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Mission Profile of Targeted Splashdown for Space Station *Mir*

Vladimir Luchinski,* Rafail Murtazin,† Oleg Sytin,‡ and Yuri Ulybyshev§
Rocket-Space Corporation "Energia," Korolev, 141070, Moscow Region, Russia

The largest man-made object to reenter Earth's atmosphere is Russia's Space Station *Mir*, which was deorbited on 23 March 2001. The major requirements and constraints of the mission, propulsion options, and attitude systems are described. The mission profile includes two phases. The first phase is a low-thrust transfer to a prereentry orbit after the Mir orbit has decreased to a very low altitude, and the second phase is a final transfer with a maximum possible thrust-to-weight ratio from the prereentry orbit to a reentry trajectory. The problems of the mission profile for a targeted splashdown in a specified region of the Pacific Ocean east of Australia are considered. Two possible mission profiles were evaluated. The results of actual deorbit burn sequence and *Mir* reentry trajectory are discussed as well as brief description of contingency situations.

Nomenclature

H = orbit altitude over oblate Earth, km
P = thrust force, N
T = kinetic energy, kg-m^2/s^2
ΔV = velocity increment, m/s

Subscripts

max = maximum magnitude
min = minimum magnitude
Σ = summarized magnitude

Introduction

SINCE the beginning of the Space Age, thousands of man-made objects reenter Earth's atmosphere when their orbits decay under influence of aerodynamic drag. As a rule, these objects burn up in the Earth atmosphere and, similar to a meteor shower, pose no hazard. A danger to people and property on the ground is present in an uncontrolled reentry of large-scale objects and objects containing incombustible, heat-resistant, or hazardous (e.g., radioactive) materials. The large size of a spacecraft means that large pieces of it would survive any reentry and impact Earth, endangering people. To mitigate the potential risk to human safety, space organizations command and control and analyze the problem to avoid the risks associated with uncontrolled reentry for such objects. The goal is to ensure that unburned fragments or space debris impact on unpopulated areas of the Earth: as a rule, the Pacific Ocean. A prime example of these analyses is the controlled reentries of more than 100 Russian Progress spacecraft with targeted splashdowns in the South Pacific Ocean.[1] Another example is a controlled reentry of NASA's Compton Gamma Ray Observatory. This 17-MT spacecraft was deorbited on 4 June 2000 (Ref. 2). Its splashdown area was spread over a region in the Pacific Ocean southeast of Hawaii.

However, there are examples of uncontrolled reentries for large-scale objects. On 11 July 1979 the Space Station *Skylab* (80 MT) reentered and rained debris in a footprint more than 1000 km long and nearly 200 km wide in southwest Australia.[3] On 7 February 1991 the Space Station Salyut 7 (43 MT) made an uncontrolled reentry over Argentina.[3]

For deorbit of such spacecraft as the Space Station *Mir*, there are troubling factors caused by (in priority order) 1) low orbital and attitude maneuverability, 2) reduced reliability of the station and/or elements after many years of spaceflight, 3) very limited fuel, 4) an uncertainty of attitude dynamics for very low Earth orbit altitudes less than 180–200 km, etc. These factors must be built into the deorbit mission profile. This paper, using reports,[4–6] describes the major aspects of analysis and design used for the Space Station *Mir* targeted deorbit.

Reentry Breakup of Space Station *Mir*

The analysis of reentry breakup for large-scale space objects such as the Space Station *Mir* is a very complicated process that is inconvenient for an analytic estimation or full complex simulation. As a rule, a model of reentry breakup is a combination of the computational, experimental, and empirical data.

It was suggested that an initial breakup occurred at an altitude of approximately 100 km in which solar panels and antennas will break off the Space Station *Mir* main body and disintegrate. Catastrophic breakup, however, occurs most probably at an altitude of approximately 70 km where the most fragments form. The breakup process will continue to an altitude of 50 km. A subset of the debris fragments with high melting temperatures, including steel, titanium, high-temperature alloys, illuminators, and optical equipment lenses, will not burn and will fall to the Earth's surface. The total number of these space debris was estimated at 1400 with the total mass up to 40 MT. Final impact velocity of the space debris is between 40 and 450 m/s. Their mass varies from 0.05 kg (bolts and lenses) to 100 kg (intact modules or units).

A list of the major space debris types, estimates of their kinetic energy, and approximate number are given in Table 1. The kinetic energy of space debris can be used as a measure of potential damage.

Numerical simulation shows that the Space Station *Mir's* reentry debris footprint should be 15,000–20,000 km long and ± 70 km wide for an uncontrolled reentry and no more than 6000 km long for controlled reentry.

Space Station *Mir* Final Status

The Space Station *Mir* was launched on 19 February 1986, replacing the successful Salyut series of space stations. Operating in an orbit near 400 km altitude, the station was modular in design and had been slowly constructed in such a manner. At the final phase of life, the Space Station *Mir* with a total mass of 130 MT included the following modules: the Base Block, the Kvant, Kvant 2, Priroda, Kristall, and Spectr modules, and last, the Progress M1 spacecraft (Fig. 1).

