ORGANIZATION AND SURVEILLANCE CONCERNING THE ATMOSPHERIC RE-ENTRY OF POTENTIALLY DANGEROUS BODIES

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ABSTRACT

Since the first atmospheric re-entry in July 1979 of an artifical object, SKYLAB, which was considered to be a threat to populations, the French government has entrusted CNES with the task of keeping it informed and preventing potentially dangerous situations while tracking these objects as they fall back to earth.

This paper deals with the organization that was set up, and in particular the cooperative effort involving both the DGA's (Direction Générale de l'Armament - General Directorate for Weapons Systems) and CNES' measuring facilities, as well as the methods and procedures used by the COO (Centre d'Orbitographie Opérationnel - Operational Orbit Determination Centre) at the Toulouse Space Centre to determine re-entry slots.

During the re-entry of COSMOS 398 in December 1995, a test campaign was conducted to validate and qualify both the organization and the operational measurement chain. This campaign was based primarily on online tracking and continued until the final orbit of the Chinese satellite CHINA 40 FSW1 during its re-entry in March 1996.

The frequency of potentially dangerous atmospheric reentries, approximately once every two to three years, reveals the need for a structured organization, efficient measurement facilities and standardized forecasting models which can be used to improve the precision of re-entry slots, mainly during the last orbit. The consolidation of measurement facilities based on a continuous exchange of information between governments and the various national and international agencies will undoubtedly make these operations safer.

1. GENERAL ORGANIZATION AND MISSION

After the fall back to earth of COSMOS-954 on 24/01/1978, the French government wanted to be kept informed about the forecasts and the risks of fall back of artificial objects from space. The CNES was entrusted with an information and situation prevention mission concerning the organization of tracking of potentially dangerous bodies when they fall back to earth.

1.1 Potentially dangerous bodies

Today, it is accepted that there are potentially two types of hazards caused by orbited bodies during atmospheric re-entry :

- Partial destruction of the body, generally weighing more than one ton, when it disintegrates in the upper layers of the atmosphere,

- Possible radioactive contamination of the earth by wreckage from the partially destroyed electronuclear generator of the satellite.

1.2 Operations monitored by the CNES

The increase in the number of orbited bodies, the increase in the payloads in orbit, as well as during the orbiting of the last stage of launchers used for satellites on a geostationary orbit, has made the number of bodies falling back to earth, and that are in the potentially dangerous category, a frequent event. In addition, it is necessary to include the accidents or incidents that occur during re-entry maneuvers. The CNES has thus tracked and organized the operations carried out on the re-entry of the following bodies :

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- COSMOS 954	January 1978	GEN
- SKYLAB	July 1979	SO
- COSMOS 1402	January/February 1983	GEN
- COSMOS 1900	September 1988	GEN
- SALIOUT-7	February 1991	SO
- COSMOS 398	December 1995	ML
- CHINA-40 (FSW 1-5)	March 1996	SM

GEN = Electronuclear generator
SO = Orbital station
ML = Lunar module
SM = Military satellite

2. ORGANIZATION OF THE MISSION

2.1 CNES internal organization

The CNES decided to set up a two-level internal organization to fulfill this mission :

- A permanent organization for the surveillance of bodies and wreckage from space, the SEPRA (Service d'Expertise des Phénomènes de Rentrée Atmosphérique - Appraisal department for atmospheric re-entry phenomena),

- An atmospheric re-entry cell for potentially dangerous bodies during the fall-back phase.

At their level, these organizations are in charge of all operations and procedures involved in fall back forecasting. These organizations are the interface between the measurement centers and the orbit determination calculation center and are responsible for the coordination of tracking, calculation and re-entry forecast facilities.

2.2 External organization

A system is set up to inform and advise governments in function of the intervention level required during a potentially dangerous re-entry.
If the body is a satellite and the weight and density of wreckage may possibly cause damage on impact in inhabited areas, the civil defense authorities will be the first informed and expected to work in close collaboration.

If the body represents a nuclear contamination hazard, for example COSMOS 1900 in September 1988, the atmospheric re-entry cell is then associated with a cell set up at prime minister level, in which the secretary for nuclear safety is directly involved.

2.3 CNES/Defense cooperation for atmospheric re-entries

An agreement signed between the CNES and the defense, through the DGA (Direction Générale de l'Armement - General directorate for weapons systems), makes it possible to make available the operational measurement systems of the defense, radar and computers, during potentially dangerous re-entries and test and calibration campaigns (2 per year).

The DGA is responsible for the orbit acquisition and measurement facilities.

