SALYUT-7/KOSMOS-1686 RE-ENTRY PREDICTIONS FOR THE ITALIAN CIVIL DEFENCE AUTHORITY

L. Anselmo+, C. Pardini*, A. Santoro+, S. Trumpy+ and P.E. Battaglia#

+ CNUCE, Istituto del Consiglio Nazionale delle Ricerche, Pisa
* Telespazio S.p.A. & CNUCE, Pisa
# Agenzia Spaziale Italiana, Rome

ABSTRACT

The work carried out at CNUCE during the Salyut-7/Kosmos-1686 re-entry campaign is presented. The technical procedures adopted are described, as well as the data sources and the problems encountered to obtain updated orbital elements for the space station. Forty-five re-entry predictions were computed during a 250-day time span and a percentage error less than 5% was obtained in 60% of the cases. The ballistic parameter of the space complex was estimated 54 times, using both the semi-major axis evolution and the nodal crossing epochs.

Another important aspect of the activity was the cooperation with the Italian Civil Defence Ministry. The kind of information that might be useful, its presentation and its timely availability were crucial issues for the ministries, agencies, local authorities and territorial units involved in the alert.

Keywords: re-entry predictions, orbital dynamics, drag modelling.

1. ORGANIZATIONAL STRUCTURE

The Soviet space station Salyut-7 was launched on April 19, 1982 into a low earth orbit with an inclination of 51.6°. During over 4 years of operational life she was docked by 10 manned Soyuz ships, 13 Progress supply craft and 2 large Kosmos modules. The last one, Kosmos-1686, has remained attached since October 2, 1985, creating a space complex 25 m long with a mass of about 40 metric tons.

After a series of re-boost maneuvres performed on August 1986, the space station was left to decay, due to air drag. On December 1989 some space listeners from the Kettering Group noticed an interruption of the radio transmissions; several Western analysts concluded that the complex was out of control and, unless a dedicated rescue mission could be accomplished, predicted a re-entry on the earth at the beginning of 1991.

In the following months the Spaceflight Dynamics Section of CNUCE, an istitute of the Italian National Research Council already involved in the re-entry prediction campaigns for Skylab (1979), Kosmos-1402 (1983), Kosmos-1900 (1988) and LDEF (1989), began the monitoring of the orbital decay for the Ministry of Civil Defence, acting on behalf of the Italian Space Agency (ASI).

It is easy to foresee that satellites out of control could re-enter in the atmosphere more frequently in the future. This means that big parts of them could reach the ground and cause damage, even though there is a very low probability. This prediction and the experience acquired in previous situations advised the Italian Ministry of Civil Defence to build a permanent organisation for monitoring the orbital decay and re-entry of uncontrolled spacecraft by using national facilities, in such a way as to be independent as much as possible of NASA for the acquisition of orbital data.

In effect, in all the previous re-entry campaigns, the delay in acquiring from NASA the two-line orbital elements represented the biggest problem, in particular during the very last days. The problem was partially avoided by an action of the ASI Representative Office in Washington, which guaranteed the transmission of additional two-line elements during the final critical phases of the flight.

The goals of the organisation proposed by the Ministry of Civil Defence should be:

1. to provide the spacecraft state vector and ancillary information;
2. to monitor the orbital decay;
3. to provide re-entry predictions;
4. to predict eventual passages over Italy during the last phases of the flight and the related subsatellite tracks;
5. to identify the targets and the activities eventually at risk;
6. to alert the concerned administrations (e.g. National Railways, Civil Aviation Authority, Defence Ministry, and so on) in order to arrange pre-emptive measures;
7. to coordinate the post-re-entry interventions in case of civil damage or nuclear contamination.

In order to examine the technical aspects and to define the necessary human and financial resources needed to build such a structure, a working group was constituted at the end of 1989. As far as the the seven points stated before are concerned, the conclusions of the working group (still not formalized) are:

- it is necessary to provide Italy with a system for tracking spacecraft in low earth orbit. Such a system should be constituted by at least a suitable radar sensor, possibly integrated into a European network;
- the overall coordination of the re-entry campaign is given to ASI, including the contacts with the international partners. The technical activities (data analysis, software engineering, dynamical modelling and re-entry computations) are performed by CNUCE within the framework of a co-operation agreement with ASI;
- the Ministry of Civil Defence provides dedicated communications lines, gathers CNUCE's predictions, identifies the targets and activities at risk and alerts the administrations involved. Moreover, the Ministry faces the eventual post-re-entry emergencies, assisted by the nuclear safety agency ENEA-DISP if a radioactive contamination occurs.

