MONITORING OF MIR REENTRY IN FRANCE

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ABSTRACT

This paper presents the organization and the activities performed in France to monitor the reentry operations of the MIR space station.
This reentry being a controlled process, it was necessary to have in real time all the information relative to the maneuvers. For that purpose a team of experts was located at the MIR Control Center in Moscow (TSUP). They were in charge to simulate the foreseen orbit maneuvers and to transmit the corresponding information to the Main Control Room in Toulouse. In parallel, tracking measurements were performed using French facilities, to determine the actual trajectory and to compare to the foreseen one. In order to take into account possible degraded cases, which could lead to an uncontrolled reentry, the position of the ground track with regard to French territories was computed with different hypothesis on the maneuvers.

1. CONTEXT

After more than 15 years' service in Space, Russia decided to terminate the mission of MIR. Given the mass of this orbiting complex and the potential risk on ground, a controlled de-orbiting scenario was adopted to ensure that debris fell in the south Pacific.

In provision of this re-entry, CNES set up an inter-directorate workgroup as of September 1999, with a view to monitoring the preparation and the sequence of operations. This monitoring activity is justified by a feared loss of control of the station, loss of attitude control or of propulsion in particular, which would transform this controlled re-entry into a random re-entry with debris possibly falling on inhabited areas.

CNES participation in the MIR re-entry is part of an organization set up nationally involving the CDAOA (Commandement de la Défense Aérienne et des Opérations Aériennes-French Air Defense and Air Operations Command) and the DGA (Délégation Générale à l'Armement) in particular.

The purpose of this paper is to summarize the organization adopted, describe the work performed and make the main conclusions in anticipation of future atmospheric re-entry operations.

2. ORGANIZATION

2.1 Organization at national level

In France, Space Surveillance is under the responsibility of the CDAOA (French Air Defense and Air Operations Command). As such the CDAOA is responsible for monitoring atmospheric reentries. To do this, it relies on the skills and means available at CNES, in particular for trajectory determination and prediction activities in the orbital or atmospheric phase. National tracking facilities (DGA/DCE and CNES radars) were used to determine the real trajectory followed by the station.

The CDAOA is in charge of informing military authorities and civilian authorities via the COGIC (French Interministerial Crisis Committee) located in the French Ministry of the Interior. Communication with the media is the responsibility of CNES.
This organization is summarized in the following diagram.

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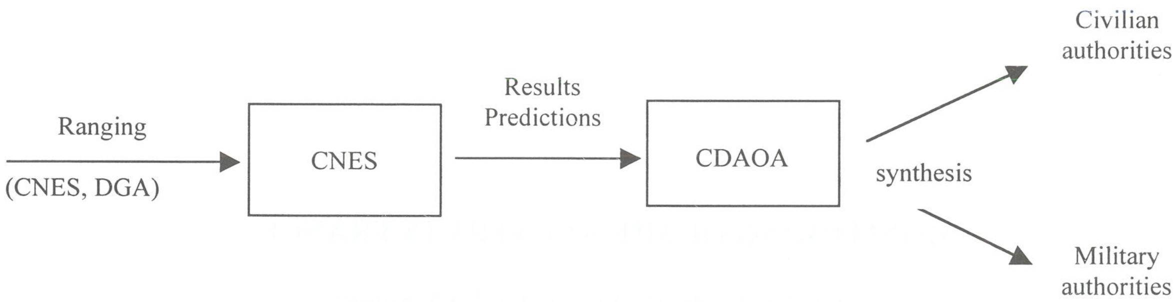

Fig. 1. Overall organization

2.2 CNES organization

As the re-entry of MIR is controlled, knowledge of the planned maneuvers is vital to precisely monitor operations and predict the trajectory. To meet this requirement, a contract was drawn up between CNES and the TSNIIMASH-EXPORT in June 2000. This contract made the following provisions:

- Supply to CNES of the mission analysis, performed by TSUP, relating to MIR de-orbiting.
- Supply to CNES of the SADIK software used by TSUP to compute and simulate de-orbiting.
- Intake of 3 CNES engineers at TSUP during the last days of operations.
- Real-time supply during operations of information on maneuvers.