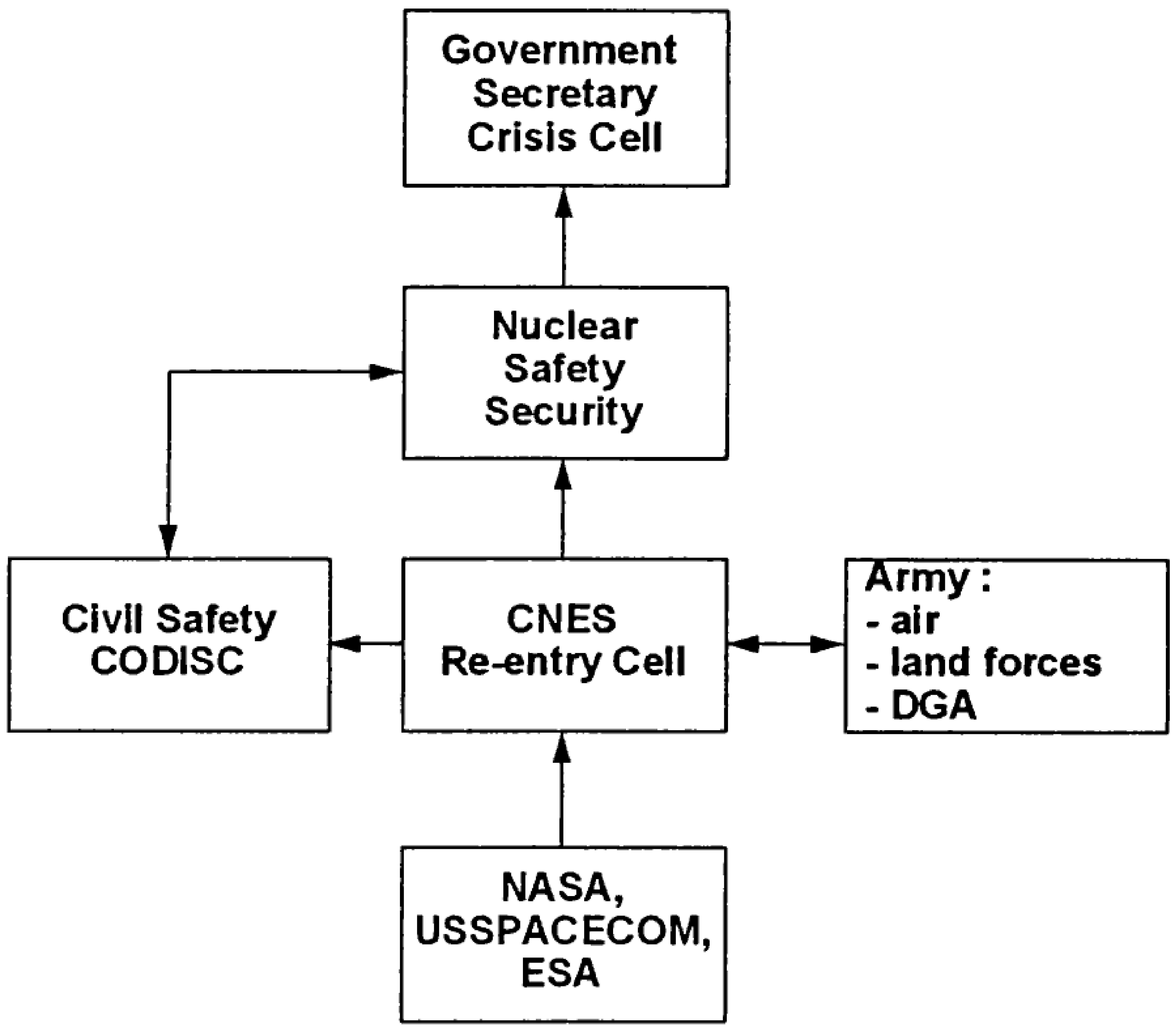

Figure 1. General organization

3. OPERATIONAL PROCEDURES

3.1 Operational phases

The operational procedures to track re-entry of potentially dangerous bodies from space are broken down into four distinct phases in which the civil and military organizations involved act at different levels.

TRACKING PHASE
Day-90
Consists in selecting and tracking an orbited body during the potentially dangerous re-entry phase by SEPRA as of D-90, informing and setting the entire CNES internal system into action.

REINFORCED TRACKING PHASE
From D-90 to D-30
During this phase, the atmospheric re-entry cell is set up and civil and military operational measurement facilities are coordinated. During this phase, the orbit is plotted and a forecast calculation carried out whenever information is provided by the data server organizations, NASA, ESA, and radar measurements.

ALERT PHASE
From D-30 to D-7
Tracking is reinforced and carried out on a systematic basis, including holidays.

REINFORCED ALERT PHASE
From D-7 to D0
The re-entry cell is on duty 24 hours a day. Radar measurement and forecast calculations are immediately carried out and sent to the authorities for each passage of the body in the re-entry phase.