The proposed structure was tested (apart for the radar, which has not yet been procured) during the Salyut-7/Kosmos-1686 re-entry campaign.

2. THE RE-ENTRY PREDICTION PROCESS

The purpose of a re-entry prediction computation is to determine the time interval in which the natural re-entry of a satellite can be foreseen, taking into account all the uncertainties at stake.

The orbital evolution of a low earth satellite is predictable if the following information is available:

1. orbital parameters, to specify, at a fixed time, the dynamic state of the spacecraft's center of mass;
2. satellite physical characteristics (e.g. mass, shape, size, aerodynamic drag coefficent) to estimate the surface forces;
3. attitude control law;
4. orbital maneuvres (if any);
5. environmental parameters (e.g. solar flux, geomagnetic index) to be inserted into a semi-empirical atmospheric model able to describe the air density.

2.1 Orbital elements

Italy has not yet a radar sensor capable of searching for and tracking a low orbiting spacecraft, so it is completely dependent on foreign agencies to get updated orbital parameters for a given satellite.

As in previous re-entry campaigns, the most reliable and easy to obtain source of data were the NORAD Two-Line Elements (TLE) sent by NASA via mail and fax. The TLE were converted into osculating cartesian coordinates using the NORAD's routine SGP8 (Ref. 1) in order to generate the input for the orbit predictor used at CNUCE.

2.2 Fast orbital monitoring

For a quick look at the orbital evolution the TLE were collected in a database and processed using CNUCE's routine TWOLINE to generate tables and figures able to show the variation of the mean Keplerian elements, the ballistic parameter, the decay rate and so on.

2.3 Environmental model

To model the atmospheric density affecting the spacecraft motion the Jacchia-71/Roberts (JR71) model was used. This semi-empirical description of the upper atmosphere temperature and density needs two different environmental inputs: a daily value of the solar flux F at 2800 MHz and the three-hour geomagnetic planetary index Kp. Both were obtained (via mail or phone) from the National Geophysical Data Center (NGDC) in Boulder, Colorado.

The crucial problem was to predict the exospheric temperature. Such a temperature is mainly affected by the solar EUV radiation correlated to the flux at 2800 MHz, while the geomagnetic storms can produce significant variations only for a few days. Therefore, the solar flux prediction is very important both for long and short term computations, while the geomagnetic conditions are relevant only during the last week of the spacecraft's lifetime.

To obtain long term forecasts for F, the monthly average predictions of the sunspot relative number R based on a modified version of the McNish-Lincoln method (Ref. 2) were used, along with the corresponding 90% confidence level. The conversion to F (in standard flux units) was made using the empirical relation given by Euler and Holland (Ref. 3), which, throughout the re-entry campaign for Kosmos-1900, was found quite accurate:

$$F = 49.4 + 0.97\ R + 17.6 \exp(-0.035\ R) .$$

At last, by using the sunspot predictions provided by NGDC, it was possible to generate a realistic density model able to follow the solar activity trend during the monitored interval of time.

In the last two months of the spacecraft's lifetime the predicted solar flux was obtained from the observed values for the latest sun rotation corrected by an amount corresponding to the expected trend. Finally, during the last few days, the NGDC short term predictions were used instead.

No effort was made to predict the geomagnetic index Kp. A standard value (2) was assumed except for the last days, when the NGDC forecasts were taken into account.

2.4 Force model

The dynamical evolution of the satellite's center of mass was computed integrating the Cowell motion equations by means of the EPHEM program of the Goddard Trajectory Determination System.

In addition to the monopole term of the earth's gravitational field, the following perturbations were considered:

- zonal and tesseral harmonics of the geopotential up to the 16th degree and order (GEM-9 model);
- aerodynamic drag with air density computed according to the JR71 model;

- third body attraction of moon and sun;
- solar radiation pressure along the sun-satellite line, including the eclipses.

