s instead of 400 s);
- thorough studies to find a practical scenario of Mir controlled deorbit;
- development and testing of new modes and scenarios of operation with the Mir station;
- search and implementation of ways, including Progress M1, to deliver onboard Mir maximum propellant amount required to implement its controlled deorbit and reentry, and other activities.

Thus the necessary conditions to accomplish the formulated task were established. But some essential problems and constraints make the final operations with Mir more difficult. Some of them are noted below.

a) The small amount of propellant onboard Mir (even taking into account the propellant of Progress M1). It was mentioned above that all measures were taken to maximize the propellant mass onboard, that was sufficient to deorbit Mir in the nominal situation, assuming Mir behavior as a rigid body at altitudes less than 200 km (this can be assumed at a stretch, it should be reminded that there was no such previous experience in space).

b) The small thrust to mass ratio of the Progress M1 engines used to execute deboost impulses. Thus with a Mir mass of more than 130 t, the SKD thrust is 300 kg plus 8 DPO additionally give 100 kg. With this ratio of mass and thrust of engines it is difficult to provide a good efficiency of deboost impulses of big magnitude execution (even applying the thrust in the orbital coordinate system).

c) The rapid increase of the atmospheric density with the altitude decrease. As the average orbit altitude changes from 400 km to 160-150 km, the density rises more than 1000 times, and at 120 km the density rises more than 10000 times. The complex Mir configuration leads to great difficulties in operating the station, first in ensuring a stable flight that, in turn, requires more propellant for the attitude control.

d) As the altitude decreases, the short Mir visibility from Russian ground stations on limited number of orbits (on some orbits no visibility at all) complicates severely the station flight control, orbit determination, telemetry downlink and settings uplink, analysis of maneuver execution (Fig. 3). To overcome this situation it is necessary to involve not only all national tracking means (radio technical, radiolocation, optical, non-traditional), but also foreign European and American means.

e) The complicated behavior of atmospheric parameters with respect to altitude. At the present time there is no reliable prediction of the atmosphere in world practice. It should be mentioned that at the end of the active operations of the Salyut-7 station its lifetime at an altitude 481 km was estimated as 8-20 years, based on the prediction of Soviet and foreign scientists. But Salyut-7 reentered in 4 years (February 7, 1991). Of course, this is not an arbitrary feature, since the atmospheric parameters depend on solar activity and geomagnetic perturbations and their behavior cannot be predicted with sufficient accuracy.

f) The short Mir lifetime at low altitudes (Fig. 4), that leads to various problems, especially in non-nominal situations.

The presented data demonstrates the great difficulties in the choice of the final scenario of the Mir operations in the final phase. We can only speak about a direction of work, solving the problem operationally taking into account the actual situation.

After the analysis of different options how to accomplish this task the following strategic plan for the operations of the Mir deorbit was adopted.

During the first natural braking stage Mir performs a passive flight in a spinning mode (in order to save propellant) and descends to lower flight altitudes being on a near-circular orbit with an average altitude H_{aver} every time. Upon reaching an altitude H_{aver}=240-250 km a decision is to be taken about the final active operations and, correspondingly, about the final selection of the parameters of a pre-reentry orbit – this is an orbit on which the active station deboost starts. As can be seen from Fig. 4a, an intensive passive (natural) braking also takes place at these altitudes. According to the laws of space mechanics, the deboost impulses must be applied in the orbit area opposite to the required area of reentry, i.e. it is necessary to lower the orbital altitude above the selected impact area. In general the number of deboost impulses can be different and as a result the station goes to a reentry orbit – an orbit on which the final deboost impulse is applied and the station goes to the reentry trajectory, enters the atmosphere, disintegrates and the unburned fragments fall in the selected area of the Pacific Ocean.

Initially a so-called three-day deorbit scenario was considered as the basis. It is presented in Fig. 5. The practical application of this scenario requires a total deboost velocity ~ 40-45 m/s, with a propellant consumption exceeding 2000 kg, not taking into account propellant for the attitude control and stabilization during burns.

The basic condition in this scenario was the requirement to operate Mir in the orbital orientation mode, that according to the laws of space mechanics provides the most favorable mode of the orbit lowering for long burn durations. On the other hand, the uncertainty of the behavior of Mir during long flights at altitudes H_{aver}<200 km resulted in the transition from the initial three-day scenario of dynamic operations first to the two-day scenario (Fig. 6) and then even to the one-day plan. In the last case the operations are carried out in the inertial orientation mode, that sharply deteriorates the flight dynamics conditions of this task.

Let us concentrate in more details on the reasons of the transition, at first sight surprisingly, to the one-day scenario of the Mir deorbit operations. As it was noted above, the search for the most reliable plan continued up to the last days, taking into account the status of the Mir onboard systems, actual available propellant, and also failures and faults in the onboard and ground equipment that took place during the last months of the station flight. As a result, the following considerations were taken into account when adopting the final decision.

