Proceedings of the First European Conference on Space Debris, Darmstadt, Germany, 5-7 April 1993 (ESA SD-01)

EUROPEAN INVOLVEMENT IN THE 1992 PION EXPERIMENT

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ABSTRACT

Two Russian PION spheres were released in September 1992 for upper atmosphere studies. For Europe this was an opportunity to test its reentry prediction capabilities. ESOC was the central node in Europe where the available data were gathered and distributed to the participating partners. FGAN (Research Establishment for Applied Science, Germany) was the most active partner providing radar data about orbit and physical characteristics of the spheres as well as reentry predictions. Together with NASA Two-Line Elements and data from IKI (Russia), the FGAN data were processed for orbit and ballistic coefficient determination and for reentry prediction. Due to quiet atmospheric conditions highly accurate reentry predictions were made.

1. INTRODUCTION

On 19 August 92 the Resurs-F 16 satellite (see Figure 1) was launched into a 82.57°, 221 x 238 *km* orbit. Onboard were the two spheres PION 5 and PION 6 which were released on 1st and 2nd of September for upper atmosphere studies via orbit decay monitoring. Further objectives of the PION spheres were radar calibration and performance testing.

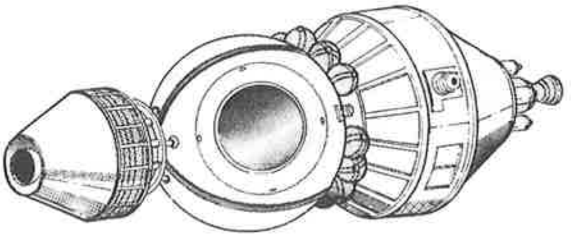

Figure 1. Linedrawing of Resurs-F 1 photo reconnaissance satellite (Ref. 1).

The 1992 mission was the third PION experiment. The first experiment was launched with Resurs-F 1 on 25 May 1989. Two spheres, PION 1 and PION 2, were released on June 8 and 9, respectively into 256 x 268 *km* orbits. After about 6 weeks they reentered on July 23 and 24. The second experiment was launched with Resurs-F 3 on 18 July 1989. Spheres 3 and 4 were released on August 7 (255 x 270 *km*) to remain in orbit for 6 weeks (decay date 19 September).

The PION satellites were designed and built by the Korolev Aviation Institute of Kuibyshev/CIS. The two spheres PION 5 and 6 had the following masses and diameters:

PION 5:	49.466 kg / 0.33 m
PION 6:	49.434 kg / 0.33 m

The resulting density of 2.63 g/cm^3 is close to the density of aluminium. However, as it turned out during the experiment, the two spheres were not homogeneous: there was a structure of three mutually perpendicular circular disks of lead, whereas the spheres themselves were made of plastic. PION 5 was covered with radar reflective and PION 6 with radar transparent material.

For Europe this experiment offered the favourable opportunity to improve its reentry prediction capabilities. As was previously experienced during the Salyut-7 / Kosmos-1686 reentry campaign, accuracy of reentry predictions of risk objects depends on availability and on correct interpretation of the non-coherent data which were delivered in different formats and different reference systems. Therefore, the objectives for the European participation in this experiment were:

- Testing and possibly improving reentry prediction tools
- Ensuring timely data exchange
- Conversion and comparison of data from different sources

The next paragraphs will show that these objectives were successfully achieved.

2. DATA ACQUISITION AND PROCESSING

2.1 FGAN High Power Radar System

FGAN developed in recent years a radar and analyses tools to assist experimental radar research. Basically the High Power Radar consists of three subsystems: a 34-m parabolic antenna, a tracking radar, and an imaging radar.

The tracking radar operates at L-band and uses a four-horn monopulse feed for tracking in elevation and traverse direction. The signal processing concept is based on correlation technique obtaining range, range rate, and narrow band coherent echo amplitude and phase measurements. Typically the pulse length is 1 ms, peak power 1 MW, pulse repetition frequency 30 Hz.

The imaging radar operates at Ku-band. The high resolution of 0.25 m is achieved by generation of linear frequency modulated impulses. The signal processing concept is based on a de-ramp technique and quadrature demodulation, yielding for each radar echo 1024 digital samples in the I,Q-channel. Typically the pulse length is 256 μs, peak power 10 kW, pulse repetition frequency 55 Hz.