2.5 Ballistic parameter

To model the drag force affecting the spacecraft motion it was necessary to estimate the ballisic parameter B, given by

$$B = CA/2M ,$$

where C is the drag coefficient, while A and M are the spacecraft cross section and mass, respectively.

B changes due to attitude and altitude variations, so an averaged value was determined before any new re-entry prediction. Two methods were used: up to 100 days before re-entry B was obtained as the parameter able to reproduce a known semi-major axis decay during an orbital propagation with a force model as accurate as possible. Hundred days before re-entry the ascending node crossing times were used as benchmarks instead of the semi-major axis, in order to have an immediate check on the correctness of the sub-satellite ground tracks.

To get the right value of B, a method like that used in artillery to adjust the range was devised. After a few short and long "shots", it was quite easy to determine the ballistic parameter searched for. At this point, the new value found (or an average of the previous ones) could be used for the re-entry prediction computations.

2.6 Re-entry windows

During the different phases of the flight the re-entry windows were obtained as follows:

- from 250 to 100 days before re-entry: by imposing a variation of the ballistic parameter used for the predictions by plus or minus 30% (the atmospheric density models for the low and high flux corresponding to the 90% confidence level were not yet available);
- from 100 to 30 days before re-entry: by assuming a variation of B by 20% coupled with the low and high predictions of the solar flux at 2800 MHz corresponding to the 90% confidence level;
- from 30 to 2 days before re-entry: by assuming a variation of B by plus or minus 20% (the flux was supposed not vary significantly with respect to the predicted one);
- during the last day but one: by assuming a variation of B by plus or minus 15%;
- during the last day: by assuming a variation of B by plus or minus 10%.

2.7 Along-track fragments distribution

In order to evaluate the possible debris distribution consequent to the space station re-entry, the program TDBM (Two-Dimension Ballistic Motion), developed and implemented at CNUCE, was used. The spacecraft was supposed to disintegrate in hundreds of fragments having very different aerodynamic characteristics and masses; consequently, their individual trajectories were expected to produce a sparse rain of debris along the sub-satellite track.

Taking into account a coarse model of the station composition and mass properties, the trajectories of several sample debris were simulated starting from different fragmentation altitudes. For instance, assuming the disintegration occurred at an altitude of 69 Km, a piece with B = 0.3 square meters per metric ton would have hit the ground 1643 Km down-range after a flight of 5.7 minutes, while a debris with B = 300 square meters per metric ton would have struck the surface 87 Km down-range after 50 minutes.

Such simulations were very useful in setting some coarse criteria for the definition of the alert periods for the Italian territory and airspace. Actually, large pieces of the space station have been found in Argentina and Chile along a footprint of about 1500 Km. A 8 Kg ring with a diameter of 1.5 m was found 130 Km from the city of Rosario, while a 3.2 m long pipe weighing 4 Kg fell in the Andes mountains near the Chilean city of Puerto Montt.

3. THE COMPUTATION RESULTS

Starting from 250 days before the disintegration of the Salyut-7/Kosmos-1686 space station over the South American sky, 45 re-entry predictions and 54 determinations of the ballistic parameter were performed at CNUCE. 26 B calibrations were obtained matching the semi-major axis decay, while the remaining 28 were inferred from the ascending node transit times.

Even though large gaps in the solar flux data were often present, affecting the determination of B and the corresponding predictions, more than satisfactory results were obtained. The computed residual time of flight showed the following error distribution (see Fig. 1):

- 60.0% of the predictions presented an error less than 5%;
- 77.8% less than 10%;
- 84.4% less than 15%;
- 95.6% less than 20%.

The resulting standard deviation was equal to 9.5%.