1. The maximum reliability of the Mir deorbit can be provided, all other factors being equal, if there is minimum interference of the onboard systems operation, minimum change of Mir flight modes, minimum uplink of the necessary data to the onboard computer and, in general, execution of the final operations within the possibly short period.
2. The orbital orientation mode is accompanied by a big station longitudinal axis drift of up to 6° per orbit. The analysis showed that in some cases it could lead to critical situations, which are difficult to correct.
3. The orbital orientation mode for the flight at altitudes below 200 km requires essential modifications and changes in the onboard software that is associated with a certain risk.
4. Sharp increase of propellant required to maintain the orientation at altitudes below 200 km. This is especially dangerous in case of non-nominal situations, in particular, when dynamic operations are shifted to later times, that is to even lower altitudes.
5. The orbital orientation mode assumes the station entry to the atmosphere with the Progress M1 cargo vehicle 'ahead'. This is a rather unfavorable attitude, since the station aerodynamic configuration gives a high probability for generating a lift force, where the lift to drag ratio can exceed 0.2-0.3. Therefore in case of an unfavorable situation, taking into account a very small entry angle, the station may rebound the atmosphere with unpredictable consequences. The operation with the station in the inertial orientation provides the station entry to the atmosphere with the cargo vehicle 'on the rear'. In this case the possible lift to drag ratio is small (less than 0.1) and, moreover, the most probable variant is the lift force directed down, that assists the reliable capture of the station by the atmosphere.

After the detailed analysis and discussions the one-day scenario of the Mir dynamic operations in the inertial coordinate system was adopted for the practical implementation. Some additional conditions and constraints were formulated in the very last days before the deorbit (see Table 1) in order to improve the reliability of the final operations, although they were far from optimal from the flight mechanics point of view.

Below is an overview of the final operations with Mir during the last two days of its flight. Before this time Mir flew in a spinning mode in order to save propellant, which would have been spent if Mir had flown in an oriented mode. One day prior to the planned dynamic operations, on March 22, 2001, a command was uplinked within the visibility zone of Russian ground stations to correct the Mir angular velocity, which had a rather big value ~2.5 deg/s, and transfer the station to the inertial orientation mode. In this mode the station longitudinal axis (coinciding with the Progress M1 engine axis) was set perpendicular to the orbital plane[†]. This attitude corresponds to current conditions and therefore requires less propellant for attitude control. Mir stayed one day in this attitude. During this day all the data were uploaded that are required for the first two maneuvers on daily orbits 15 and 16 on March 23, 2001. According to the requirements (see Table) Mir had to be within the visibility of Russian ground stations for a certain time (~3 min) after the first maneuver execution. This was necessary to assess operationally the engines and the functioning of other supporting systems and to be able to upload a command for canceling the second maneuver in a non-nominal situation.

Note that on this orbit altitude there is visibility from Russian ground stations on daily orbits 13-14 (Fig. 3).

The execution of the first maneuver on the daily orbit 15 is explained, first, by the need to reorient Mir to the attitude where the resulting thrust vector is within the orbital plane and, second, to update orbit parameters and, if necessary, recalculate and upload onboard Mir all required data within the station visibility on daily orbits 13 and 14. It should be stressed that during this phase of the flight the data obtained from foreign tracking stations (at first American) on the 'blind' orbits (daily orbits 6-12 on March 23, 2001) were especially important. The availability of this data gave the Russian specialists confidence in the decision to start the dynamic operations.

The engines cut-off after the second maneuver also took place within the Russian ground sites visibility (not less than 5 min before the end of visibility) in order to be able to estimate the maneuver execution, recalculate, upload and execute all commands before the final third maneuver, and also to reorient the station by the pitch angle. Note that the first two maneuvers were executed by 8 control engines (DPO) of Progress M1 vehicle, and the third one by a joint burn of Progress M1 main engine and 8 DPO engines.

Fig. 7 presents some information about the dynamic operations and also the nominal and actual impact area of the Mir unburned fragments. The analysis showed that all operations were executed very close to the nominal plan, without any faults and non-nominal situations. It is obvious that all maneuver parameters (magnitude, orbit of application, burn start time, initial orientation of the resulting thrust, etc.), were selected after thorough and deep studies taking into account all necessary conditions and constraints, and also possible non-nominal situations. Note only some principal decisions taken in the very last time, also in the course of the dynamic operations.

1. It was noted above that the inertial orientation mode together with the additional strict constraints (see Table) did not allow the flight mechanics specialists to apply optimum solutions in the final maneuvers. In particular this led to a situation, that with the available resources it was not possible to provide an optimum orientation of the reentry orbit axes by the first two maneuvers, i.e. a position of the minimum orbit altitude above the given impact area. To partially correct this situation and improve conditions of the station capture by the atmosphere the target point (a center of the fragments impact area) was shifted by 850 km along the orbit ground-track in the Northwest direction: from 47°S and 140°W (initial target point) to 44°S and 150°W. In this situation the maximum downrange dispersion relative to the center of impact area was reduced from ±3000 km (initially announced data) to ±2000 km at the final impulse value ΔV_3=23.5 m/s. The lateral dispersion did not exceed ±100 km. The presented data show (Fig. 7) that the fragments impact area stays within the announced area.
2. Note once again that all Mir operations were planned assuming the worst situation development. In particular, the last impulse magnitude was selected also taking into account non-nominal situations, assuming in some cases a shift of the third maneuver to the next day. To provide normal operation in this case a special propellant reserve was allocated for the attitude control, but the actual events went nominally and this reserve could be utilized during the final maneuver. As a result the decision was taken to spend all propellant up to the complete burn out. Consequently the final executed impulse was ΔV_3~28 m/s. This led to a shift of the center of the nominal impact area in the Northwest direction (φ=40°S, λ=160°W) and to a decrease of the dispersion area: not more than ±1500 km in the downrange direction and ±100 km in the cross range direction. All formulated tasks were accomplished.