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*Section Head, Space Ballistic Department.
†Deputy Head, Space Ballistic Department; rafail.murtazin@rsce.ru.
‡Principal Scientist, Space Ballistic Department; oleg.sytin@rsce.ru.
§Head, Space Ballistic Department; yuri.ulybyshev@rsce.ru. Member AIAA.

Inside the common propulsion system (CPS) tanks (in the Base Block) only 628 kg of fuel remained. The Progress spacecraft carried fuel in the refueling system (RS) (1620 kg) and filling system (FS) (720 kg) tanks. The major parameters of the Progress spacecraft engines are presented in Table 2. The Base Block and filling system tanks could be connected after pressure equalization at the expense of fuel consumption.

The orbital lowering of the Space Station *Mir* could be executed in two modes of engines firing. The first mode is the simultaneous firing of the eight docking and attitude thrusters (DAT). The second mode entails firing the Progress main engine (ME). At engine cutoff the burn result could be determined using the accelerometer data of the Progress spacecraft with a ΔV accuracy no less than ± 0.02 m/s. The accelerometer would be disconnected if the acceleration is less than 0.0067 m/s^2. (The measured acceleration in this mode reached 0.0074 m/s^2.) In this case the engine cutoff is based on an estimated time with the ΔV accuracy up to $\pm 4.5\%$ of a nominal value. Additionally, cutoff could be planned to coincide with fuel tank depletion, but this would only be acceptable for the final burn.

In the flight phases the Space Station *Mir* can hold attitude in the orbital coordinate system (OCS) or inertial coordinate system modes. The OCS rotates with Mir at its geocentric orbit rate. One axis is defined as always pointing toward the Earth's center along the radius vector; another axis is normal to the orbital plane, and the third axis points in the direction of the velocity vector and is perpendicular to the radius vector.

At the eight-DAT firing a perturbed moment is produced on the Space Station *Mir* because its mass center was displaced relative to the longitudinal axis of the Progress spacecraft. Attitude thrusters on the Base Block compensated for this disturbance, so, that there is an additive antithrust force. An example, for the burn in the eight-DAT mode, with the inertial attitude mode, the effective thrust vector is

$$\boldsymbol{P}^T + \Delta\boldsymbol{P}^T = (-981, 0, 0) + (24.5, 34, -71), \qquad \mathrm{N} \quad (1)$$

in the body reference system of the Base Block ($\Delta\boldsymbol{P}$ is the perturbed thrust force).

For an estimation of orbital transfer possibilities, a Monte Carlo simulation of the fuel usage was made. The random perturbations were displacements of specific impulse, ratio between fuel components, and perturbed force of the Base Block attitude thrusters. As a result, a guaranteed summarized characteristic velocity ΔV_Σ and characteristic velocity ΔV_f for the final burn were determined. Minimum values (with probability of $\pm 3\sigma$ or 0.9986) were $\Delta V_\Sigma = 42.5$ m/s and $\Delta V_f = 19.95$ m/s and average values $\Delta V_{\Sigma m} = 44.2$ m/s and $\Delta V_{\mathrm{fm}} = 20.48$ m/s. Furthermore, after joining of the CPS and FS tanks, an additional 200 kg (the equivalent $\Delta V \cong 4$ m/s) of fuel was made available. The mission profile was based on the guaranteed estimations.

Table 1 Space Station *Mir* space debris

Fragments	T, kg-m^2/s^2	Number
Docking unit at base block	10^6–10^7	1
Docking unit for space shuttle	10^6–10^7	1
Gyrodines	10^5–10^6	19
Elements of external engine unit	10^6–10^7	20
Elements of thruster modules	10^1–10^5	~200
Sphere balloons, pipes	10^4–10^5	~100
Elements of docking units	10^4–10^6	~100
Steel and titanium details	10^1–10^5	~200
Elements of control system equipment	10^1–10^5	~100
Lenses	10^1–10^5	~100
Instruments	10^1–10^5	~100

Requirements and Constraints of Mission Profile

A main requirement for the splashdown mission is the assurance that the majority of the space debris lands in an unpopulated area. The acceptable splashdown area is shown in Fig. 2. This requirement could only be satisfied using a mission profile with target margins that protect a debris footprint twice as large as the planned footprint. For this mission safe operations should be planned in which there are a minimum number of dynamical processes and transient states.

The Space Station *Mir* had a low thrust-to-weight ratio. In a sense the orbit transfers are similar to low-thrust transfers. However, in this case the execution of the one-burn deorbit with specified argument of perigee is ineffective. Therefore, the Space Station *Mir* deorbit mission with limited fuel should be executed by a sequence of burns.

