THE MANAGEMENT OF THE MIR REENTRY IN ITALY

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ABSTRACT

The paper presents a review of the management of the Mir deorbiting in Italy, with special emphasis on the role played by CNUCE, active in the field of reentry predictions for civil protection purposes since 1979.

After a short historical introduction, the criteria used for the definition of potentially risky space objects are presented and discussed, together with the lessons learned during previous reentry campaigns. The activity carried out for Mir is then described in detail, highlighting the end products needed for the civil protection emergency planning.

Mir was never declared a risk space object in Italy and only a limited alert status was activated, ready to switch to full emergency if needed. However, the event represented a useful training opportunity and a good example of international cooperation, paving the way for the future end-of-life disposal of large low earth spacecraft.

1. INTRODUCTION

After the uncontrolled reentry of the nuclear powered satellite Cosmos 954, on January 1978, a reentry prediction team was established at CNUCE, an institute of the Italian National Research Council (CNR), to monitor the orbital decay of potentially risky space objects and to provide timely information to the national civil defense authorities. The first reentry campaign in which CNUCE was involved was carried out, in 1979, for the American space station Skylab, then the heavier object ever returning from space.

Since Skylab, several reentry campaigns were accomplished, to predict the orbital decay of potentially risky spacecraft [1][2][3][4] (Table 1), to monitor the altitude evolution of interesting space objects [5], or as a test to check the available models and the data flux (Table 2). In particular, three reentry test campaigns (Inspektor, GFZ 1 and Soyuz rocket body 1999-062E) were promoted by the Inter-Agency Space Debris Coordination Committee (IADC), to improve the level of international cooperation and the harmonization of the decay prediction work [6].

Following the world-wide alarm aroused in the previous decade by the end-of-life failures on board of three Soviet nuclear powered satellites, during 1989-1990 CNUCE contributed, together with other national institutes and agencies, to the drawing up and formal issuing of an operational manual, based mainly on the experience matured during the Cosmos 1900 event. It was requested by the Italian civil protection authorities to manage future nuclear reentry emergencies [7].

Table 1

Risk Objects Reentry Predictions Campaigns

Satellite	Type	Year
Skylab	Space Station	1979
Cosmos 1402	RORSAT	1982-1983
Cosmos 1625	EORSAT	1985
Cosmos 1714	Tselina-2	1986
Cosmos 1767	Scientific S/C	1986
Cosmos 1900	RORSAT	1988
Salyut 7/Cosmos 1686	Space Station	1990-1991
Progress-M 17	Supply Vessel	1994
Granat	Scientific S/C	1999

Table 2

Other Reentry Campaigns

Satellite	Type	Year
FSW-1 5, object A	Service Module	1993
Cosmos 398	Test Lunar Module	1995
FSW-1 5, object H	Reentry Capsule	1993-1996
TSS 1R	Tethered Satellite	1996
Inspektor	Technological S/C	1998
GFZ 1	Scientific S/C	1999
Soyuz 1999-062E	Upper Stage	2000
Interball 1	Scientific S/C	2000

In the same years, the new Italian Space Agency (ASI) and the Civil Protection Department of the Italian Government concluded an agreement on the future management of emergencies due to the uncontrolled return of space objects, and CNUCE was entrusted with the official duty of providing reentry predictions and technical support under ASI contract. This situation was consolidated in 1994, with the establishment, at CNUCE, of the Space Objects Monitoring Service

(SMOS), reporting directly to the national civil protection authorities, but funded by ASI in the framework of a broader ASI-CNUCE cooperation contract [8].

2. CNUCE REENTRY CLASSIFICATION

In order to characterise in a synthetic way the reentry in the earth's atmosphere of a space object, a classification scheme, including a magnitude scale, was introduced at CNUCE in 1995 [9][10]. According to it, the risk associated with the uncontrolled return of an artificial satellite can be qualitatively assessed in terms of mass *categories* and event *classes*. The reentry *category* or *magnitude* [*M*] is defined by the following relationship:

$$M = Log_{10}\left(m/100\right) \qquad (1)$$

where m is the mass of the space object in kg. Table 3 shows the CNUCE scale in detail, together with an approximate risk descriptor.