Due to the narrow beam width of the radars (0.5 degree for L-band) the spatial search volume is limited. There

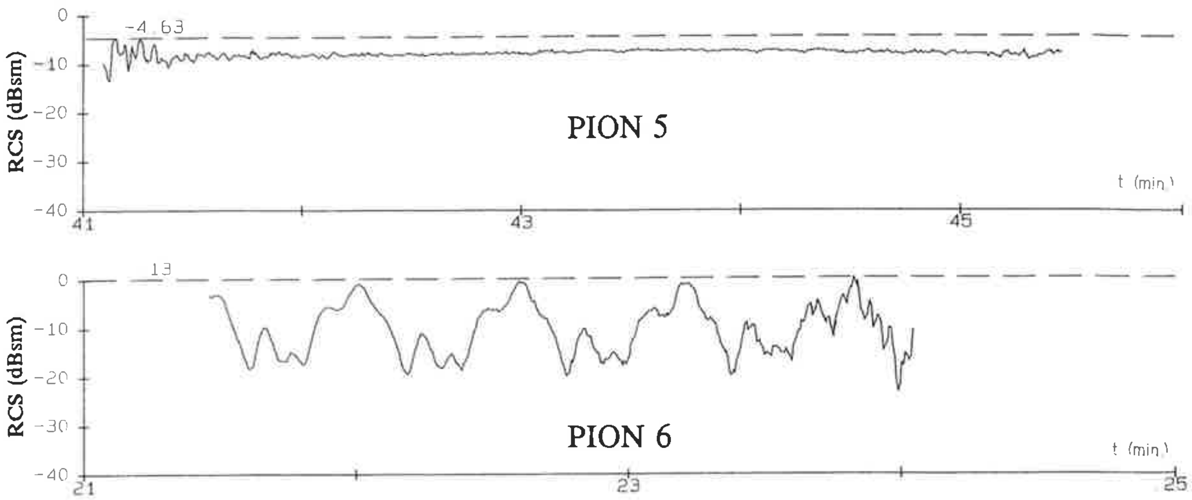

Figure 2. Radar signatures of PION 5 and PION 6 taken by the FGAN high power radar system.

are also problems in the separation of two or more targets being simultaneously in the search volume: In 400 km range the diameter of the radar beam is about 3.5 km, a satellite needs less than 0.5 s to pass the beam. The example also shows how accurate pre-information has to be in order to initiate tracking.

In Figure 2 radar signatures of PION 5 and PION 6 are presented. In case of PION 5, the signature is typical for a sphere. The signature of PION 6 shows a periodic structure, however, from this it can not be concluded that it is from a circular trihedral corner reflector. The problem is that the size of the corner reflector is in the order of the radar wave length.

2.2 Orbit determination at ESOC

FGAN delivered radar data (slant range, range rate, azimuth and elevation) for 45 PION 5 and for 14 PION 6 passages to ESOC. During normal working days three to four passages of PION 5 were observed. Figure 3 illustrates the geometry of the last four passages over Wachtberg-Werthhoven, Germany. Many passages had very low maximum elevation degrading the radar data due to atmospheric refraction. At ESOC the pre-processed radar data were used to derive the orbital position at the end of the last passage and the ballistic coefficient of the spheres (data with elevation angles below 5° were not included).

An iterative least squares algorithm was used to improve the initial estimate of the orbital position and the ballistic coefficient. The initial estimate was either the propagated solution of the previous day or a state vector provided by FGAN. To determine the ballistic coefficient at least 3 orbital passages are needed.

This algorithm was intensively applied and improved during the Salyut-7 / Kosmos 1686 reentry campaign (Ref. 2). Due to these past experiences only a small number of iterations was necessary to find an orbital position and ballistic coefficient that fitted extremely well the observed radar data. In total, orbit determination was performed 10 times for PION 5 and once for PION 6.