The uplink and downlink operations and orbit measurements for the Space Station *Mir* could be realized only from Russia's ground stations (GSs). The visibility zones for these GSs are on the 1st–4th and 13th–16th daily orbits. (See a definition of this term in the Appendix.) Usually the GS geographical locations formed an almost continuous visibility zone. For safe control the burnouts (possible except after the final burn) should be complete several minutes prior to ground station loss of signal.

Mission Profile Selection

Basic Principles of Design

The main problem of the Space Station *Mir* final mission profile, with a low level of thrust-to-weight ratio, was a determination of the magnitude of the initial lowering maneuver and then the determination of how many orbits to wait, after the initial lowering maneuver, before performing the actual deorbit burn. As already mentioned, the mission is to be, at minimum, two phases. The first phase is a burn sequence with a prereentry orbit forming after the Space Station *Mir* has decreased to a low altitude. At this phase the eight-DAT mode with the smallest thrust-to-weight ratio is to be used. The second phase is a final reentry burn in the ME+ eight-DAT mode with the maximal possible thrust-to-weight ratio.

In the case of complete failure of the final burn, the execution of this burn must be considered in the mission design not only for the nominal day but also for a backup day. This means that the

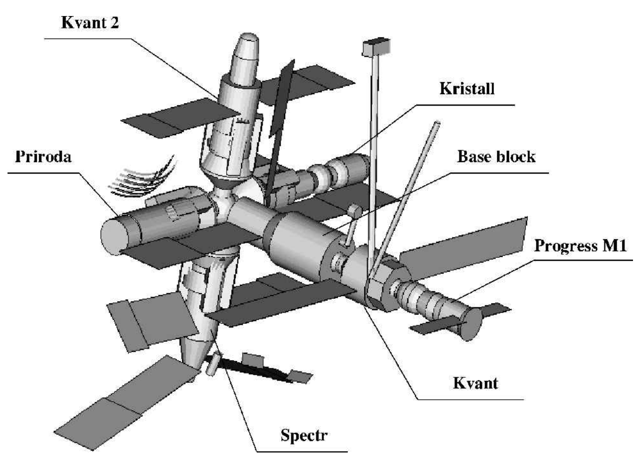

Fig. 1 Final configuration of the Space Station *Mir*.

Table 2 Progress spacecraft engines

Engine	Number	Nominal thrust, N	Specific impulse, s	Angle between thrust vector and longitudinal axis, deg	Maximal firing time, s
Main	1	2493	302	5	Unconstrained
Docking and attitude thrusters	8	130.5	295	20	2000

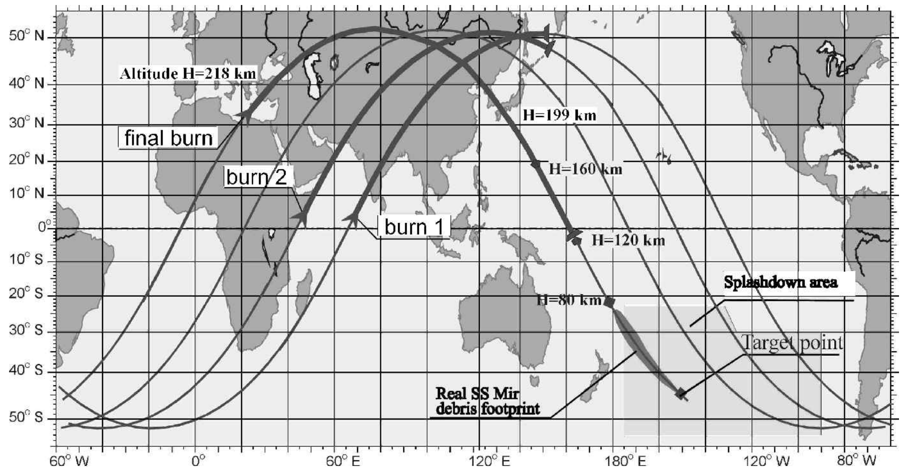

Fig. 2 Acceptable splashdown area and final burns.

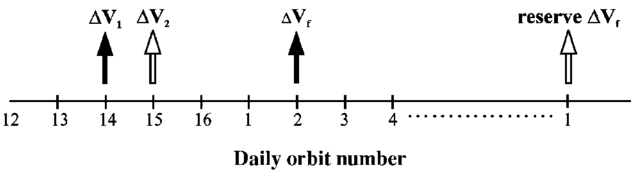

Fig. 3 Four-orbit three-burn mission profile.

prereentry orbit has to be high enough with a guaranteed lifetime at least 24 h. Based on guaranteed estimations of Progress power possibilities and Space Station *Mir* atmospheric flight simulation, maximum perigee altitude of an orbit before a final burn should be in a range of 159–165 km, and perigee altitude after the final burn should be no more than 80 km.

We have considered multiple mission profiles, which are distinguished by maneuver number, attitude modes, and durations. Examples of such missions are four-burn and three-burn mission profiles, which are provided during two days. Based on the mission reliability was chosen the profile with the three burn during four orbits.