The monitoring objective was to continuously have real-time information on operations already performed, those in progress and those planned.

The monitoring principle first of all consisted in obtaining all required information directly from TSUP, then in simulating the sequence of maneuvers envisaged to determine the planned trajectory and lastly in determining the real trajectory of MIR using external measurements. Predicting the trajectory in particular highlighted the MIR flyover zones in the case of degraded operation.

MIR reentry was monitored with the help of the following entities:

- The Orbitography Computation Center (COO), in charge of designating tracking facilities, determining the trajectory from the measurements made and predicting the evolution of this trajectory.
- The CNES team at TSUP, in charge of interfacing with the Russian teams and the real-time transmitting of all information to evaluate the situation and predict the trajectory
- Space Flight Dynamics team in Toulouse, in charge of simulating maneuvers based on the information received from TSUP, and of distributing the 3D animation used to monitor the mission.
- Reentry unit in the SCP (Salle de Contrôle Principale-Main Control Room), in charge of co-ordinating all operations. This unit also included Communication and Defense representatives in charge of transmitting information to the CDAOA.

The operation of this organization is summed up in the following diagram:

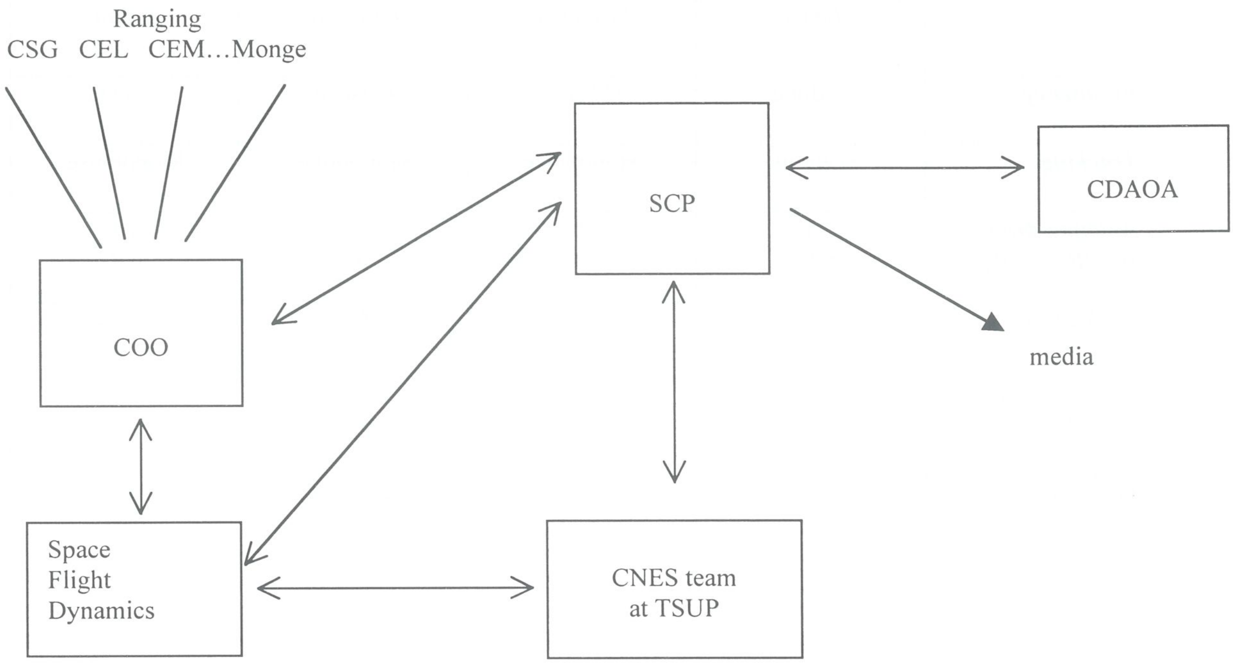

Fig. 2. Internal organization

3. ASSESSMENT REPORT OF ACTIVITIES

3.1 Links with other Agencies

The MIR reentry was also monitored by ESA and the other European Agencies. Information exchanges between ESA and CNES took place at the following levels:

- A CNES correspondent had been appointed with respect to the ESA reentry unit.
- At European level, in the frame of the Network of Centers, pilot project on space debris, it had been agreed that available information would be exchanged.
- The ESA and CNES "communication" units remained in close contact throughout the last weeks of the operations.