The analysis of the results suggests the following:

1. the assumptions made to define the re-entry windows were adequate;
2. the percentage error distribution is not symmetrical around the actual re-entry epoch, but presents a higher occurence of excess computed lifetimes (28 vs 17). This could be explained taking into account the non linearity of the decay process, in which a given bias on B produces a smaller variation of the spacecraft lifetime if subtracted instead of added;
3. during the last two weeks, an error larger than 10% was found 4 times in 16 predictions;
4. averaged values of B were used for 5 predictions (from 6 to 1 week before re-entry) and never gave an error larger than 3%;
5. no clear correlation was discovered between the relative length of the time span used for the B calibrations with respect to the residual time of flight and the percentage errors of the corre-

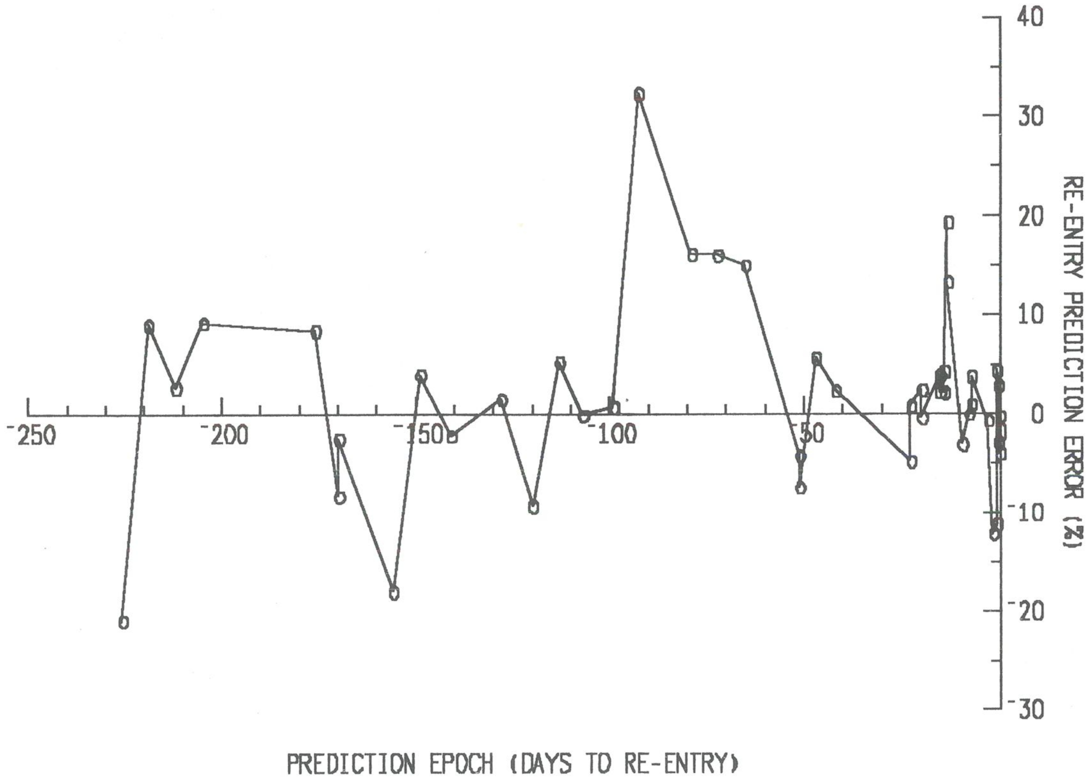

Figure 1. Re-entry predictions percentage errors.

sponding predictions. Probably the lack of the measured solar flux and geomagnetic index during most of the calibration time intervals introduced a large uncertainty that masked any eventual correlation;

6. the long term (over a few months) predictions of the solar flux were in agreement with the actual averaged values, but large daily discrepancies were inevitably observed.

From 250 to 100 days before re-entry the average value obtained for the ballistic parameter was 3.632 square meter per metric ton, with a standard deviation of 12.6%. During the last hundred days the average B was 3.004 and the standard deviation 8.5%; however a quite systematic trend was observed, with a larger value at the beginning (around 3.2 square meter per ton) and a smaller value at the end (about 2.8). All these values have not been re-computed "a posteriori", and therefore include the environmental uncertainty at the epoch in which the estimation was performed.