Four-Orbit Three-Burn Mission Profile

A schematic diagram of a four-orbit three-burn mission is presented in Fig. 3. All of the burns are performed in the inertial attitude mode, and times between the burns are minimal. The mission profile consists of two stages. The first stage is a two-burn transfer to a prereentry orbit, and second is a final transfer to a reentry trajectory. It is very important that the attitude for the first two burns is the same and for the final burn that the attitude maneuver be very small. To accommodate these constraints, the profile includes a common attitude mode, that is, the inertial mode.

For successful splashdown there was a window of a few days during which fuel constraints could be satisfied. The window is shown in Fig. 4. Table 3 presents examples of minimum and maximum orbit altitudes for initial orbit before burns, prereentry orbits before final burn on the nominal day and on backup day, and also required characteristic velocities for first two burns ($\Delta V_{12} = \Delta V_1 + \Delta V_2$) final burn ($\Delta V_f$), and their sum ($\Delta V_\Sigma$) for nominal day depending on a calendar day of the deorbit start.

Possible Contingency Situations

In the case of a contingency situation, primarily, an incomplete and/or inaccurate execution of a burn, the successfully targeted splashdown would not occur. In a sense the contingency situation set formed an infinite set of trajectories. A bound of this set is the reentry trajectories with a part of their debris footprint outside splashdown area. As a limit case, another bound is an uncontrolled reentry of the Space Station *Mir*. For such situations we could encounter a debris footprint between latitudes ±52 deg.

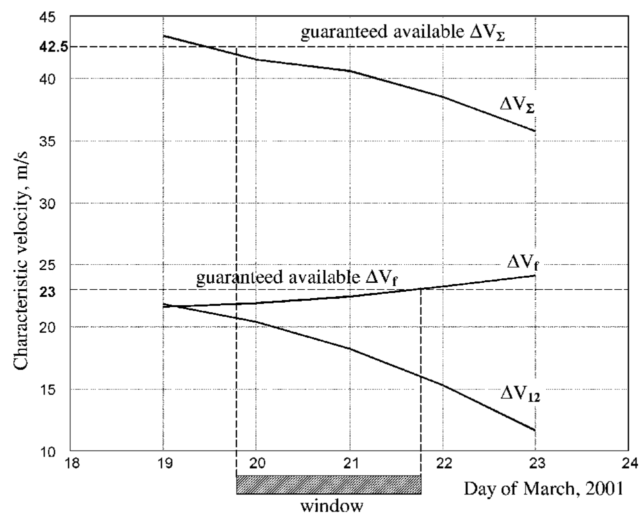

Fig. 4 Splashdown window based on orbit determination 12 March 2001.

Main Engine Breakdown

As a possible contingency situation, a Progress ME failure was considered. In this case the debris footprint length is more than the possible lengths of the trace parts belonging to the splashdown area because the eight-DAT mode cannot achieve the required entry flight-path angle. The eight DAT produce very low thrust and have a constraint for burn duration of 2000 s. This constraint would limit the velocity for final burn to an unacceptable $\Delta V_f = 15$ m/s; therefore, final orbit should be with altitude no more than 140–145 km.

A main design point for this situation is the choice of a daily orbit for a reentry with a ground track almost continuously over water. The 16th daily orbit (the first daily orbit is backup) (Fig. 5) satisfies this condition. During daily orbit 16, acceptable splashdown area coincides with the ground track east of Japan up to the African coast. This area does include only a small populate area in southern Argentina. For reentry at 16th daily orbit with an altitude of 140–145 km, a small retrograde or posigrade burn ΔV_1 (no more 3–4 m/s) on third-fourth daily orbits of the previous day (Fig. 6) would be required because there was a probability of an uncontrolled reentry with debris footprint in very populated areas.

Contingency Deorbit with Very Small Fuel Resource

A burn breakdown could cause a contingency situation in which there was a possibility of a very small fuel resource for final burn. In such an event, a profile with a waiting period up to the orbit lifetime of a day and final burn of several meters per second was considered. This transversal maneuver (posigrade or retrograde, depending on

Table 3 Examples of prereentry orbits

Day, March 2001	$H_{min} \times H_{max}$, km: Initial orbit (13th daily orbit number)	Prereentry orbit: Nominal day	Prereentry orbit: Backup day	Characteristic velocities, m/s: ΔV_{12}	ΔV_f	ΔV_Σ
		Orbit determination on 5 March 2001				
19	221.6 × 241.2	161.4 × 228.1	152.7 × 208.5	19.9	22.9	42.8
20	217.7 × 236.2	165.0 × 223.7	155.8 × 205.4	17.0	23.2	40.2
21	213.3 × 230.7	163.9 × 217.3	152.9 × 198.2	15.6	23.4	39.0
22	208.3 × 224.5	165.6 × 213.3	153.0 × 192.9	13.3	23.5	36.8
23	202.3 × 217.4	165.7 × 207.4	150.3 × 184.8	11.3	23.5	34.8
		Orbit determination on 12 March 2001				
19	222.3 × 241.2	158.5 × 231.2	150.1 × 210.0	21.9	21.6	43.5
20	218.9 × 238.2	159.3 × 227.0	149.8 × 205.4	19.9	21.9	41.8
21	214.9 × 232.9	161.2 × 220.2	148.9 × 200.0	19.0	22.4	41.4
22	210.3 × 227.0	164.0 × 218.2	152.0 × 196.5	14.7	23.2	37.9
23	205.3 × 220.9	167.0 × 212.6	153.1 × 190.9	11.8	24.1	35.9