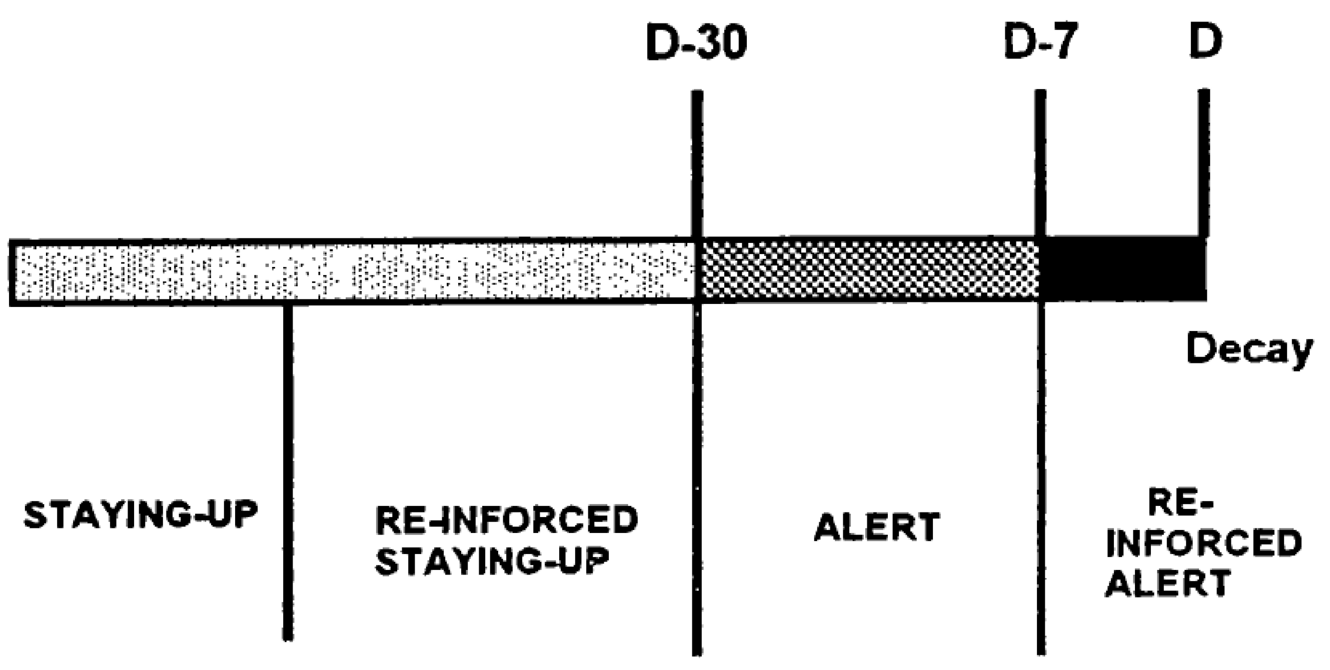

Figure 2. Operational phases

4 TRACKING AND FORECASTING FACILITIES

4.1 Data

4.1.1 Object description data

Where high atmospheric drag occurs, as in re-entry events, it is essential to have exact knowledge of the object's mass as well as continuously available data on the surface area of the section being exposed to drag. This involves receiving data not only on the physical aspect of the object but also on its attitude. It is sometimes possible to obtain simple diagrams which allow crude estimates of average surface to mass ratio, as was the case for the JIANBING re-entry event. Unfortunately this is far from being the norm. As a general rule, all attitude checks are stopped and all such information is dispensed with. It is obvious from this first point alone that the customary lack of data in these situations can only impair the accuracy of results, and this cannot be easily counteracted.

4.1.2 Data on solar activity

Solar activity has a major impact on atmospheric density. Whereas in normal trajectory calculations (for sun-synchronous satellites), approximate data are usually adequate, in the case of atmospheric re-entry calculations it is essential to include realistic flow values and geomagnetic indices.
The observatory at MEUDON routinely sends data to the OCC on past solar activity as well as forecasts on anticipated solar activity.
These data are sent directly to the OCC by electronic mail. This method has proved to be entirely satisfactory and it even allows data to be processed and managed automatically.
The main problem lies in the difficulties encountered in making accurate predictions of solar activity within the following few days : some measurements are not available until 1 or 2 months after the events.

Raw data on the probable re-entry of a potentially dangerous body is obtained from Space Warn Bulletin type catalogues or is directly sent by NASA, RKA space agencies or the ESA, which is in charge of distributing this data to the various member countries of the European Space Agency.

4.1.3. Data Two-lines elements :

Most organizations using the data employed in the calculation of atmospheric re-entry forecasts work with the TLE (Two Lines Elements) provided by NASA, via modem or the Internet, from the USSPACECOM data base.
When atmospheric re-entry occurs, atmospheric drag is obviously the predominant force at work. This is difficult to model analytically. It seems that the greater the intensity of drag, the less representative is the TLES SGP4 model. But the loss of accuracy observed, especially in the final stages of re-entry, may also be due to poor interpretation of the state vectors for which we do not have the necessary modelling data.
These two-line state vectors are not exploited directly through their associated models. Each two-line state vector is converted into osculating elements which are then taken as measurements of satellite position and velocity at the time of the state vector.
The osculating state vector derived from the two-line parameters is computed in such a way as to produce maximum consistency between the trajectory obtained from the two-line state vector together with our own digital extrapolation model, and the trajectory which would have been obtained by using the analytical TLES model. A number of points (for position and velocity) are thus obtained, according to the numbers of two-line state vectors available for the two or three days prior to the date of calculation.

Once the object is designated and its orbit known using the TLEs, the CNES through the COO (Centre d'Orbitographie Opérationnelle - Operational orbit determination center) checks all re-entry forecasts and orbit astronomical calculations up to re-entry. Also, the CNES/COO indicates the orbit points each time the tracked body becomes visible to the tracking radar.