The operational accuracy attained at CNUCE during the last days of the flight provided the Italian Civil Defence Authority with useful information to prepare the intended precautionary measures. More than 37 hours before re-entry CNUCE issued the coordinates of 3 potentially risky passages over Italy, down to only one passage less than 25 hours later (see Fig. 2). As far as the global predictions are concerned, about 4 hours before re-entry (by using a 5-hour old TLE dictated via phone by the ASI representative in Washington) it was possible to issue a re-entry window consisting of only one orbit, including, unfortunately, the above mentioned transit over Italy (see Fig. 3).

The last two useful predictions computed before the re-entry obtained a decay to the altitude of 70 Km at 4:00 and 3:35 UTC, respectively, on February 7, 1991. Two other predictions, based on the latest TLE received after the actual re-entry, gave as results 3:42 and 3:44 UTC. The United States Space Command set the re-entry of Salyut-7/Cosmos-1686 at 3:44 UTC, plus or minus 1 minute.

4. PREDICTION BULLETINS

An important aspect of the re-entry prediction activity was the cooperation with the Italian Civil Defence Ministry. The kind of information to be supplied, its presentation and its timely availability were crucial issues for the ministries, agencies, local authorities and territorial units involved in the alert. Therefore, a lot of effort was dedicated in translating the technical results of the prediction work in practical and easy to understand operational guidelines and prescriptions.

The results of the prediction process, as described in the previous sections, came out in a tabular format which is not easily readable. Since the final information was devoted also to personnel whose activity field is not space or computer oriented, a graphic representation helped give a compact and intelligible format to these results.