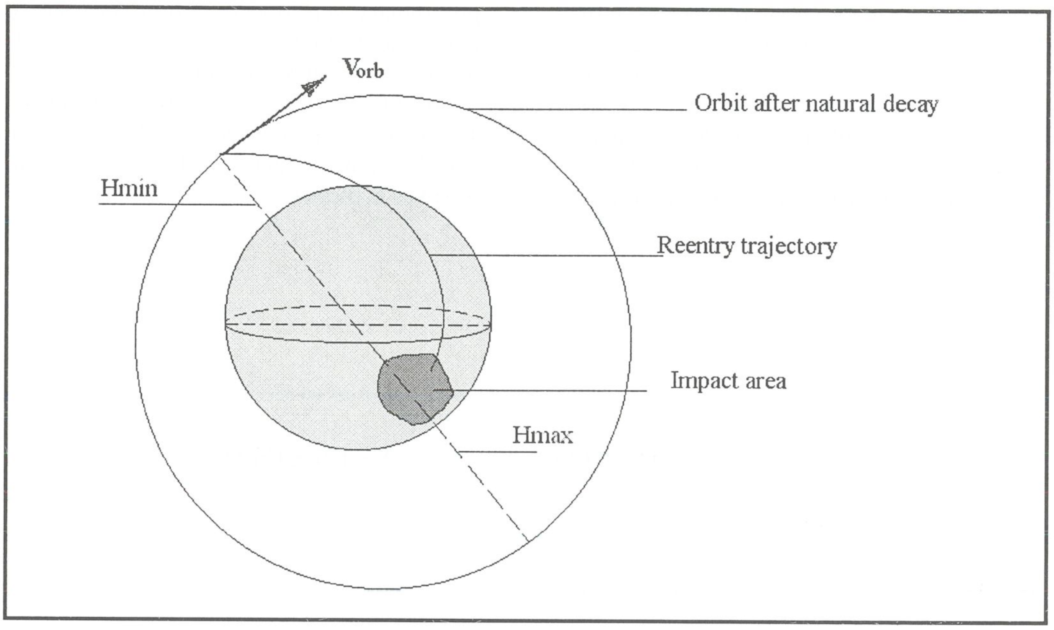
[†] Note that Mir had an average orbit altitude H_{aver}~217 km by this time.

Note in conclusion that the presented data describe only the nominal situation, while the majority of analyzed variants assumed various failures and disturbances. That was necessary since even from the above data it is clear that the final operations took place under severe time pressure for the incoming data processing and adoption of right decisions. It was necessary to have a set of prepared solutions; the work was organized, literally, without a right to make mistakes. Any mistake or defect could lead to unpredictable consequences. Therefore many tens of variants how to act in each specific situation were available in order to exclude the transition to an uncontrolled flight mode of Mir. The great volume of preparatory work, thorough studies of each non-nominal situation, preliminary selection of actions in each specific case led to the desired outcome – a successful, faultless and precise accomplishment of the unique and unprecedented task. It is difficult to overestimate the significance and importance of the performed studies and the gained experience for the further development of space activities.

Table 1.

BASIC CONDITIONS AND CONSTRAINTS

- Small propellant amount onboard Mir (taking into account Progress M1 propellant).
- Small thrust to weight ratio of Progress M1 engines, that are used to execute deboost impulses:
  - SKD thrust is 300 kg,
  - 8 DPO thrust is ~ 100 kg.
  - To apply dV=1 m/s it is required:
    - 44-46 kg of propellant for SKD, burn time $\Delta t=44\text{-}46$ s,
    - 48 kg of propellant for 8 DPO, burn time $\Delta t=132$ s,
    - 44-46 kg of propellant for SKD+8 DPO, burn time $\Delta t=33\text{-}35$ s.
- Rapid rise of atmospheric density as the altitude decreases (as average altitude changes from 400 km to 120 km, density rises 10000 times).
- Short Mir visibility from Russian ground sites on limited number of orbits.
- Complicated behavior of atmospheric parameters with respect to altitude.