Table 3

CNUCE Uncontrolled Reentry Scale

Category		Risk Descriptor
Mass [kg]	Scale (M)	
100	0	Negligible
1,000	1	Small
10,000	2	Minor
100,000	3	Moderate
1,000,000	4	Substantial

Table 4

CNUCE Reentry Event Classes

Reentry Event Description	Class
Possible nuclear, biological or chemical contamination	C
Complete object disintegration in the high atmosphere	D
Fall of large fragments (≥ 10 cm) on the ground	F
Object able to maintain its structural integrity during the reentry	S

However, the space object mass alone is not sufficient to characterize a reentry event. Therefore, some reentry *classes* were defined as well, to take into account the structural and compositional properties of the returning satellite, and the potential contamination on the ground due to hazardous substances carried on board (Table 4). In Table 5, a few examples of the application of the CNUCE classification scheme to actual reentry events are shown.

Table 5

Classification of Some Reentry Events

Reentry Event	Classification
Cosmos 1900	1.6 CF
Salyut 7/Cosmos 1686	2.6 F
FSW-1 5	0.8 S
TSS 1R	0.8 D
Mir (controlled reentry)	3.1 F

3. RISK OBJECT DEFINITION

A returning satellite is defined a *risk object* when all the following criteria are satisfied at the same time:

1. The orbital decay is uncontrolled;
2. The reentry footprint may intersect the Italian territory;
3. The object mass, composition and structure may result in a sizeable rain of macroscopic fragments, or nuclear, biological or chemical (NBC) pollution on the ground is possible.

Translated into the CNUCE classification scheme, the third rule can be reformulated as follows:

3. The event *magnitude* M must be equal or greater than 1.6, corresponding to a returning space object *mass* $m \geq 4000$ kg, or the *class C* – meaning possible NBC contamination on the ground – can be associated to the reentry.

It is therefore clear that Mir could not be classified as a risk object in Italy, because the space station was working properly and the mission control centre at Korolyov City had the full command of the situation, carefully planning a safe deorbiting in the Southern Pacific Ocean. However, taking into account the large size and mass involved, it was decided to maintain a limited attention status, to closely monitor the evolution of the operations and to prepare the civil protection machinery in the event of a critical failure, followed by an uncontrolled reentry.

4. LESSONS LEARNED IN THE PAST

During the reentry campaigns carried out in the past, some very important lessons were learned. First of all, when the intrinsic physical uncertainties (atmospheric density models, solar activity predictions, satellite aerodynamics, mass, effective cross-section, attitude, structure, materials, etc...) are significant, it is useless to resort to sophisticated modelling tools, because their high level of precision does not guarantee, in any case, a comparable level of real world accuracy. Therefore, the complexity of the software codes and the level of detail of the models should be maintained compatible with the intrinsic problem uncertainties and the data available.

A second lesson concerns the interaction and the communication with the civil protection authorities and personnel, which are the end users of the orbital decay analysis and reentry prediction work. Any output or technical information provided (bulletins, risk assessments, charts, maps, etc...) must be simple and understandable for people that often lack any formal scientific education and are not, in any case, flight mechanics experts. Moreover, the technical results obtained should be easy to translate into practical real world operational measures.

The third lesson pertains to the information exchange with the media and the public. There is, in fact, a tendency to misinterpret and exaggerate what the experts say, and special care must be devoted into stressing what *predictions* actually mean for a returning space object, putting the reentry *risk* in the broader context of everyday antropogenic and natural hazards (for instance, ten meteoroids heavier than Mir hit the earth's atmosphere every year). Moreover, a careful check of the media interviews should be exercised, as far as possible, to avoid errors and unjustified alarms.