4.2 Tracking and measurement facilities

The tracking and measurement facilities used for operations involving re-entry of potentially dangerous bodies are the civil radar of the Kourou Space Center in French Guiana and the military radar of the DGA/DME.
Geographic position of the civil and military radar sites :

- CNES radar at Kourou in French Guiana,
- DGA/DME radar in metropolitan France,
- Quimper, Brittany,
- Mediterranean, Toulon,
- Brest, Brittany.

The Brest site is the home port of the LE MONGE ship, specialized in satellite and missile tracking. The ARMOR radar in "skin echo" mode can track a 1 m² surface area satellite at 750 km.

5. RE-ENTRY CALCULATIONS

5.1. Calculations methods

The basic program used for these calculations is the same as that used daily by the OCC to compute SPOT satellite trajectories. Because the OCC is a multi-mission service, it is highly flexible and will adapt to the various activities required for missions of widely differing types.
The core processing activity is orbit computation by means of the classic least squares method, associated with a Cowell-type numerical integrator of the order of 8.
Upstream from this, it was obviously necessary to incorporate the pre-processing procedures mentioned earlier, in order to convert the two-line state vectors and radar measurements into usable input data for the program.
The least-squares program did need to be adapted to some extent, however, essentially to enable more systematic incorporation of perturbations associated with atmospheric drag :

- incorporation of the CIRA atmospheric model for altitudes below 120 km.,

- use of numerical derivatives for re-entry calculations.

The re-entry window is calculated on the basis of an error calculation in which the following essential components are taken into account :

- an order of uncertainty relating to the value retrieved for the drag coefficient

- the quality of the measurements taken

It goes without saying that estimating these values is a very delicate matter which is somewhat subjective. The order of uncertainty relating to atmospheric drag observed during previous re-entries is $\pm$ 15 %.
In fact, because of these orders of uncertainty, calculating an accurate re-entry prediction is a hazardous exercise indeed, in which the notion of expertise in orbit calculations comes into its own. Moreover, because the elements to be plotted cannot be readily observed, any inflection given to orbit determination input parameters (mass associated with measurements, solar activity, inclusion of calculation time, etc.) will influence the result. This is still more the case where autonomy is sought with regard to the two-line state vectors.

6. RE-ENTRY OF COSMOS 398

6.1 Organization and tracking of COSMOS 398 re-entry

The fall back to earth of COSMOS 398 was tracked using information provided by the ESOC in the bulletin dated November 30, 1995.
A request for TLEs was made directly to NASA. The re-entry cell was set up and put into action on December 4, 1995, during the alert phase. The COO completed an initial forecast calculation using the TLEs, dated December 1, 1995, for December 10 to within + or - 1 day.
The measurement facilities employed were those of MONGE and TOULON.

6.2 Final forecasts

- On December 10, 1995, using a TLE dated December 9, 1995, the forecast calculation estimated re-entry for December 10 at 14:23 UT.
  The ESOC indicated a re-entry forecast for :
  December 10 at 20:52 UT.

  A difference of 6 hours 29 minutes was found between the forecasts of the two agencies.

- On December 10, 1995, using a TLE dated December 10, 1995 at 13:46, the re-entry forecast calculation indicated :
  December 10, 1995 at 21:10 UT.
  The ESOC indicated a re-entry forecast at :
  21:15 UT.

- On December 10, 1995, using a TLE dated December 10, 1995 at 16:40, the last re-entry forecast calculation indicated : 20:00 UT.
  The ESOC indicated at re-entry forecast at :
  20:15 UT.

6.3 Final re-entry

The information on COSMOS 398 re-entry transmitted by the ESOC indicated the time : 20:15 UT and located it in the Pacific, to the east of Hawaii.
NASA indicated the re-entry time : 20:40 UT and located it in the South Atlantic to the north of the Falkland Islands.
The SRC, the Russian agency, confirmed fall back to earth at 20:15 UT in the Pacific.

6.4 Conclusions on the re-entry of COSMOS 398

The setting up of the tracking cell for COSMOS 398 re-entry took place only ten days before the effective fall back to earth. Some radar measurement facilities were not activated.
The radar measurements were not systematically processed in real time to replot the TLEs.
The re-entry of COSMOS 398 made it possible to validate the operational tracking and calculation procedures of the French facilities.
Certain TLEs sent by NASA were inconsistent 24 hours before the re-entry, which explains the difference of six hours given on a forecast.
The final forecast on the time of re-entry shows an appreciable difference between the different agencies. This difference is undoubtedly due to the accuracy of the tools employed and the reference on the fall back to earth altitude point.