H_{min}, km	160	150	140
H_{max}, km	180	170	160
ΔV, m/s	27	23	20
Lifetime, orbits	11	7	3

To execute ΔV=1 m/s requires:

SKD	44 kg of propellant	Δt=44 s
8 DPO	48 kg of propellant	Δt=132 s
SKD+8 DPO	46 kg of propellant	Δt=33 s

Fig. 1. One-impulse deorbit scenario

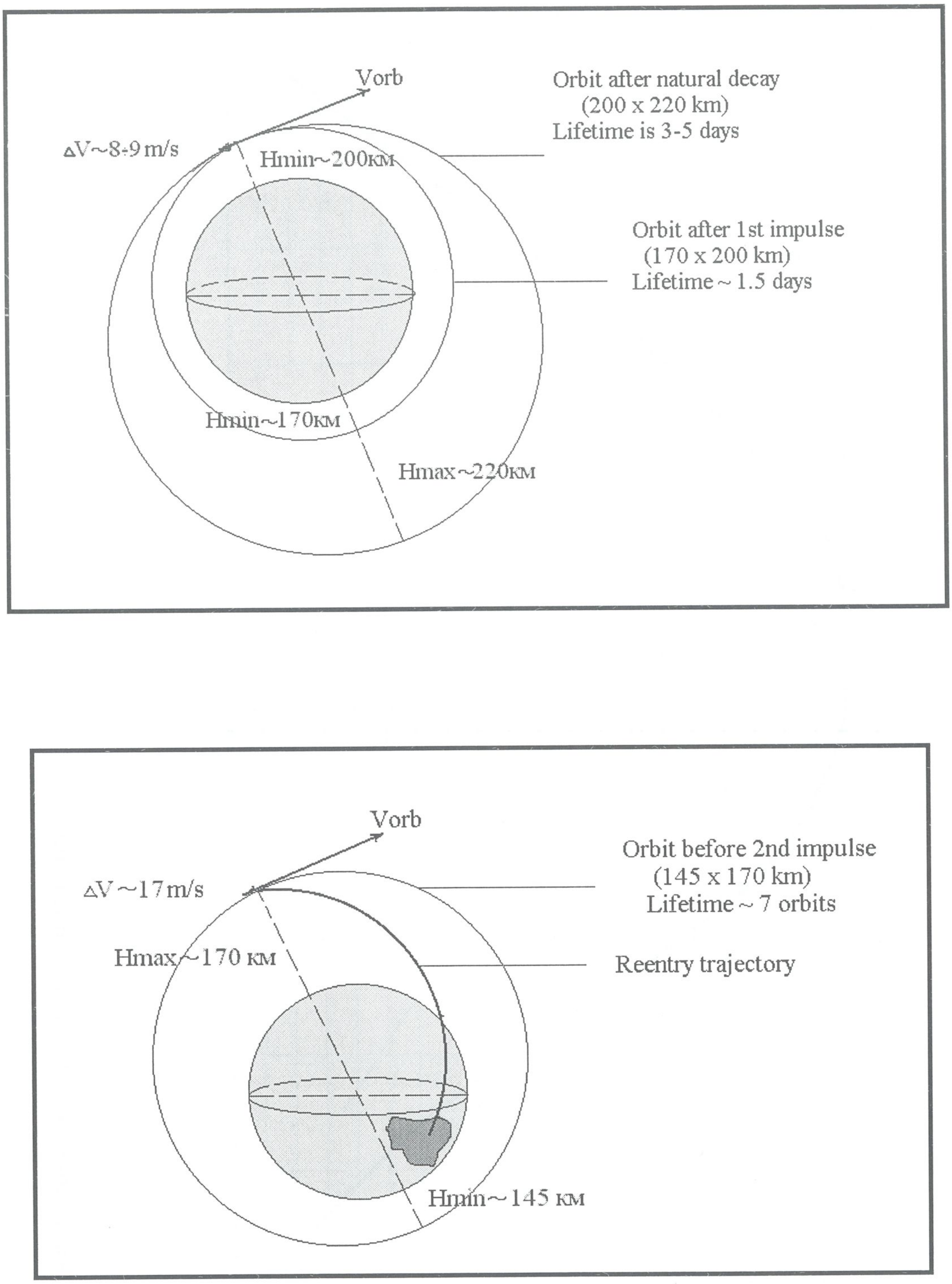


Fig. 2. Two-impulse deorbit scenario

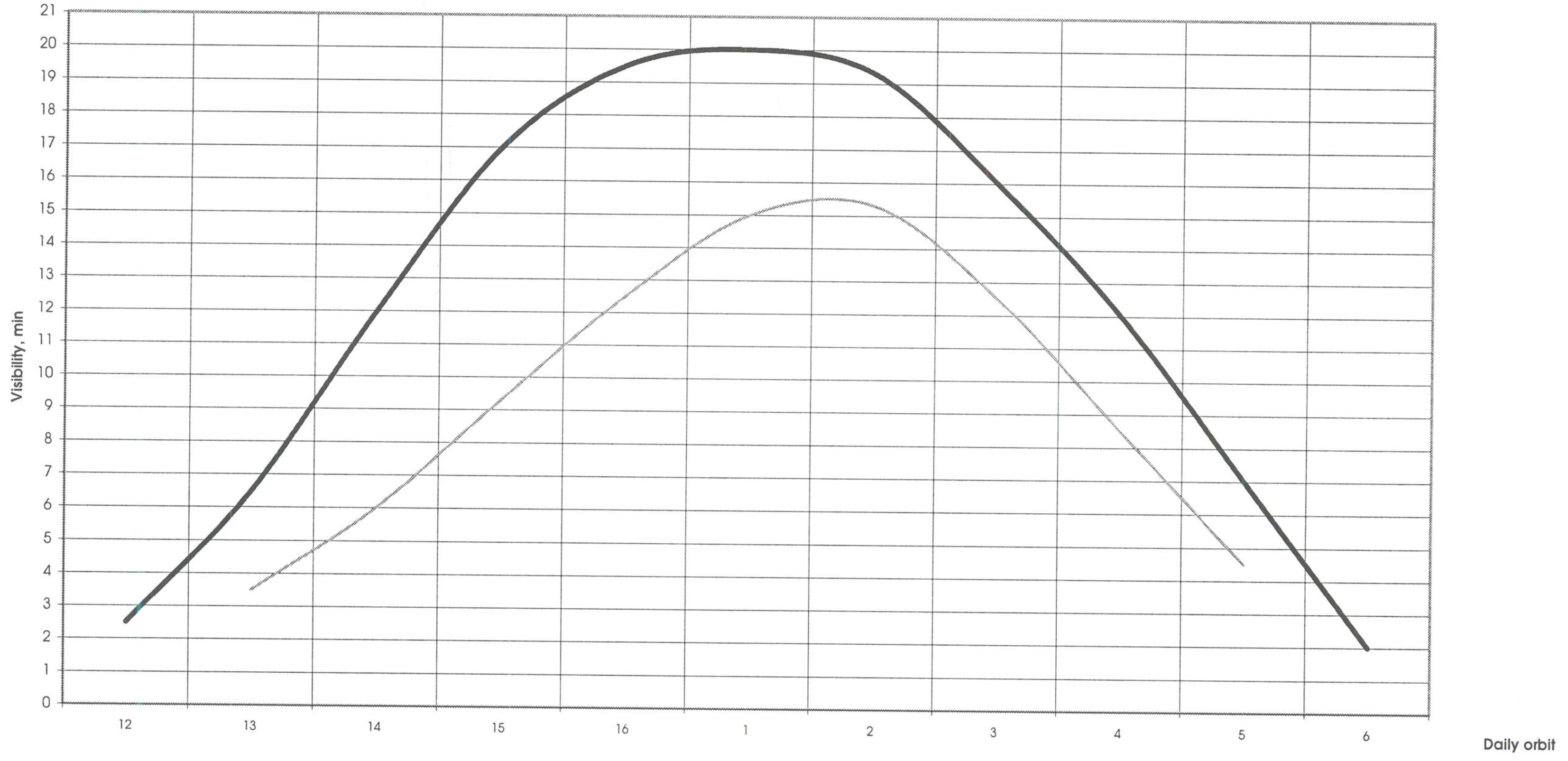