5. MIR RELATED CNUCE ACTIVITY

In Italy, Mir was never declared a risk object because:

- The space station was fully controlled by the Russian control centre, that many times in the past had demonstrated the ability to face much harsher emergencies;
- No nuclear, biological or chemical hazard was identified;
- Due to the deorbit strategy selected, the probability of an accidental debris impact on the Italian territory was estimated to be less than 1/1000;
- The openness and the information flow coming from Rosaviakosmos and the mission control centre in Korolyov City was unprecedented and outstanding, giving confidence in a timely communication of any sudden problem that might arise;
- The level of international cooperation and information exchange was very good, due in particular to the leading role played in this field by the European Space Operation Centre (ESOC), that acted as an information hub, collecting all the data and news coming from different European countries, Russia included.

Because the Mir deorbit was controlled, the main CNUCE activities during the past reentry campaigns, that is orbital decay monitoring and residual lifetime estimation, were not so critical and high priority in this case. In fact, the deorbit was planned a few days before the natural orbital decay and, in the event of a forced cancellation, a sufficient amount of time was available to declare the emergency and resume the standard work of reentry windows computations, using the trajectory predictor SATRAP [11].

The CNUCE activity was therefore concentrated in the following areas:

- Issuing of bulletins (via electronic mail) to the Mir Contact Point and to the Emergency Room of the Civil Protection Department in Rome;
- Analysis of failure scenarios;
- Analysis of Mir transits over Italy in the event of deorbit failures;
- Working out of predicted maps and event time tables for the organisation of the Civil Protection personnel activity;
- Computation of alert time windows, to be activated in case of partial deorbit failure and possible debris fall on the Italian territory;
- Analysis of debris endo-atmospheric dynamics.

In order to have an idea of the impact velocity and the time needed for the reentering fragments to strike the ground, the Mir reentry – at an altitude of 120 km – and breakup – at an altitude of 78 km – were simulated with a realistic initial flight path angle derived from the deorbit plan. The intent of the simulations, carried out with a two dimensional software tool [12], was not to model in detail the distribution of the fragments, but to obtain reasonable upper limits for defining the nature of the hazard (vertical dive of objets with mass of hundreds of kg and maximum impact speed of about 90 m/sec) and the amplitude of the alert time windows (30 minutes in total, from 5 minutes before the predicted satellite transit, to 25 minutes later). Some of the results obtained, with no lift force, are summarised in Figs. 1-4, as a function of the debris ballistic coefficient B [m^2/kg], defined as

$$B = \frac{C_D A}{2m} \qquad (2)$$

where C_D is the non-dimensional drag coefficient, A [m^2] the average cross-section towards the air flux and m [kg] the fragment mass.

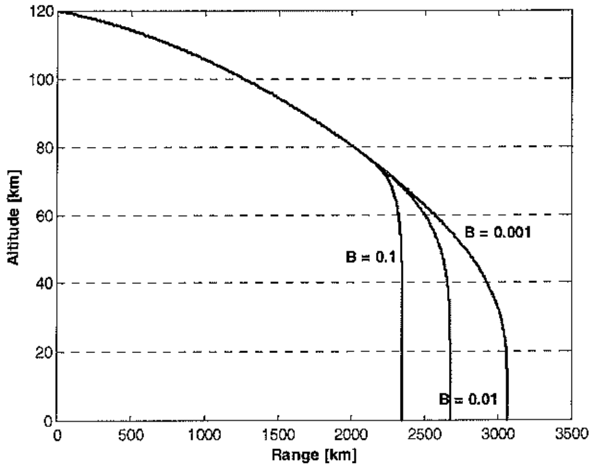

Fig. 1. Reentry Down Range as a Function of the Ballistic Coefficient B [m^2/kg]

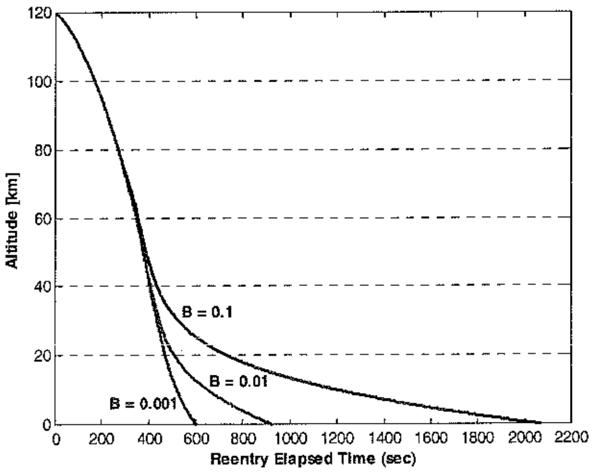

Fig. 2. Reentry Elapsed Time as a Function of the Ballistic Coefficient B [m^2/kg]