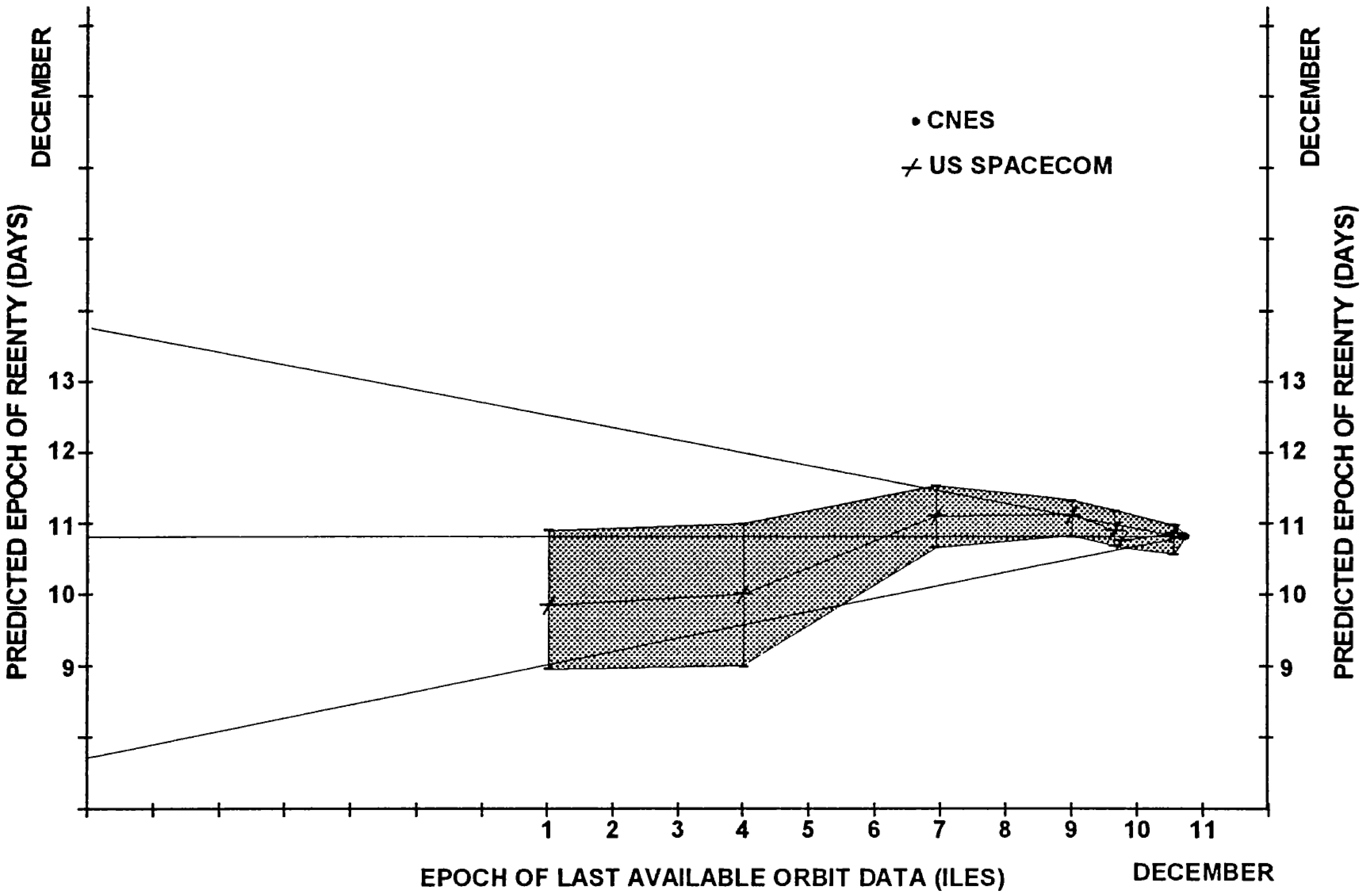

Figure 3. Cosmos 398 re-entry prediction - Uncertainty : ± 20 % of remaining lifetime