This mutual information was necessary to ensure the coherence of our communications in the eventuality of a case of degraded operation.
In accordance with this decision, CNES information bulletins were sent to our partners. In the same way ESA information bulletins were sent to CNES. Frequent phone calls were also made between ESA and CNES.
Our orbit determination results were sent for information to ESA and to NASA.

3.2 Radar tracking

The MIR trajectory was monitored using the CNES-CSG (Centre Spatial Guyanais) radars in Kourou (Bretagne 1, Bretagne 2 and Adour 2) and the following DGA/DCE facilities:

- The military vessel “Le Monge” of the French Navy, in the port of Brest throughout the measurement phase
- The CEL (Centre d’Essais des Landes) test center in Quimper, near Brest
- The CEM (Centre d’Essais de la Méditerranée) test center in the south of France near the Mediterranean

The main technical characteristics of the radar facilities available in these three centers used during MIR operation are summarized in the table below.

Table 1. Main characterisrics of the DGA radars

	Bearn	*Provence*	*Gascony*	*Armor*
Frequency	C Band	C Band	C Band	C Band
Tracking	Scanning	Monopulse	Monopulse	Monopulse
Antenna* ϕ*(m) ***θ 3dB (°)***	4 0.96	4 0.96	4 0.9	10 0.4
Peak Power	1 Mw	1 Mw	500 Kw	1 Mw
RCS (1 m^2) ***S/B : 10 dB***	160 km	160 km	596 km	3500 km
Location ***(and Number)***	CEM (*3) CEL (*2)	CEM (* 1)	MONGE (*1)	MONGE (*2)

The following two remarks can be made upon examination of this table:
1 – the capacities of the Bearn and Provence radars, despite being far below that of the Armor radars, were nonetheless sufficient for the MIR reentry, given both the size and the proximity of MIR. As proof of this, MIR locked on with the Bearn radars around 8° at rise, and tracking ended around 8 to 10° at setting.
2 – the CEM station, given it was geographically the furthest south/east, was of particular interest. It was used to make the first passes in the morning not visible by other radars. It was moreover, strategically located, as it was used to see, in the case of problems after the last thrust, MIR's next orbit.

The first tests were begun on February 5 and were used to train our radar operator teams on one hand and to verify data interchange procedures with CNES (file format, transfer procedure, etc.) on the other.
The last test took place on March 23, immediately after reentry into the atmosphere. The radar of the CEL in Toulon was pre-positioned in case the final maneuver were to go wrong.

Radar tracking operations throughout this period can be accounted for as follows:

- 19 operations performed by the CEL station
- 24 operations performed by the CEM station
- 20 operations performed by Le MONGE station

There was therefore a total of 63 radar tracking operations performed by the DGA/DCE throughout the reentry phase.

Throughout this period, DGA/DCE supplies consisted of:

- radar measurements sent to CNES
- radar measurements and two-lines bulletins sent to the French Air Force
- radar measurements and two-lines bulletins sent to ESA
- radar measurements and two-lines bulletins sent to NASA

3.3 Orbitography Computation Center

During MIR reentry monitoring, the Orbitography Computation Center was responsible for computing the current orbit with available external data, computing pass predictions within the visibility of national ground support equipment, for the designations of this equipment, and for computing natural reentry predictions.

- Monitoring of MIR altitude in February and March 2001: as from January 29, 2001, the Orbitography Computation Center implemented a procedure designed to monitor the altitude of the MIR orbit. At each computation, the first step consisted in determining the current MIR orbit using available measurements (two-lines bulletin and/or radar measurements); the second step, in extrapolating the trajectory up to natural reentry. The last natural reentry prediction was made on March 20, 2001.