The ballistic coefficient adopted for the intact space station before the breakup was that determined by fitting the observed orbital decay in the weeks preceding the deorbiting:

$$B = 2.40 \times 10^{-3} m^2 / kg \tag{3}$$

After the fragmentation, simulated at an altitude of 78 km, the endo-atmospheric flight of three representative fragments, with ballistic coefficients of 0.1, 0.01 and 0.001 m^2/kg, was modelled and analysed with the TDBM software tool [12], obtaining results both in tabular and graphical form (e.g. Figs. 1-4).

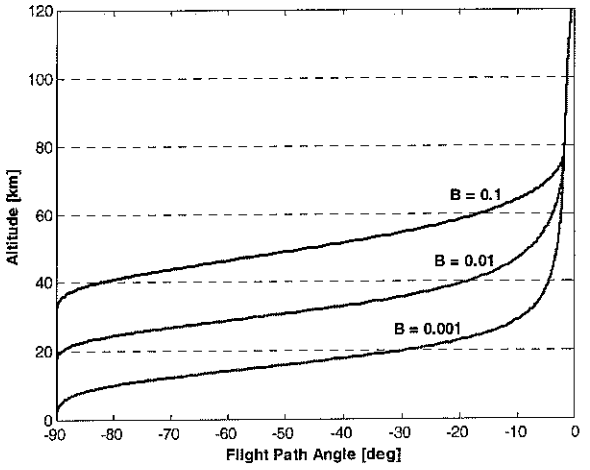

Fig. 3. Debris Flight Path Angle as a Function of the Ballistic Coefficient B [m^2/kg]

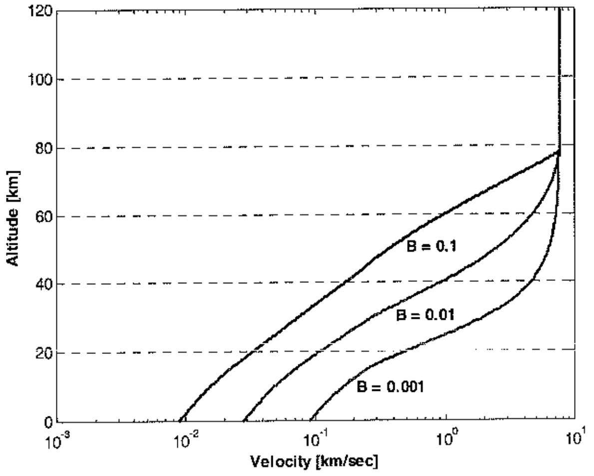

Fig. 4. Debris Velocity as a Function of the Ballistic Coefficient B [m^2/kg]

6. CIVIL PROTECTION ORGANISATION

At the Civil Protection Department, in Rome, there is an Emergency Room, staffed 24 hours a day, every day of the year, ready to face any natural, or human induced, disaster in Italy. The Emergency Room has a direct link with the national government, prefectures, military forces, police, firemen, national and local agencies, local governments, transportation authorities, health operators, high-risk plants, etc... Therefore, it was not needed to create an ad hoc structure to manage the situation created by the Mir planned deorbiting, because the Emergency Room, in its standard operating mode, was more than adequate to the scope. In order to make more effective, in the specific case, the communication and the coordination with external agencies and centres, like CNUCE, a Mir Contact Point was appointed.

Due to the nature of the potential hazard – heavy debris falling perpendicular to the ground at 100-300 km/h – the secondary effects of impacts were considered much more critical, for the public safety, than primary impacts on people. The safety priorities were then the preparedness of the high-risk plants and facilities (~ 200 in Italy), and the protection of the transportation system (in particular air traffic, dangerous ground transports, railways, Eurostar high velocity trains).