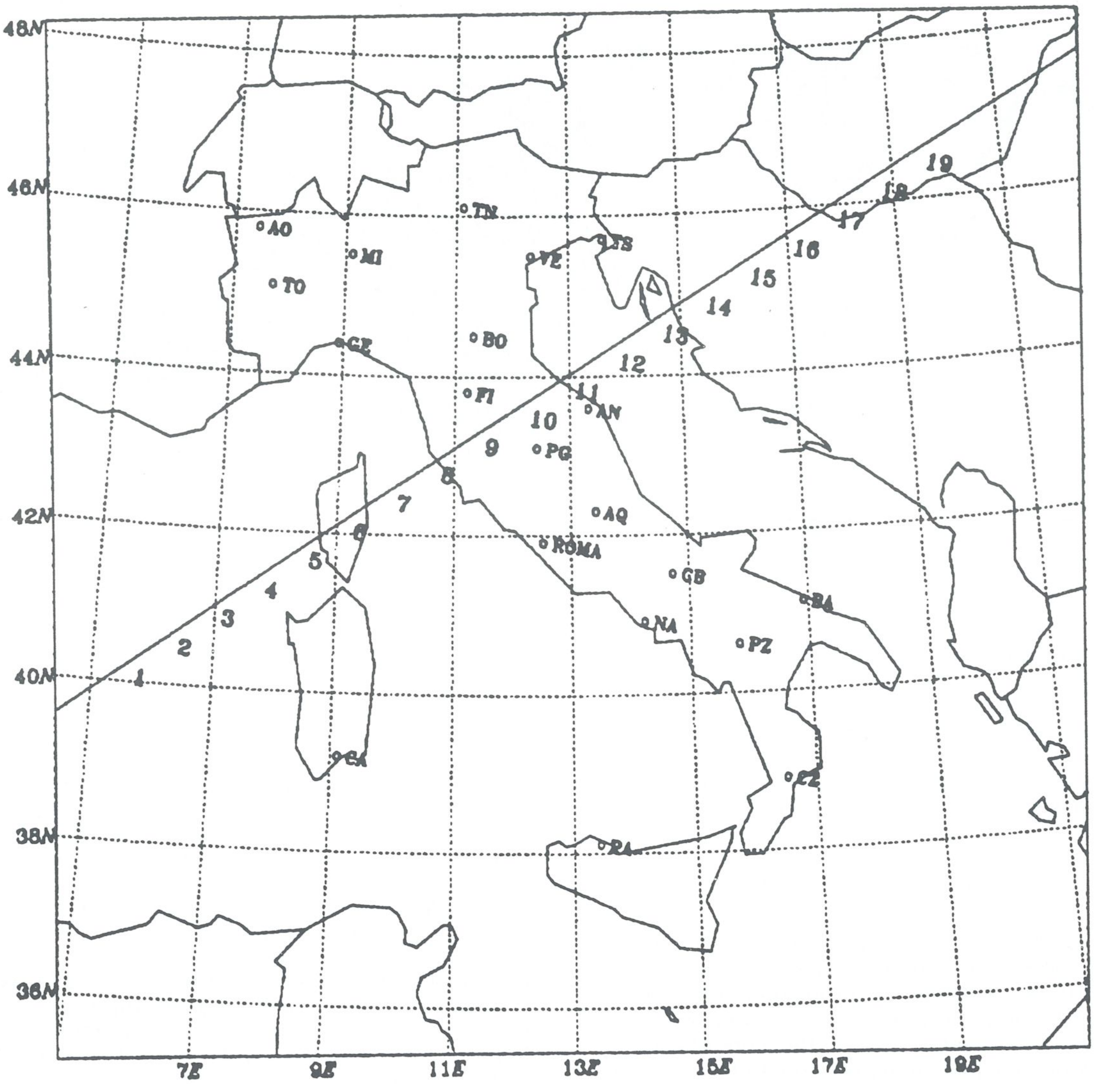

Figure 2. Potential risky passage over the Italian territory.

The final bulletins included two types of information, graphic and textual. The first graphic output (see Fig. 3) displayed almost all the world in Mercator projection within a suitable latitude belt, over which the ground track of the satellite was plotted. This gave an overview of the situation, with regard to the countries overflown by the risky paths around the re-entry predicted epoch.

Other information attached (not shown in the figure) were the name of the satellite, the originator of the initial orbital elements used to propagate the state vector and the time interval for which the ground tracks were plotted.

The second graphic output displayed the geographical area of interest to the Ministry of Civil Defence (i.e. Italy) and, superimposed, the sub-satellite tracks (see Fig. 2). The gnomonic projection (in which great circles are rendered as segments of a straight line) was used to reduce to a minimum the error of representation due to the finite time-step generation of the orbital ephemeris.

Great care was devoted to the clearness of the graph. This was accomplished by giving the user the option to select a suitable data subset from the generated ephemerides. Different graphs could then be produced in relation to different time intervals chosen by the user.

In each graph the data points of the track were marked by progressive numbers. This made it possible to see the space-time evolution of the orbit at a glance. Within a close window (not shown in the figure), alpha-numeric data were reported corresponding to any marked point, typically date, time, longitude and latitude. Such information was used by the Civil Defence Authority to plot the risky tracks, along with a hazard swath 200 Km wide, on detailed territorial maps including critical facilities and targets (e.g. airports, chemical depots, dangerous industrial plants, power stations and so on) and administrative boundaries. The Image Processing and Territorial Data Bases Section of CNUCE was able to duplicate such an effort if it was needed.

Other sheets were provided, giving explanatory and integrative information about the re-entry. Mainly they consisted of re-entry windows, alert periods (taking into account the time the fragments needed to strike the ground), hypotheses used for the predictions