The natural reentry predictions made for MIR at the Orbitography Computation Center since January 29, 2001 are summarized in the following graph.

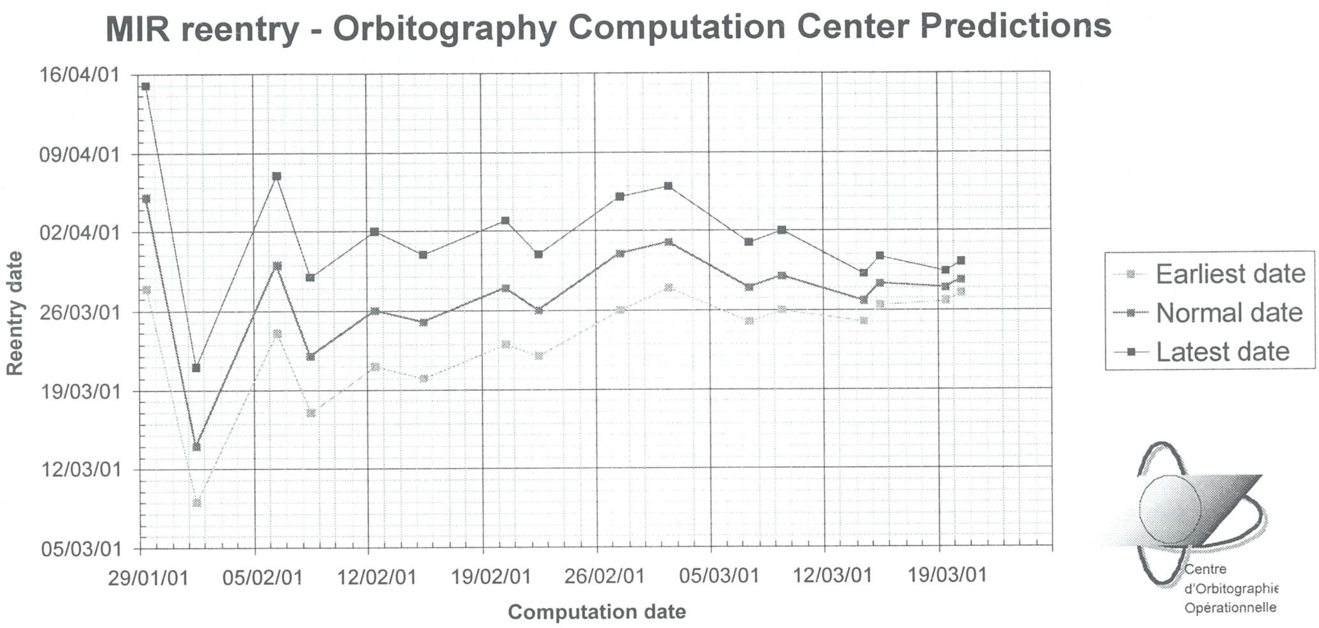

Fig.3. Natural reentry predictions

- Distribution of results to outside organizations

The last two weeks of MIR trajectory monitoring, the Orbitography Computation Center distributed the results of the current orbit determination to the CDAOA, to NASA and to ESA.

- Interfaces with radars:

  - Pass predictions: the last two weeks before the planned reentry, the Orbitography Computation Center computed once a week, passes predictions, for each radar so that the CSG and the DGA could schedule tracking.

  - Designations: the Orbitography Computation Center sent designations to DGA radars (every day, automatic transmission of the most recent two-lines) and to CSG radars: before each scheduled tracking operation (transmission of tabulations and orbit bulletins).

  - Radar measurements: up to Monday, March 19, radars performed tracking operations according to their availability. From Tuesday March 20, all passes within visibility were scheduled.