7. MIR DEORBIT

The last transit of Mir over Italy, before the deorbit, occurred around 13:20 UTC, on 22 March 2001. At that point, the following failure scenarios were possible:

1. Control loss of the complex before the beginning, or during the first, deorbiting manoeuvre. In this case, at least 4-5 days would have still been available before the Mir orbital decay;
2. Control loss of the space station during, or after, the second manoeuvre. In this case, the natural decay would have occurred after 2-3 days;
3. Failure during the third deorbit manoeuvre, with a residual lifetime lower than two days, but probably much shorter.

The first two failure scenarios were not of immediate concern, because enough time would have been available to evaluate the situation and predict the following orbital decay evolution. Moreover, the second failure scenario would have probably entailed a reentry on the Southern Hemisphere, due to the eccentric orbit and argument of perigee resulting from the manoeuvres.

This was also true for the third failure scenario, but in this case the reaction time available would have been very short, about one hour – in the worst case – for Italy. In addition, there was a slight chance that, due to an insufficient deorbiting firing, the station could enter a reentry corridor leading to the fall of debris on the Italian territory, half an orbit past the intended target area (Fig. 5).

The probability that such a situation might occur was very small, but taking into account the short reaction time available, this failure mode was the only one considered truly critical for Italy, and most of the civil protection planning was conceived to face just such a possibility. According to it, two alert time windows were defined (see Table 6), corresponding to a morning (Fig. 6) and to an afternoon (Fig. 7) possible transit over Italy.

Table 6

Mir Deorbit Events

Event Description	Time (UTC)
Last transit over Italy before deorbit	March 22, 13:20
Mir alert team activated in Rome	March 23, 05:00
Final deorbit maneuvre	05:08 – 05:27
Alert withdrawal (deorbit confirmed)	05:40
Fragments hit the ocean surface	06:00
First Italian alert time window	06:30 – 07:00
Second Italian alert time window	12:40 – 13:10

The Mir alert team was activated at the Emergency Room, in Rome, at 5:00 UTC, on March 23, a few minutes before the start of the final deorbit manoeuvre. If the deorbiting had failed, a full emergency was ready to be declared in Italy, between 6:30 and 7:00 UTC, taking all the necessary precautionary measures, but in a way to minimise the public alarm, and the ground and air communications disruption (Table 6).

However, the third and final deorbit manoeuvre was completely successful, and the alert status was withdrawn in Italy at 5:40 UTC, only 40 minutes since the beginning, and 20 minutes before the splashdown of the largest Mir fragments on the planned area of the Southern Pacific Ocean (Table 6).

8. CONCLUSIONS

The Mir deorbit was a technical challenging and highly successful operation. It set a very high standard, to which any future satellite removal from orbit will be compared. It also marked a dignified conclusion for the mission of a glorious space station, symbol of the Russian technical prowess and ingenuity.

As explained in the paper, Mir was never considered a risk object in Italy and only a limited (40 minutes) alert status was activated, to be ready to face a quite improbable failure scenario involving a very short reaction time.

The responses of the press and the media to the event were quite accurate and supportive, stressing the positive aspects of the Mir history and final burial in the ocean. No alarmist message was published or put on air, at least by the most important and largest information sources, and the general public was not worried at all.