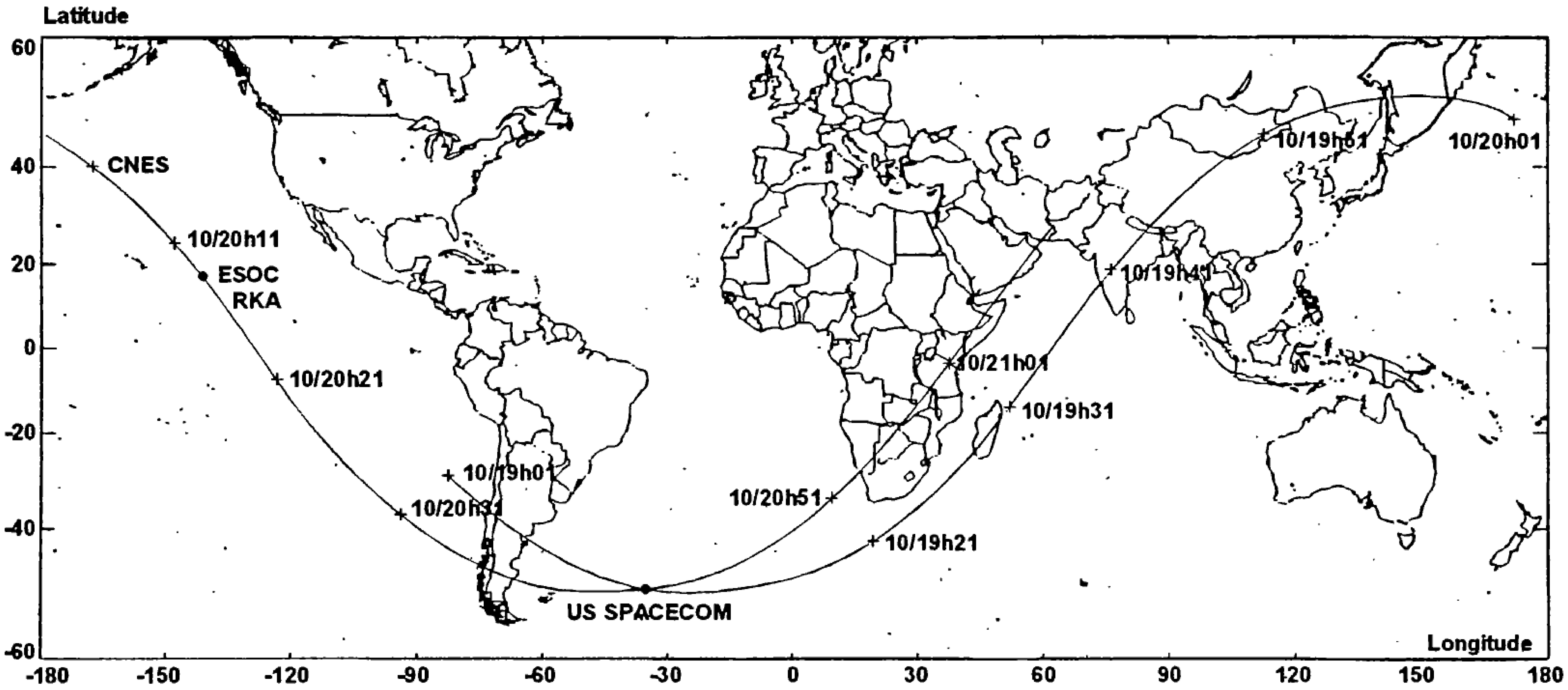

Figure 4. Cosmos 398 re-entry final orbit

7. RE-ENTRY OF CHINA 40 FSW-1

7.1 Organization and tracking of CHINA 40 FSW-1 re-entry

As of October 1995, the SEPRA set up the organization to track fall back to earth of the Chinese satellite CHINA 40 FSW-1, whose heat shield possibly would not be destroyed and therefore represented a danger during its re-entry.

The specialized re-entry cell was set up and put into service on January 25, 1996 and, on March 6, 1996, the reinforced alert phase was set up and provided forecasts for each TLE received and radar measurements made.

All measurement and tracking facilities were mobilized for this campaign, especially the SPOT2 and SPOT3 satellite radar transponders for tracking radar calibration.

Fifteen forecast bulletins were issued by the COO using the TLEs, and also the measurement calculations made by the French tracking radar.

7.2 Final fall back to earth

The first re-entry forecast, dated January 30, 1996, indicated a fall back to earth around the March 15, 1996, to within 5 days. The last bulletin, issued on March 12, 1996 at 1:00 UT using the MONGE tracking radar measurements, scheduled the re-entry for March 12 at 3:10 UT, to within 1 hour.

ESA results were consistent with those obtained by the OCC. The differences between these two entities are due to the means and accuracy criteria used. The OCC computed its re-entry windows (earliest and latest times) with an order of uncertainty of 15 % relating to the drag coefficient CpS/M. Re-entry dates were computed for an altitude of 80 km.

The radar measurements from the Monge were the decisive factor enabling re-entry predictions to established, thanks to their accuracy and the remarkable level of performance of its ARMOR radar systems. The last two passes determined from the Monge enabled the OCC to refine the re-entry prediction window to a considerable degree.

Regarding the final prediction, an exact time cannot readily be determined unless the object has been observed during its re-entry phase. As we have seen, the TLES data for the 10th and 11th March 1996 predict re-entry at 3.55 a.m. With measurements from the Monge only, re-entry is predicted at 3.15 a.m.

When TLES data based on observations of the object itself, from late on March 11th to March 12th at 3.12 a.m., was received and processed a posteriori, predicted re-entry time was found to be 3.45 a.m. CHINA 40 actually re-entered the atmosphere on March 12th. 1996 between 3.15 and 3.50 a.m.