Fig 3. Total ground site visibility on one orbit

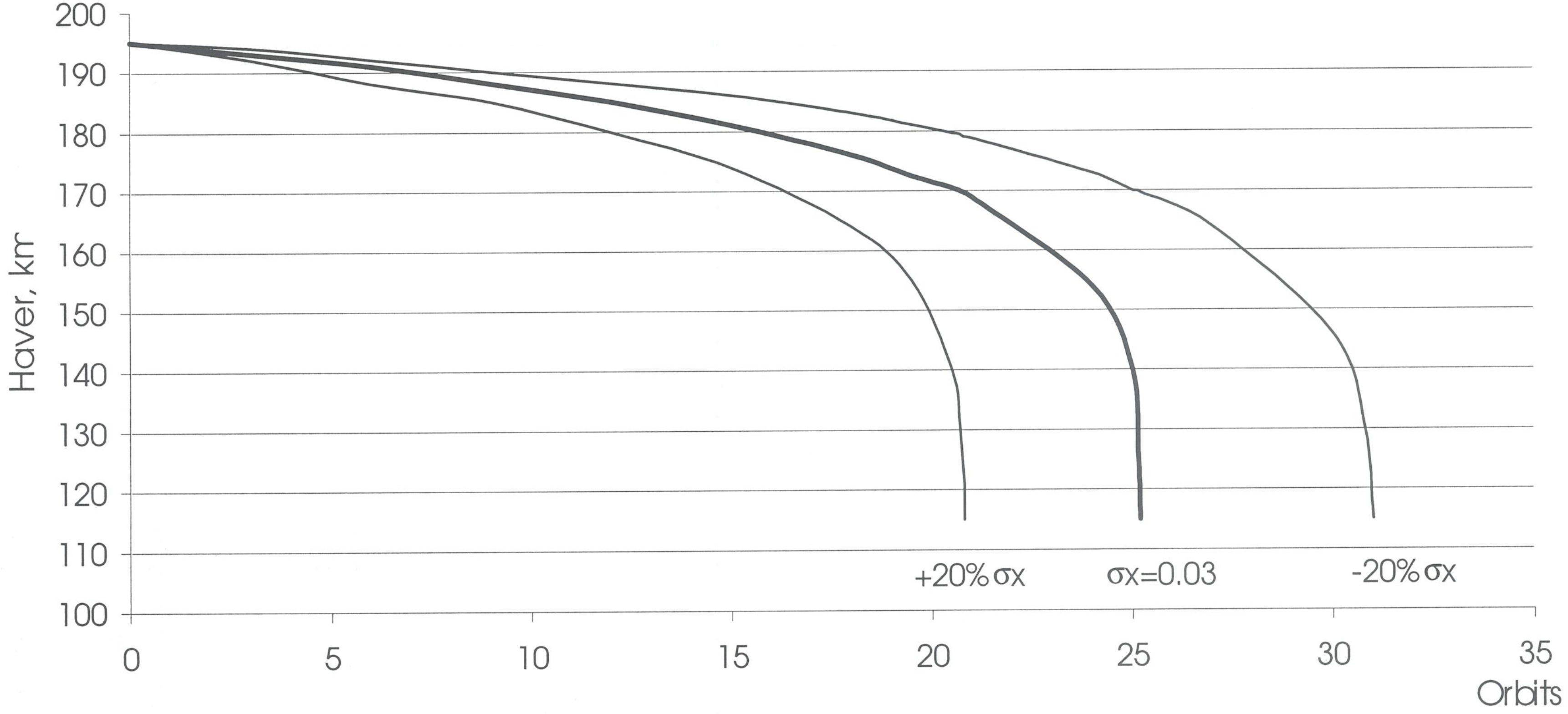


Fig 4. Mir lifetime on last orbits

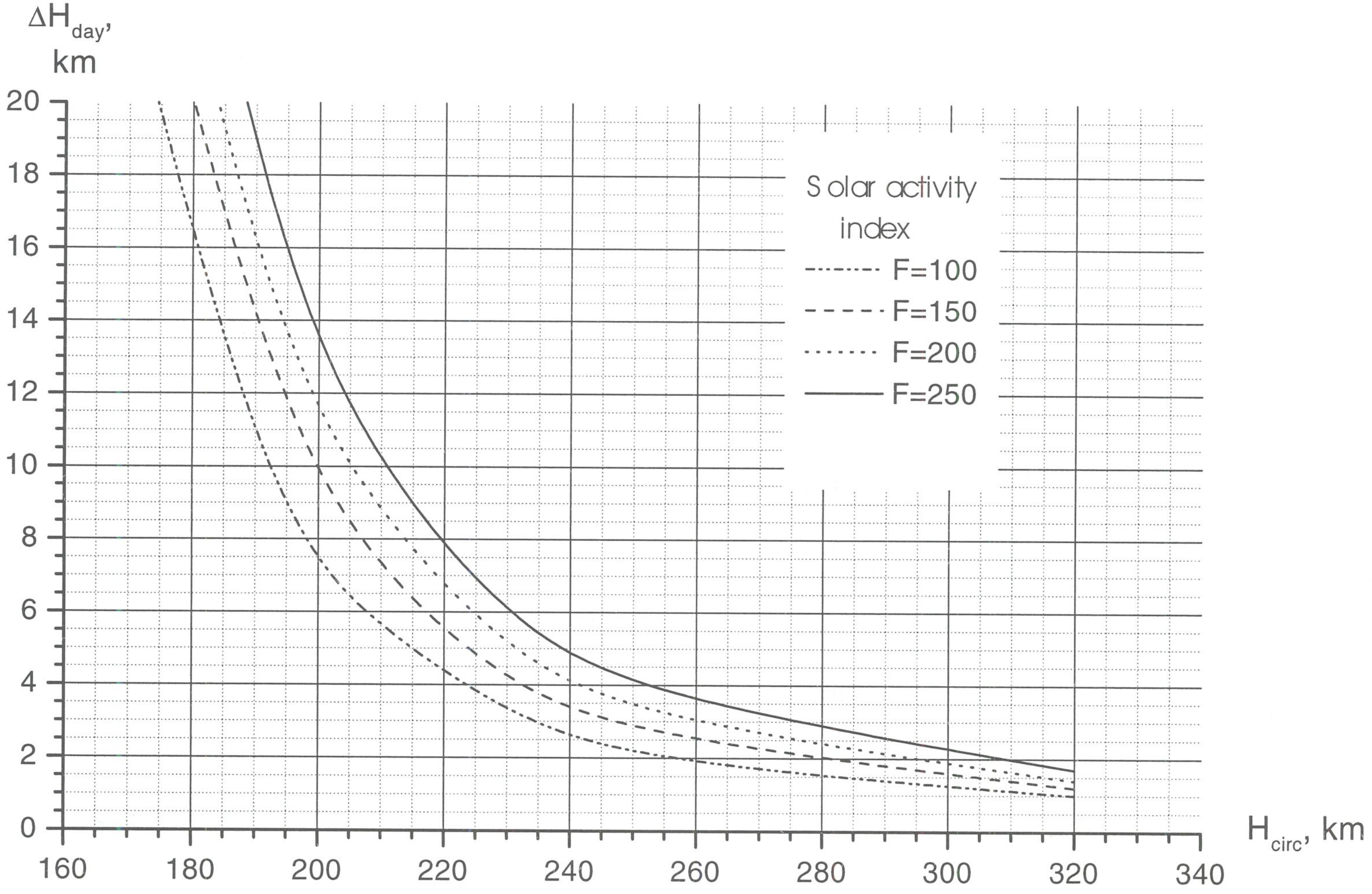
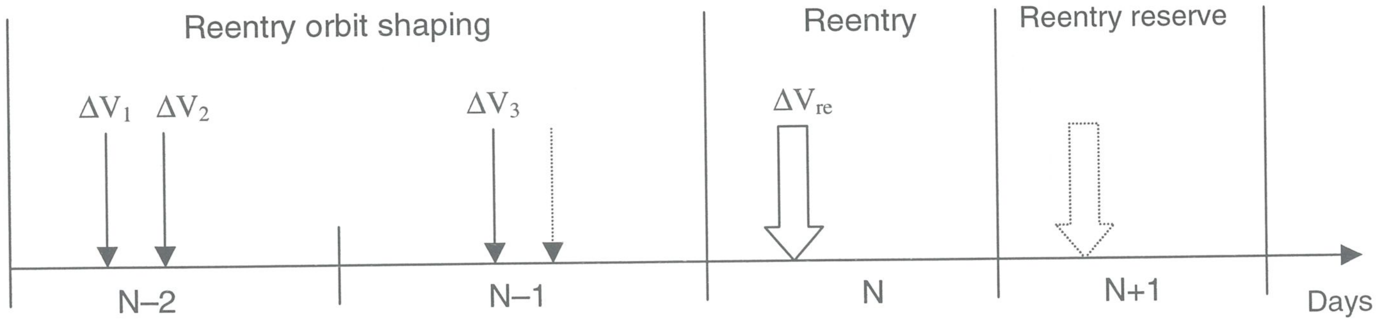