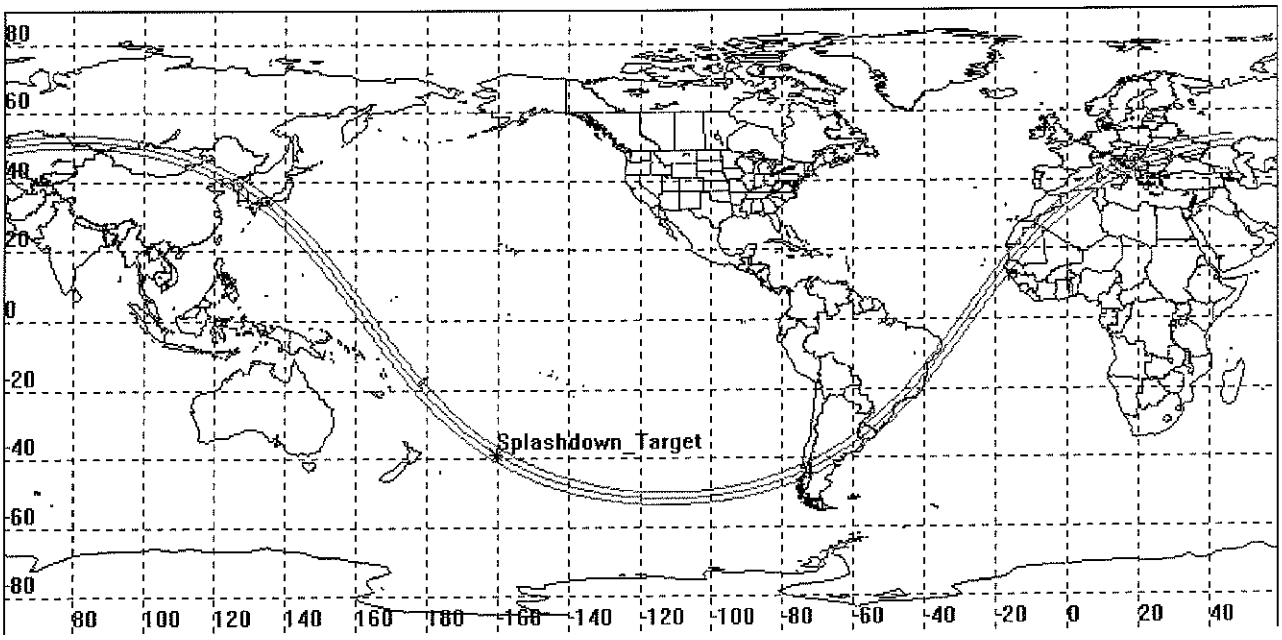

Fig. 5. Last Trajectory of the Mir Space Station (Swath Width: ± 100 km)