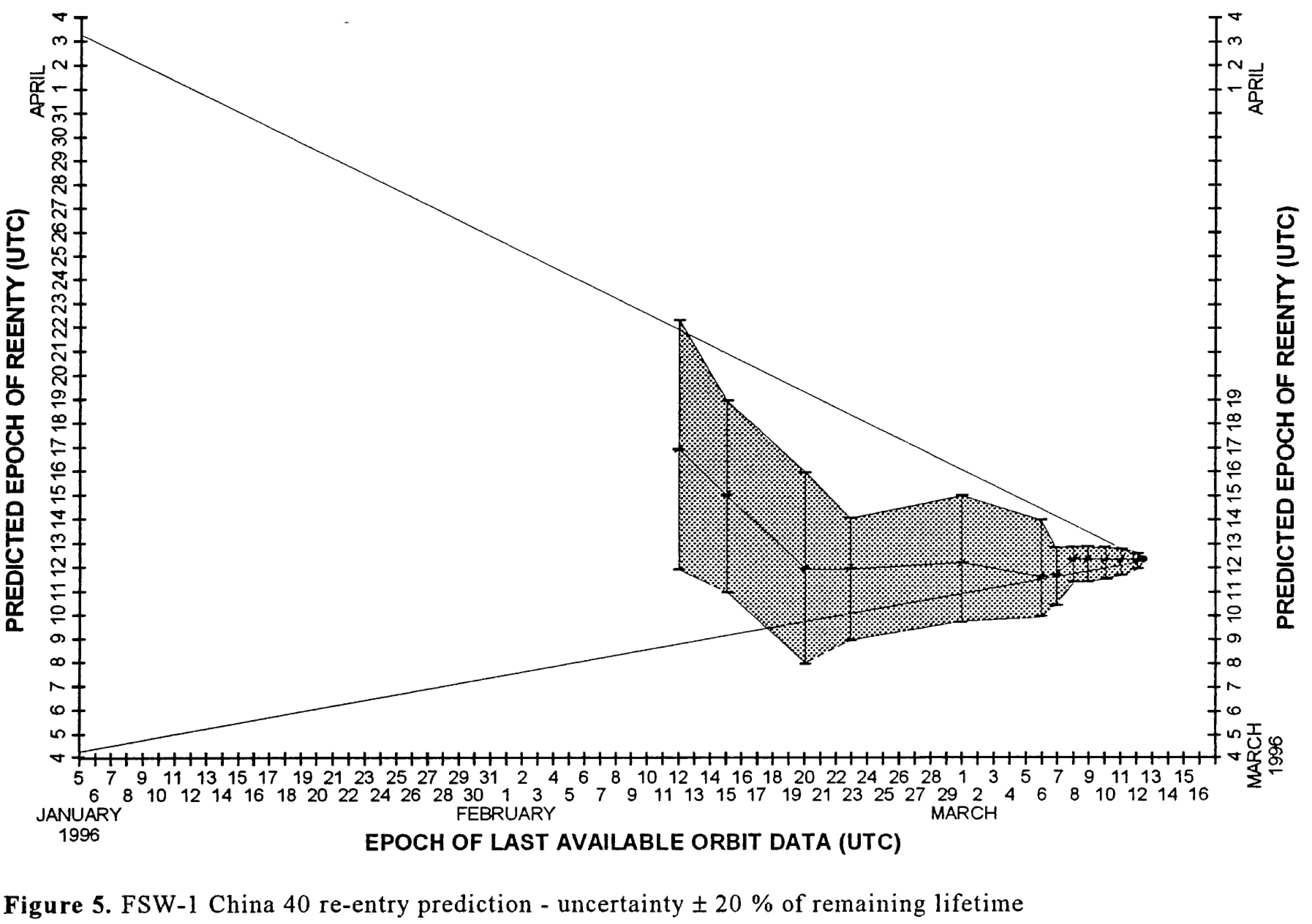

Figure 5. FSW-1 China 40 re-entry prediction - uncertainty ± 20 % of remaining lifetime