Fig 4a. Intensive passive (natural) braking at altitude H_{aver}=240-250 km



	Impulse value, m/s				Orbit parameters			
					Before maneuver			
	ΔV_1	ΔV_2	ΔV_3	ΔV_{re}	H_{burn}, km	H_{lan}, km	H_{burn}, km	H_{lan}, km
N–2	7	7	-	-	240	249	239	203
N–1	-	-	10	-	232	195	231	162
N	-	-	-	21	216	150	-	-

Note:
1. Average altitude prior to dynamic operations ~ 245 km.
2. H_{burn} – orbit altitude during burn,
   H_{lan} – orbit altitude above landing area.

Fig. 5. «Three-day» scenario of final dynamic operations

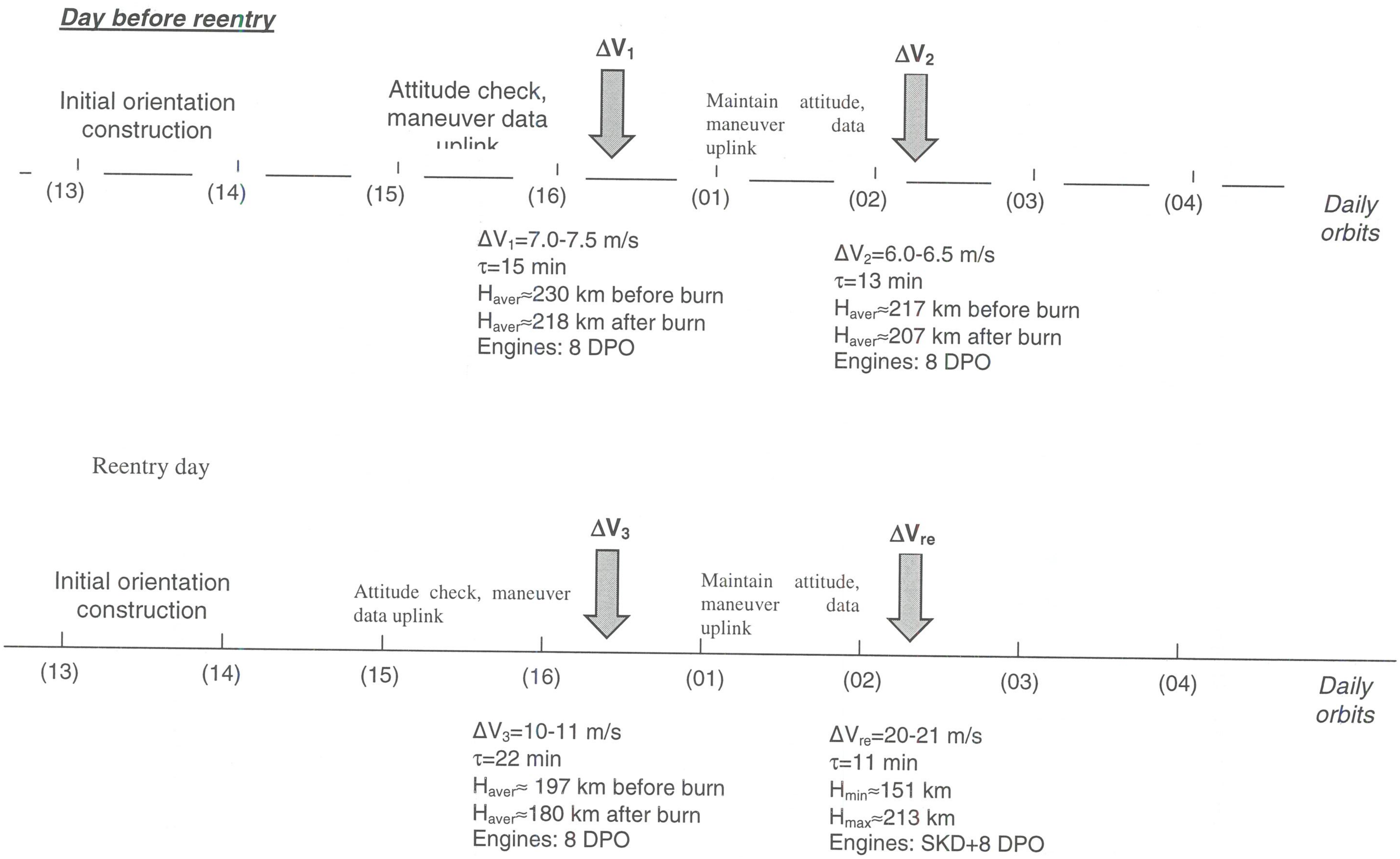


Fig. 6. «Two-day» scenario of final dynamic operations

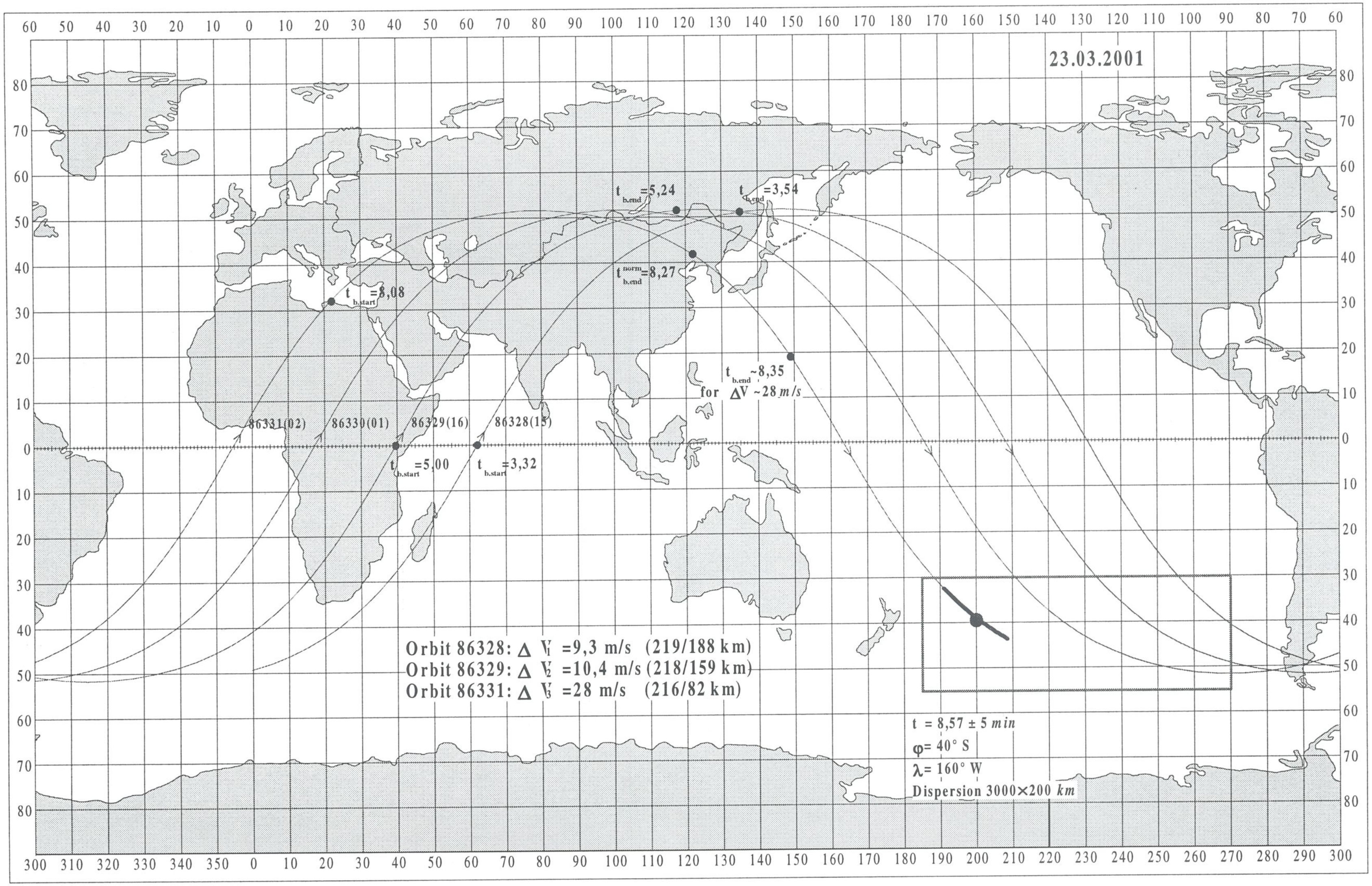


Fig. 7. Final Mir maneuvers