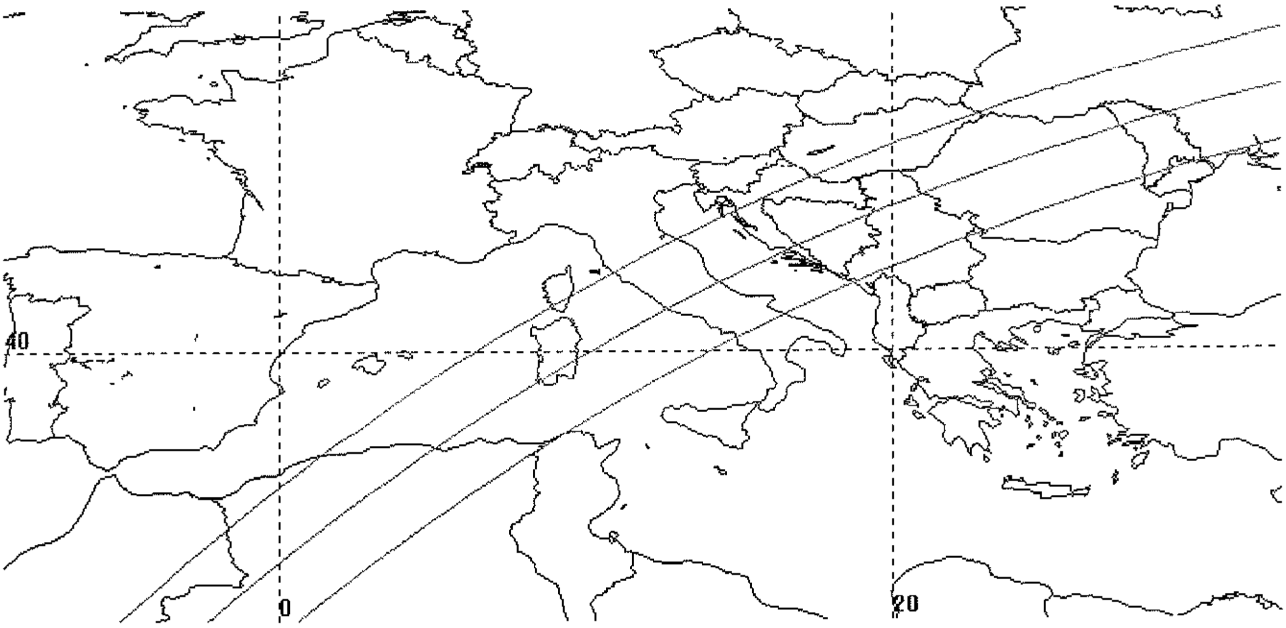

Fig. 6. First Mir Transit over Italy in Case of Deorbit Failure (Swath Width: ± 100 km)

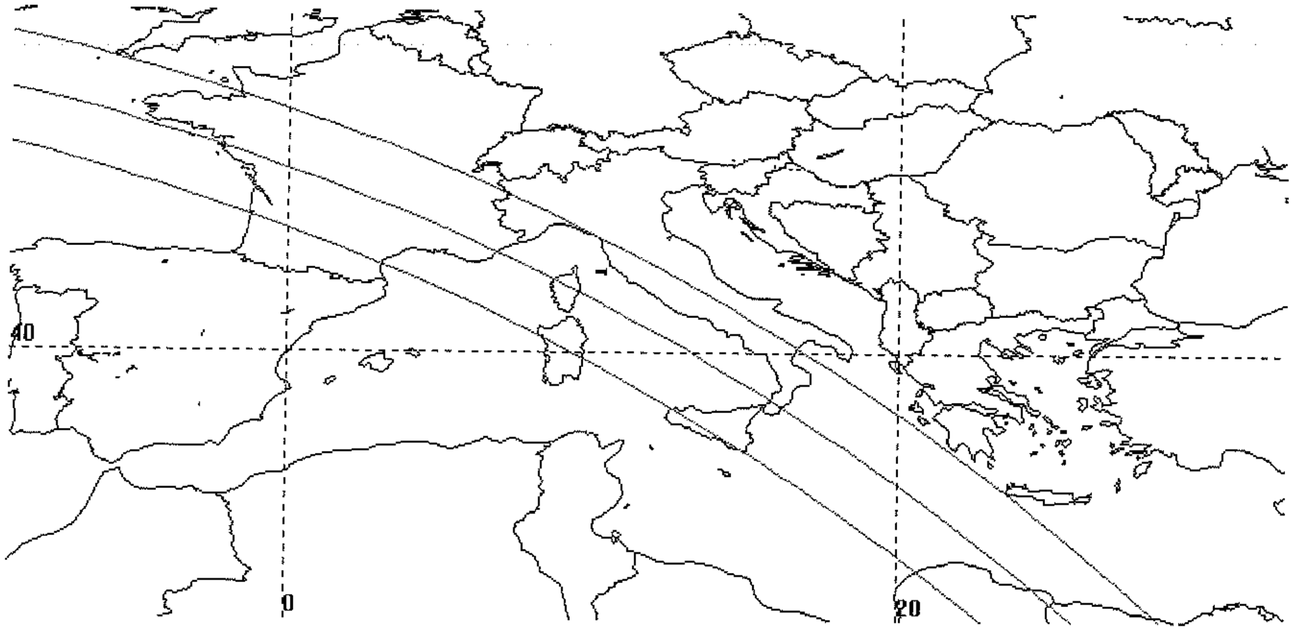

Fig. 7. Second Mir Transit over Italy in Case of Deorbit Failure (Swath Width: ± 100 km)

The Mir deorbit represented an outstanding example of international cooperation and data exchange, as well as a profitable large-scale training exercise. The experience gained, and the international confidence built, during the event will certainly prove very useful in the future to manage similar situations, in particular the final disposal of the International Space Station, at the end of its operational life.

9. ACKNOWLEDGEMENTS

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