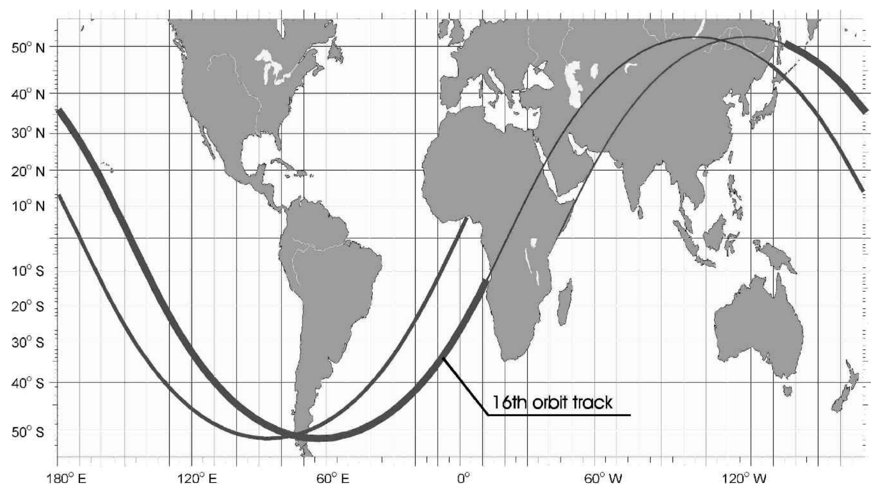

Fig. 5 Possible track for a contingency situation with the ME breakdown.

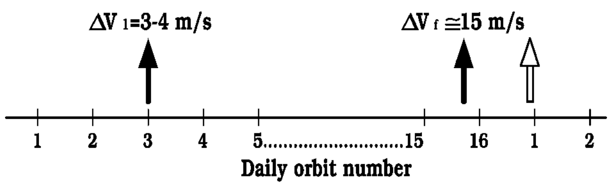

Fig. 6 Two-burn mission profile for ME breakdown.

the situation) could be executed for the purpose of postponing reentry to avoid space debris falling on very populated areas.

It is evident that this choice is very complicated and contains not only technical requirements but also political considerations. As a daily orbit choice criterion, we could use the ratio between land and water surface parts for reentry orbit trace. This ratio vs ascending node longitude is illustrated in Fig. 7.

Uncontrolled Reentry

The Space Station *Mir* reentry could expose some area under its orbital path (between 52° north and south latitudes) to the risk of falling debris. Probability of space debris falling on the land or water surface can be estimated as 28 and 72%, respectively. For several regions these estimations are Community of Independence States, the former Soviet's republic (CIS), 1.0%; United States, 1.7%; Western Europe, 0.5%; Asia (without CIS), 6.9%; Africa, 8.2%; Australia, 1.5%; and Latin and South America, 8.6%. We estimated a 3-in-10,000 chance that the uncontrolled Space Station *Mir* reentry would result in space debris falling on cities with populations over one million.

As a part of the preparation in case of such a dangerous situation, special software for analysis of the Space Station *Mir* reentry trace passing through countries (~200) and major world cities (~300) was developed. The analysis was based on computational geometry methods. All of the countries were presented as polygons of boundary points and the reentry trace as a street with debris footprint width. In addition, a large table of traces passing through the countries and major cities vs longitude of ascending node was developed. A fragment of this table is displayed in Fig. 8. Notice that such tables can be used for other applications.

Execution of Space Station *Mir* Targeted Splashdown

Preliminary Operations

Before beginning the final deorbit operations, the daily forecast of the Space Station *Mir* deorbit window with current parameters of solar activity and the Space Station *Mir* status was thoroughly analyzed. On 18 March 2001 two dates for the Space Station *Mir* deorbit were chosen: 22 and 23 March. The main criterion for the choice was a constraint on total magnitude of the first two burns for prereentry orbit forming, that is, $\Delta V_{12} \leq 19$ m/s. On 19 March it was clear that the Space Station *Mir* deorbit could be executed no earlier than March 23.

According to plan, on 21 March (the 13th daily orbit) the Space Station *Mir* was oriented to the Inertial-1 attitude mode, which provided optimal charging of the solar arrays. Space Station *Mir* held this attitude until the first burn.