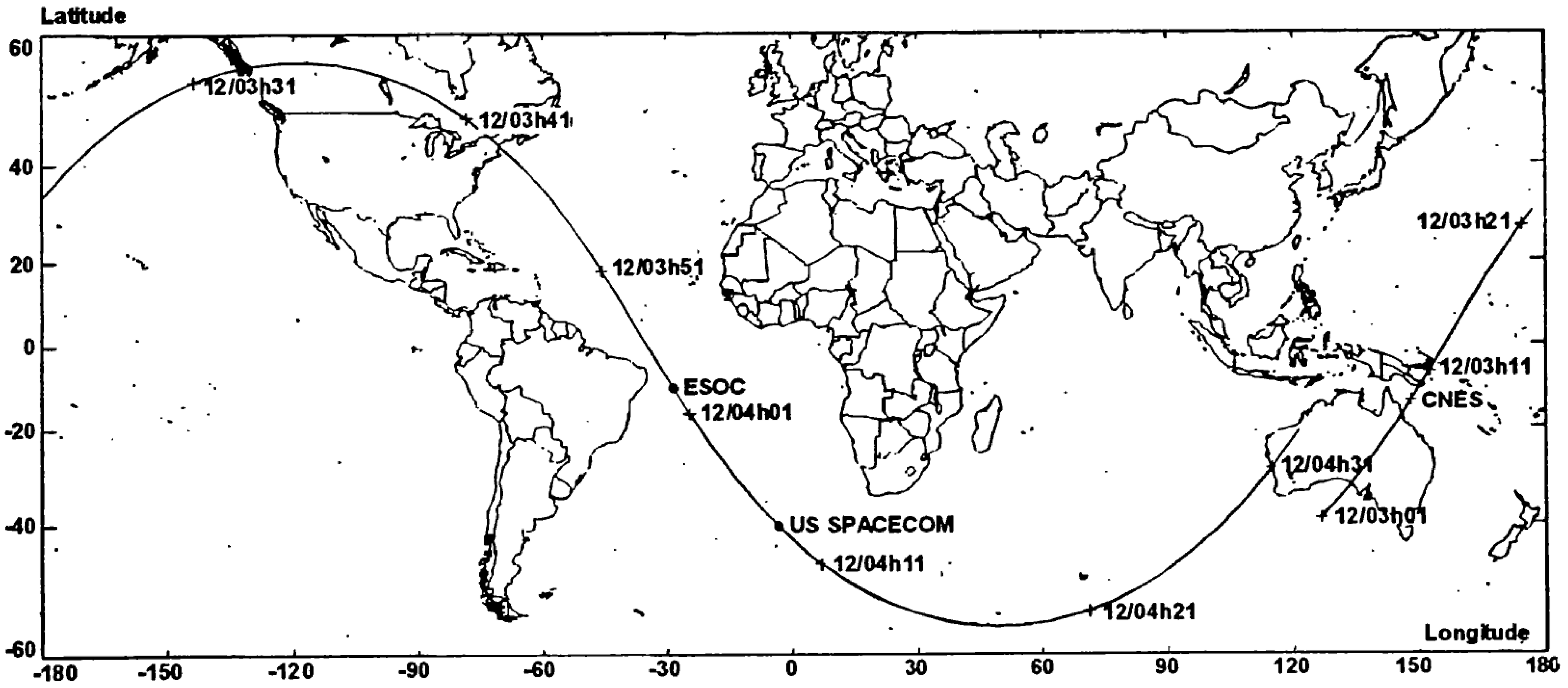

Figure 6. Jiambing - n.22870 - China 40 FSW-1 - Re-entry final orbit

COO Calculation Dates	COO Re-entry previsions	Window re-entry	Means used	ESA Bulletins Foreseen re-entry dates
08/03/96	12 March 1996 at 04:34	Soonest date : 11/03/96 at 7.50 Latest date : 12/03/96 at 21.00	TLEs data Monge and Quimper radar measures	Soonest date : 11/03/96 at 02:00 Latest date : 13/03/96 at 04:00
09/03/96	12 March 1996 at 04:34	Soonest date : 11/03/96 at 7.50 Latest date : 12/03/96 at 21.00	TLES data Monge radar measures	12/03/96 at 02:50 Soonest date : 11/03/96 at 12:00 Latest date : 12/03/96 at 18:00
10/03/96	12 March 1996 at 03:30	Soonest date : 11/03/96 at 20:00 Latest date : 12/03/96 at 15:00	TLES data Monge radar measures	12/03/96 at 03:54 Soonest date : 11/03/96 at 21:00 Latest date : 12/03/96 at 12:10
11/03/96 at 09:00	12 March 1996 at 05:00	Soonest date : 11/03/96 at 20:00 Latest date : 12/03/96 at 15:00	TLEs data Monge radar measures	11/03/96 at 15:30 Soonest date 12/03/96 at 00:15 Latest date 12/03/96 at 08:00
11/03/96 at 18:00	12 March 1996 at 05:00	Soonest date : 11/03/96 at 23:00 Latest date : 12/03/96 at 09:00	TLEs data Monge radar measures	11/03/96 at 20:30 Soonest date 12/03/96 at 01:13 Latest date 12/03/96 at 06:45
12/03/96 at 01:00	**12 March 1996 at 03:52** **12 March 1996 at 03:15**	Soonest date : 12/03/96 at 02:00 Latest date : 12/03/96 at 05:00	TLEs data only MONGE radar measures only	**12 March 1996 at 04:05**

7.3 Conclusions on the fall back to earth of CHINA 40 FSW-1

The tracking operation on the re-entry of the Chinese satellite CHINA 40 FSW-1 was carried out in compliance with the operational plan set up, using French civil and military facilities.
The re-entry of COSMOS 398 made it possible to carry out the test and calibration operations required to coordinate all operational measurement facilities employed.
The calculation of the forecast and the locating of the re-entry window are in compliance with the slot defined by USSPACECOM, since after the first forecasts based on the NASA TLEs, the calculations were carried out using the national measurement facilities by reconstituting the TLEs.

8. CONCLUSIONS

The frequency of atmospheric re-entry of potentially dangerous bodies in space, taking place at a rate of about one re-entry every two to three years, shows the need for monitoring and an operational organization in order to track and forecast the fall back to earth of these bodies. France has set up an organization, through the CNES, which satisfies this requirement.
The re-entries of COSMOS 398 and CHINA 40 FSW-1 were tracked in compliance with the defined procedures using national military and civil facilities, thus making it possible to acquire a certain degree of autonomy.
These monitoring operations can never be scheduled in advance and may have to be implemented at the most awkward times. The availability of any one of the various units involved can be a considerable problem. Because these operations are - fortunately - of an exceptional nature, the procedures involved are still fairly rudimentary, despite recent improvements.
On the other hand, calculations are a far more complex matter in these cases than in standard orbit determination, because of the numerous unknown factors that will always remain, the lack of available tracking facilities, and especially the major impact of atmospheric drag. This force is of much lesser account where other orbits are concerned, and is one of the most difficult to model with any accuracy.

However, it would be necessary from an international, and mainly European, standpoint that the countries cooperate to facilitate the exchange of information and improve the accuracy of forecasts. To this end, it is necessary to create a special access to a data base on the bodies to track, making it possible, in particular, to obtain information on their main characteristics. Also, access to reliable and recent orbit data from a main server is necessary, as well as the normalizing of the definitions and models of re-entry forecast calculations.