- Study of cases of degraded operation:

Several cases of degraded operation were envisaged, in particular the partial performance or non performance of the last maneuver. This case was the most critical as it could lead to a random reentry in the short term.
In this case the plots of the MIR trajectory were printed for Friday 23/03, from the nominal date of $\Delta V3$ (23/03 5h 8mn 48s in UT) to 24/03 0h:

-on the two hemispheres,

-on French territories (zoom on each territory).

Had we been in this case of degraded operation, it was planned to take a maximum number of measurements on these passes, to compute as accurately as possible the end of the MIR trajectory until the natural reentry. All radars concerned were ready to provide this support.

- Real time monitoring of the reentry (March 22 and 23, 2001)

To ensure the real time monitoring of the reentry, 2 engineers from the Orbitography Computation Center were placed on stand-by duty. The last MIR orbit determination was performed on March 22 at 14.00 hours (UT), integrating all the day's radar measurements. There were no passes within visibility of the CSG and DGA radars, throughout the period between the 1st maneuver and the reentry.

- Assessment

All Orbitography Computation Center operations were performed nominally.
The work performed at the Orbitography Computation Center for MIR reentry monitoring operations was used to finalize the interface documents for atmospheric reentries, validate all technical interfaces, Orbitography Computation Center processing and procedures, used for reentries into the atmosphere.

3.4 CNES team at TSUP

TSUP provided CNES with a room equipped with the following:

- a PC (Pentium III with Windows NT4 / 128 Mb RAM + 17" screen) to determine trajectories using SADIK;
- a video monitor used to show the main control room and miscellaneous TM pages, in particular the video images retransmitted from MIR;
- an interphone used to listen to the comments in the control room;
- two telephones (internal and external).

De-orbiting principle:
Several maneuvers were required to de-orbit MIR. Uncertainties as to the attitude control capacity at low orbits unusual for MIR incited Russian engineers to envisage the following strategy:

- two initial maneuvers of approximately 10 m/s to prepare the orbit for a third and last thrust (adjustment of the semi major axis and positioning of the argument of perigee while keeping the latter sufficiently high to remain in orbit at least 24 hours if the last maneuver is postponed). These maneuvers are performed with the eight Progress attitude control engines;
- a final maneuver of approximately 25 m/s was performed in the following two steps:
  - the first with the main engine and Progress attitude control engines
  - the second with the attitude control engines only
- once again, as a result of uncertainties on attitude control, an inertia stabilization mode was adopted even during maneuvers

Constraints:
It would appear obvious that on such critical maneuvers the Russians wanted to have as much visibility as possible and to have the possibility of uploading before the last data and being able to determine the orbit or at least of making an initial estimate of the orbit obtained following maneuver(s) immediately afterwards.
Some more specific constraints were also applied. For example, the first two maneuvers had to be finished before the pass within visibility of Petropavlovsk. This request had been submitted by engineers responsible for attitude control to be able to have a complete pass from station if an attitude problem were to arise.
For the reentry of Progress, the target longitude is approximately 140 degrees west. For MIR, the Russians finally preferred leaving a margin in case the thrust were not to be as strong as that planned, targeting a point 150 degrees west.
Numerous back-up studies have been studied by TSUP engineers, such as the following:

- postponement of the three maneuvers by shifting one orbit in the event of a problem prior to the execution of the first maneuver;
- postponement of the last maneuver to the next day in the event of a problem following execution of the first two;
- postponement of the three maneuvers to March 25 in the event of a problem with attitude control and the need to switch to a mode using analog facilities.

Operations:
All times given are at Moscow standard time, i.e. UT + 3.

- First maneuver: as the start of the maneuver (3h31mn59s) was not within visibility (approximately 3'30'' before), we discovered, via the video images retransmitted from MIR, that the attitude was, in fact, in conformity with predictions and that the thrust was nominal. Approximately 30 seconds before the theoretical end of thrust (3h52mn32.8s) propulsion stopped as the target ΔV had been reached. The thrust level used to compute the maneuvers had, in fact, been given the lowest possible value. An initial estimate by those in charge of attitude control also showed that attitude errors had not exceeded 3 degrees.