During the final days, there was concern with the possible excessive fuel usage for attitude control. According to an analysis in last days before deorbit, such assumption had a probability. If this

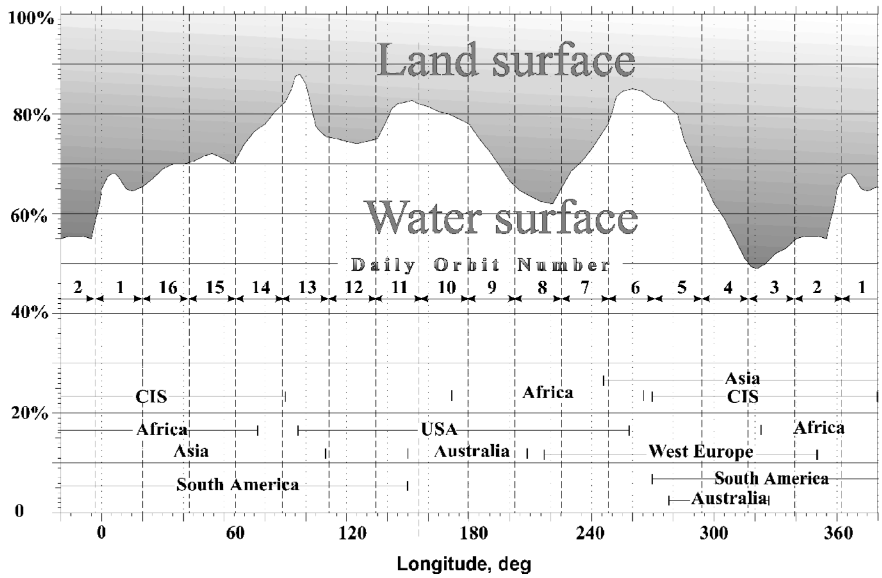

Fig. 7 Ratio of land and water surface parts of the Space Station *Mir* traces.

	Country	Mean coordinates		Longitude of ascending node,deg											
		λ,deg	φ,deg	0	2	4	6	8	10	12	14	16	18	20	22
1	Afghanistan	68	35												
2	Albania	20	41												
3	Algeria	3	30												
4	Andorra	2	43												
5	Angola	17	-11												
6	Antarctica	-10	-72												
7	Antigua and Barbuda	-62	17												
8	Area under dispute	46	29												
9	Argentina	-65	-39												
10	Armenia	45	40												
11	Australia	135	-25												
12	Austria	13	48												
13	Azerbaijan	47	40												
14	Bahamas	-76	24												
15	Bahrain	51	26												
16	Bangladesh	90	24												
17	Barbados	-60	13												
18	Belarus	27	54												
19	Belgium	5	51												
20	Belize	-89	17												
21	Benin	2	10												
22	Bermuda	-65	32												
23	Bhutan	91	27												
24	Bolivia	-65	-17												
25	Bosnia-Herzegovina	18	44												
26	Botswana	25	-22												

Fig. 8 Fragment of table for the Space Station *Mir* trace passing through countries.

concern proved true, there would be insufficient fuel for the final deorbit burn, resulting in an increased debris footprint. So literally 24 h prior to the deorbit burn (22 March), a decision was made to shift the deorbit target point closer to the western boundary of the splashdown area. The original target point had a latitude of 50.4°S and longitude of 135.9°W (the middle of the splashdown area; see Fig. 2). After the change the target point was updated to have a latitude of 44.2°S and longitude 151.4°W. The shift of the targeted point to the western boundary provided an additional guarantee that the most dangerous fragments (such as gyrodines or titanium bolts) would not reach the west coast of South America.

First Two Burns

After performing orbit measurements on the 14th–16th daily orbits, it was determined that total magnitude of the first two burns required 19.68 m/s (9.28 and 10.40 m/s, respectively). An excess of ~0.7 m/s from a value accepted as a constraint ($\Delta V_{12} \leq 19$ m/s) was caused by an orbit rise after the first attitude maneuver. The new burn data were uplinked in the visibility zone of Russia's Ground Stations on the third daily orbit.

On 22 March the attitude was changed from the Inertial-1 mode to the Inertial-2 mode. The last attitude mode provided increased aerodynamic drag but was convenient for execution of the maneuvers. The major parameters of the first two burns on 23 March are given in Table 4. Durations and fuel consumption for each burns were received from telemetry.