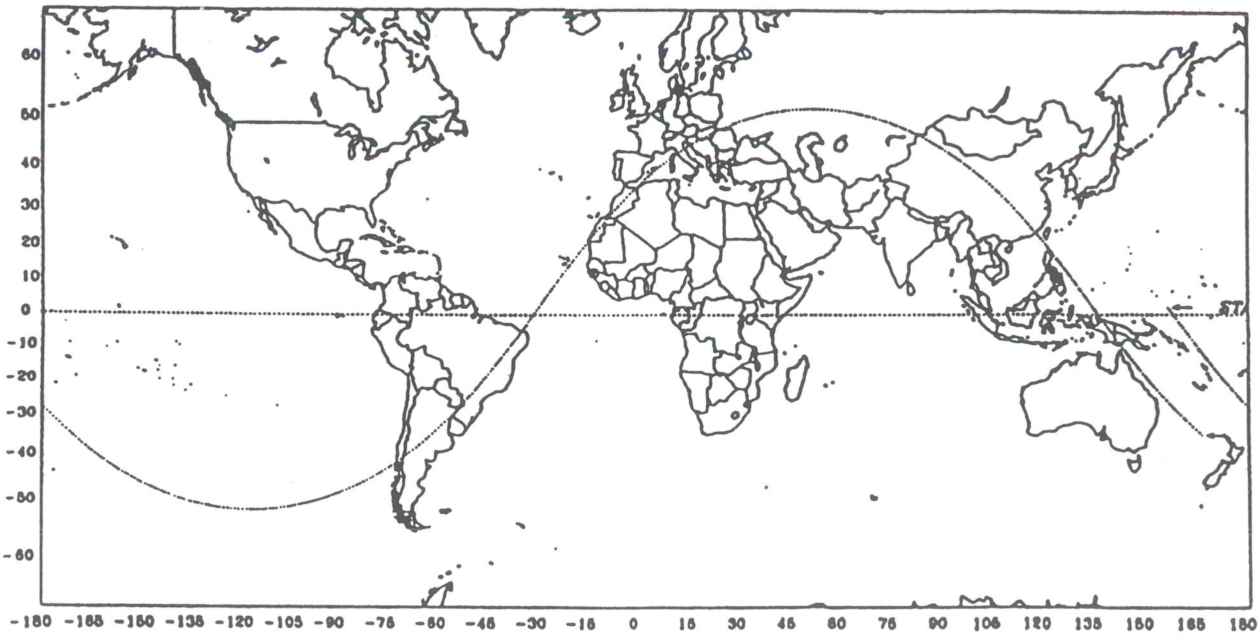

Figure 3. Ground track corresponding to the last re-entry window issued.

(solar activity, spacecraft attitude, etc...) and operational suggestions for the Civil Defence Authority.

5. CONCLUSION

Since the Skylab re-entry campaign, about twelve years ago, several improvements have been introduced at CNUCE to refine the prediction work. Many operational procedures were devised and a lot of software was developed to support the work of a small group of 3-4 people dedicated part-time to this activity. The results obtained and the profitable cooperation interwoven with the Ministry of Civil Defence and the Italian Space Agency can be considered more than satisfactory, even though a few areas requiring further action have been identified.

The main problem is the lack of a national source of space surveillance data. Considering the possibility of dangerous developments in world affairs, this deficiency is quite serious from several points of view, not last the impossibility to monitor the passages and the re-entry of large uncontrolled spacecraft.

The two-line elements provided by NASA in the past were a very valuable source of data, but it was ever more difficult to get them and during the last and critical phases of a spacecraft's lifetime they were never timely enough.

The problem could be solved with a national radar facility dedicated, among other purposes, to space surveillance activities. Such a sensor could be integrated into a European network, set up in the framework of international agreements following national or supranational initiatives. With regard to the last point, the activity carried out by ESA in promoting awarness in Europe on space debris related topics and a more active cooperation and data exchange between the member states must be welcomed with deep satisfaction.

Another progress might be represented by the creation at CNUCE of 1-2 new staff positions integrated into the Spaceflight Dynamics Section, but dedicated full-time to space debris research, monitoring of space activities and re-entry prediction work. At present such topics are addressed only desultorily, when other institutional activities allow it.

An "a posteriori" analysis of the computations performed is planned. By using the right values for the environmental variables and the "a posteriori" knowledge of the attitude control carried out by the Soviets, a thoughtful test of our software and hypotheses should be possible.

6. ACKNOWLEDGMENTS

The authors are indebted to Vincenzo Letico, ASI representative in Washington, for helping them obtain the updated two-line elements from NASA; to Adam Johnson, GSFC/NASA, that provided the elements via facsimile; to Walter Flury and Haines Klinkrad, ESOC/ESA, for the valuable information supplied in critical moments and their fruitful cooperation.

7. REFERENCES

1. Hoots F.R. & Roehrich R.L. 1980, Models for propagation of NORAD element sets, Project Space Track Report, No. 3, Aerospace Defence Command, Peterson AFB, Colorado, 100 p.

2. Solar-Geophysical Data - explanation of data reports, No. 515 (Supplement), NOAA 1987, Boulder, Colorado, 10

3. Tobiska W.K. & al. 1987, Predicted solar cycle twenty-two 10.7 cm flux and satellite orbit decay, The Journal of the Astronautical Sciences, Vol. 35, No. 4, 419-433