- Second maneuver: the second maneuver took place according to the same pattern as the first: start of thrust outside visibility (5h0mn24s) and end of thrust slightly before that computed (5h22mn38s instead of 5h24mn28.6s). Following this thrust, an initial estimate of the orbit was made revealing that everything had gone perfectly, as maximum altitude was 219 km and minimum altitude 158 km. With this data the application of the last maneuver showed a nominal point of impact which had shifted by approximately 2.5 degrees longitude (i.e. approximately 250 km) which was totally acceptable.

- Last maneuver and reentry: here again as the start of the last maneuver (8h7mn36s) was before the beginning of visibility and as soon as the first information from the telemetry then the video images reached us (approximately two minutes), we were able to see that everything was going fine. As planned too, the engines thrust until there was no more propellant. Nonetheless, if we rely on the onboard information received, this thrust was a great deal more than that planned and reached 40 m/s instead of 23.5 m/s. It was, in fact, that the display management software did not integrate the fact that the end of the thrust only had the Progress attitude control engines hence a factor of 4 on the value of ΔV displayed from the time the main engine switched off. An initial estimate of the real ΔV gives approximately 28 m/s (20.6 m/s and 7.4 m/s).

Lastly, all that remained for us was to follow the comments of the main control room announcing the various steps from fragmentation up to the final impact and the End of Life announcement of MIR (planned point of impact: latitude 40°S, longitude 160°W).
Fig. 4 gives the final orbits given the latest information obtained.

Assessment:
This approximately five-day mission ran perfectly. From either a logistic or purely computation viewpoint, we were able to see the perfect collaboration with the different TSUP teams concerned.
The TSUP "ballisticians" always provided us with the required information in due time without us having to beg for it.
Lastly, the Russians once again showed us their know-how, their efficiency, their realism and their capacity to adapt to unusual situations.

3.4 Flight Dynamics team in Toulouse

This was set up at 21.00 hours Toulouse time on Thursday March 22, 2001. Operations ended about 09.00 hours Toulouse time on Friday March 23, 2001 after a quasi nominal reentry of MIR into the south Pacific Ocean.

The Flight Dynamics team at the Orbitography Computation Center performed the following activities during these operations:

- Update of the reference trajectory once new bulletins delivered by the Russians were obtained by telephone. This data was used to readjust the MIR reference trajectory using Sadik software (that used at TSUP by the Russian de-orbiting team) and the CNES PSIMU software.
- Graphic animation: 2D and 3D viewing of the trajectory using LIO and OPALE software, coherence check of the information on the screen with information relayed by the Flight Dynamics team at TSUP.
- Computation of an estimated reentry time.
- Relay of the information obtained from TSUP by the Flight Dynamics team.

It must be noted that the nominal aspect of the MIR reentry considerably lightened the workload of the Flight Dynamics team at the Orbitography Computation Center.

These operations were used to monitor a destructive reentry into the atmosphere thanks to the collaboration with the Russians. They also enabled use of the OPALE product for the first time in operations in anticipation of the ATV control center.

4. CONCLUSIONS AND RECOMMENDATIONS

At the reentry of MIR, TSUP engineers demonstrated their perfect control of the de-orbiting process of a complex structure: the scenario set a few days earlier was followed precisely.

The privileged relations that had been established for several years between CNES and TSUP teams for the different MIR onboard missions were of particular use when monitoring MIR reentry operations. The arrangement set up enabled us to reach the set objectives, i.e. continuously have the information required to precisely monitor operations, to deal with the eventuality of a case of degraded operation which may have led to debris falling on national territory. Our relations with our correspondents at TSUP were, moreover, excellent.

Monitoring of this reentry is also valuable experience gained by CNES in anticipation of the ATV control center, to perform mission analysis and to prepare operations.

Last of all, the reentry of MIR was the opportunity to set up and test national monitoring dispositions, involving the French Air Force and the DGA, in real operations. These dispositions gave full satisfaction. This organization and this operating mode will serve as a future reference for monitoring the next risky atmospheric re-entries.