An increase of fuel consumption was a result of an antithrust force of ~25 N as a result of attitude hold of the Space Station *Mir* during the burns. During both burns, the Space Station *Mir* attitude was unchanged, and its accuracy was estimated to less than 1 or 2 deg. After these burns using tracking dates on 15th, 16th, and 1st daily orbits to the beginning of the 2nd daily orbit was formed the prereentry orbit with $H_{\min} \times H_{\max} = 157.7 \times 216.7$ km and perigee argument of 226.25 deg. This orbit was near the precomputed orbit altitude $H_{\min} \times H_{\max} = 158.2 \times 216.4$ km and confirmed nominal burn execution. The Space Station *Mir* trace on its final orbits is

Table 4 First two deorbit burns

Burn number	Time, GMT	Duration, s	Characteristic velocity ΔV, m/s: Based on accelerometer data	Characteristic velocity ΔV, m/s: Without antithrust loss	Pitch angle in the OCS at burn beginning, deg	Amount of fuel expended, kg
1	00:31:59	1257	9.28	9.49	−47.0	460
2	02:00:24	1374	10.40	10.72	−47.0	510

Table 5 Final burn timeline

Time, GMT	ΔV_s, m/s	ΔV_τ, m/s	ΔV_r, m/s	Mode	Fuel consumption, kg	Notes
5:07:37–5:19:15	21.7	21.05	1.34	ME + 8DAT	713(RS) + 258(FS)	100% thrust
5:19:15–5:19:58	0.84	0.73	0.20	ME + 8DAT	22(RS) + 21(FS)	50% thrust
5:19:58–5:29:05	6.88	4.56	5.01	ME + 8DAT	350(FS) + 13(CPS)	26% thrust
5:29:05–5:30:40	0.74	0.28	0.68	8DAT	21(FS) + 15(CPS)	End of visibility zone
5:30:40–5:37:40	3.14	0.26	3.09	8DAT	155(CPS)	Altitude ∼120 km (rough estimate)

shown in Fig. 2. A postflight analysis using orbit estimations and the Progress burns estimated Space Station *Mir* mass before the first burn was 130.8 ± 0.25 MT.

Space Station *Mir* Final Burn

At the end of Russia's Ground Station visibility zone on the 16th daily orbit, the data for the final burn were uplinked to the onboard computer. The first daily orbit was planned as a backup uplink opportunity. Similar to the first two burns, the Space Station *Mir* maintained a constant inertial attitude. At the beginning of the burn, the pitch angle (the longitudinal axis of the Progress spacecraft) in the OCS was −20 deg.

On the first daily orbit the fuel usage on attitude and stabilization during execution of the first two burns was determined. It was determined that the estimations on fuel usage for attitude were close to planning, but on attitude hold they were overestimated. As a result, at the start of the final burn the CPS tanks contained approximately 450 kg, an expected 340 kg. Thus the fuel remainder was defined for the CPS as ∼450 kg ($\Delta V \sim 7$ m/s), RS as ∼650 kg ($\Delta V \sim 13$ m/s), and FS as ∼720 kg ($\Delta V \sim 16$ m/s).

The final burn can be presented as three sections: first, the guaranteed characteristic velocity parts along transversal (firing the ME + eight-DAT mode), which was estimated as $\Delta V \sim 19.4$ m/s; second, the depletion of fuel from the ME up to the GS visibility zone ending (firing the eight-DAT mode), which was estimated at $\Delta V \sim 3.3$ m/s; and third, the firing of engines (eight-DAT mode) 7 min after the ground zone, which was estimated at $\Delta V \sim 0.2$ m/s.

Based on this information, the summary transversal characteristic velocity should be no less than $\Delta V_f \sim 22.9$ m/s for which reentry trajectory was an acceptable debris footprint. However, actual ΔV_f could be as high as 23.5 m/s.

There was an additive way for increasing of the final burn characteristic velocity through a connection of the CPS and RS tanks and following engine work in the eight-DAT mode. This regime could be realized between a time for which the pressure in both tanks would be approximately equalized and down to loss of inertial attitude control at low altitudes. Therefore based on a computation the tank connection was selected 15 min after the beginning of the burn.

After switch to the eight-DAT mode, the onboard computer will continue the characteristic velocity calculation with acceleration of the ME + eight-DAT mode (0.031 m/s^2). By this means the characteristic velocity setting was assigned as 40 m/s.

Furthermore, as a consequence of a pressure difference between the RS and FS tanks at moment of RS fuel ending (∼12–13 atm) the ME engine continued to work on a low thrust (∼26% from nominal). The reason is that there was a fuel flow-over from the FS tank to the RS tank. This fact was validated telemetry data. As a summary result, the ME switch-off was occurred after achievement of a fictitious characteristic velocity of 40 m/s at 5:29:42 (GMT). The actual characteristic velocity was estimated as 29.42 m/s. The timeline of the final burn is shown in Fig. 9 for precomputed (dashed line) and actual (solid line) data.

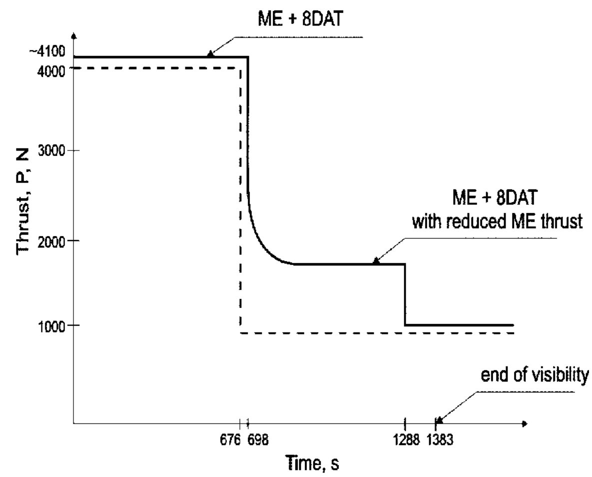

Fig. 9 Final burn thrust profile.

Table 5 shows the data of characteristic velocity increments on the Progress's longitudinal axis ΔV_s, its projections along transverse ΔV_τ, and radial axes ΔV_r of the OCS and fuel consumption from fuel tanks on depending execution's time of final burn.

Space Station *Mir* Reentry Trajectory

The data presented in Table 5 illustrate that the final burn characteristic velocity was more than the precomputed value. Therefore, the Space Station *Mir* had a steeper reentry trajectory and an essentially smaller area of the space debris footprint. The center of the space debris footprint had shifted to western boundary of the splashdown area with a latitude of 26.221°S and a longitude of 175.875°W. Time of impact in the Pacific Ocean was approximately 05:53:10 (+5/−0.5 minutes) GMT. The postflight calculated reentry trajectory is given in Table 6. This trajectory appropriate ballistic coefficient ∼400 kg/m^2.

As additional information, our computational estimations were confirmed with reliable visual observation of the Space Station *Mir* reentry trajectory from the island Viti-Levy (Ref. 7). Time of observation was about 5:46:30–5:47:30 GMT. Change of altitude during observation was about 75–69 km. Minimal distance during observation was about 104 km. Maximal elevation angle during observation was about 44 deg.

These data were correlated with eyewitness visual observations of the time and angle of falling fragments and, at last, sound effects (probably overcoming a sonic barrier) in 5 min after observations. Furthermore, the absence of observations of the Space Station *Mir* by Bob Citron's team[8] (which used two aircraft) also corraborates the reentry trajectory. The first aircraft was located on a latitude near 30°S and longitude of 173°W. An analysis of these positions has shown both aircrafts had no opportunity to

Table 6 Space Station *Mir* reentry trace

Time, GMT	Altitude, km	Geographic latitude,°	Geographic longitude,°
5:35:43	125	17.59N	150.04E
5:37:29	115	12.20N	154.51E
5:39:24	105	5.96N	159.11E
5:41:33	95	1.09S	164.13E
5:44:01	55	9.25S	170.01E
5:46:34	75	17.41S	176.29E
5:48:03	65	21.85S	179.96W
5:48:51	55	23.97S	178.04W
5:49:25	45	25.15S	176.93W
5:49:54	35	25.82S	176.29W
5:50:27	25	26.13S	175.98W
5:51:10	15	26.21S	175.89W
5:52:06	5	26.22S	175.88W

observe fragments of Space Station *Mir* because the most spectacular blazing part of its trajectory was much northwest of their positions.

Conclusions

The design of the final mission for the Space Station *Mir* as the largest object ever returned to Earth was defined primarily by the limited fuel margin allocated for orbital maneuvering and low level of thrust-to-weight ratio. The first factor relies on expected orbit decay under atmospheric drag, whereas the second calls for a significant decrease of prereentry orbit altitude. As a result, all final operations should be carried out at extreme low altitudes. Additionally, many items were experienced for the first time: space station attitude maneuvers at low altitude, attitude hold of the space station under relatively dense atmosphere, and Progress main engine cutoff designed to end at fuel depletion. A reduced reliability of the Space Station *Mir* systems after a very long lifetime should also be considered.

Review of the Space Station *Mir* deorbit data showed that the targeted splashdown was performed in accordance with designed mission profile. The minor anomalies did not affect the final positive result. The Space Station *Mir* targeted splashdown was actually a unique flight mission.

It is evident that in a not too distant future a similar problem will arise regarding the International Space Station. In this case thrust-to-weight factor will be greatly decreased with respect to Space Station *Mir*. The main recommendation, based on the Space Station *Mir* targeted splashdown experience, is to design a profile with a single deorbit burn using a spacecraft with a relatively high thrust and high reliability. As an example, the boost block DM-SL for the sea launch missions can be used for this purpose (after a modification). We recommend this modification be made in the near future.

Appendix: Daily Orbit Number

A term *daily orbit number* for low Earth orbits is used very often in Russian astronautics. This term indicates the number of ascending (northward) passes over the Earth's equator. This orbit count begins with launch orbit and increases for each ascending node. The orbit number resets to orbit one for the first ascending node with a value of geographical longitude west of 20° East longitude (for orbit inclination of 51.6 deg). The daily orbit number is a well-behaved parameter for a mission analysis related satellite visibility from a particular region.

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C. A. Kluever
Associate Editor