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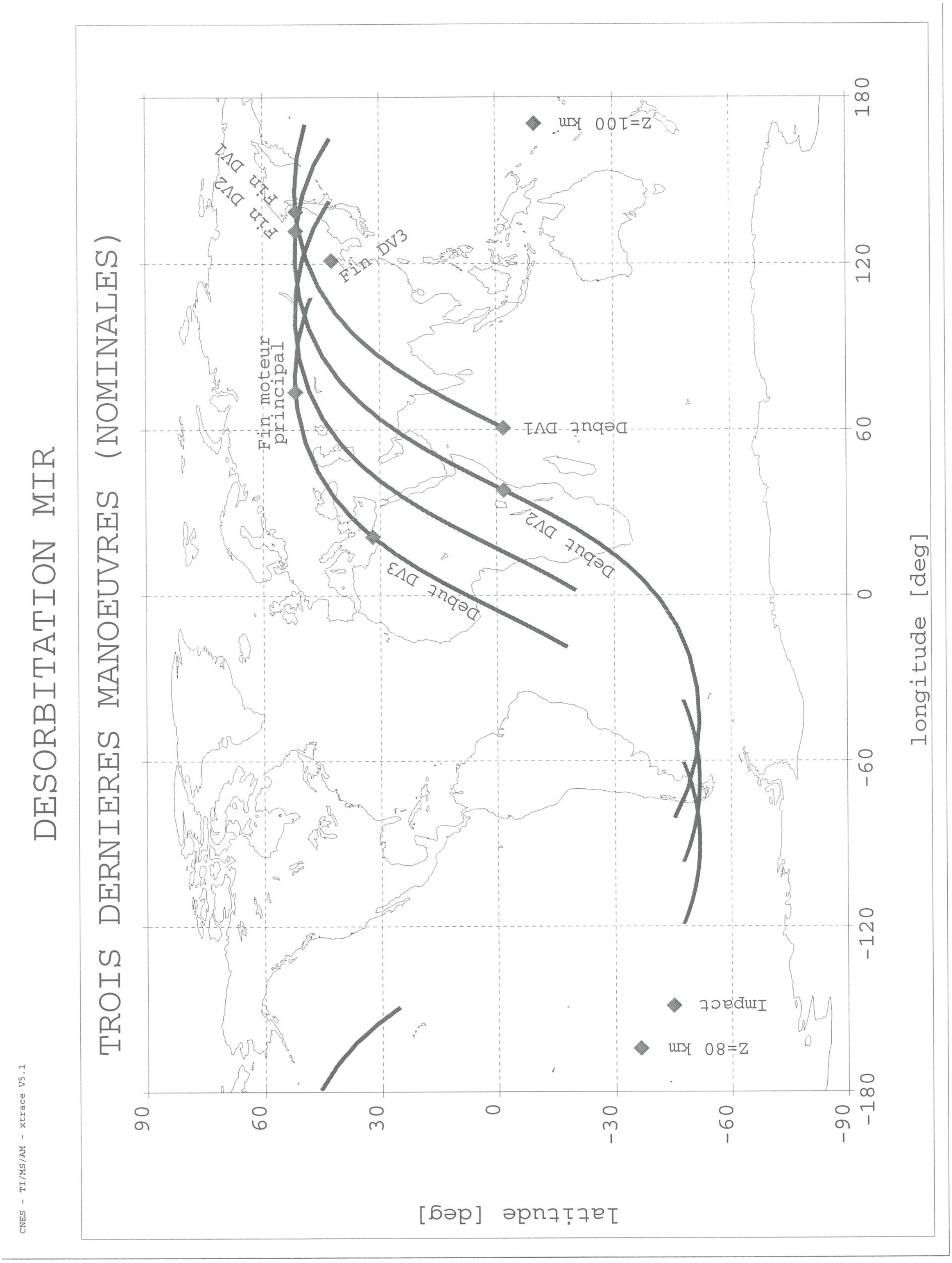

Fig.4. Plot of the last 4 orbits