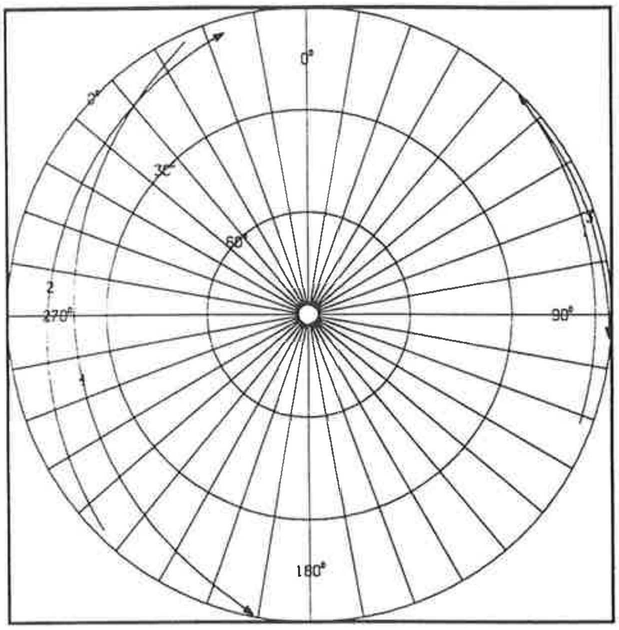

Figure 3. Azimuth and elevation angles of PION 5 during its last four passages over Wachtberg-Werthhoven, Germany on 24 September 1992.

2.3 Data Distribution

Primary data sources were:

- DoD / IKI (CIS)
  providing osculating Kepler elements, with nodal period instead of semimajor axis; time is given as UTC for epochs of ascending node crossings; the coordinate system is a mean-of-date system of 1950. Before further processing, the draconic period in the CIS data was converted to semimajor axis (see Ref. 3).
- USSpaceCom / NASA (USA)
  providing Two-Line Orbital Elements (TLEs). Most of the TLEs which are available at ESOC now had been transmitted 6 weeks after reentry. Therefore, they could not be used for the reentry predictions.

Accessible Data Sources	Orbital Elements		Tracking Data	
	PION 5	PION 6	PION 5	PION 6
DoD/IKI (CIS)	**13**	**10**	**–**	**–**
FGAN (D)	**15**	**1**	**45**	**14**
SpaceCom/NASA (USA)	**53 (*)**	**46 (*)**	**–**	**–**
ESOC (ESA)	**10**	**1**	**–**	**–**

Table 1. PION data sources available to ESA.
(*) during the campaign 8 TLEs of PION 5 and 6 TLEs of PION 6 were available.

- FGAN (Germany)
  providing pre-processed radar data (corrected for atmospheric refraction) as well as TLEs.

In Table 1 the number of available orbital elements as well as pre-processed tracking data is summarised. Since the CIS data always came in with some delay and since the US data transmission was discontinued during the last week, FGAN remained the most reliable data source.

During the PION experiment ESOC was the central node of data exchange in Europe. Whenever new data were acquired they were immediately distributed with or without being processed. From 31 August to 28 September thirty-three faxes were sent to CNES, DRA (formerly RAE) and FGAN giving the latest updates. Additionally all information was stored on the ESOC communications computer which was accessible to the campaign participants.

3. ORBITAL DECAY OF THE SPHERES

3.1 Separation of PION 5 and 6

The epochs were the only details about the separation of the two spheres which Russia released: PION 5 on 1 September at 8:48 UTC and PION 6 on 2 September at 5:37 UTC. However, having Two-Line Elements of the spheres and of the Resurs-F spacecraft it is possible to derive the separation velocities and the location where the separation took place.

The epoch of the first TLE of PION 5 was 8 h 40 min after release. Propagating back PION 5 and also propagating back the Resurs-F spacecraft (by 2 h 45 min) to the time of separation, the following results were achieved:

difference in position:	160 m (due to propagation errors)
separation velocity:	0.8 m/s (out-of-plane)
geodetic position:	34.8°E, 58.3° N (North of Moscow)
geodetic altitude:	243.3 km

For PION 6 the propagation time was 10 h 8 min and for Resurs-F 11 h 40 min. The results were:

difference in position:	567 m
separation velocity:	0.8 m/s (out-of-plane/radial)
geodetic position:	83.0°E, 62.5° E (North of Novosibirsk/Siberia)
geodetic altitude:	244.6 km

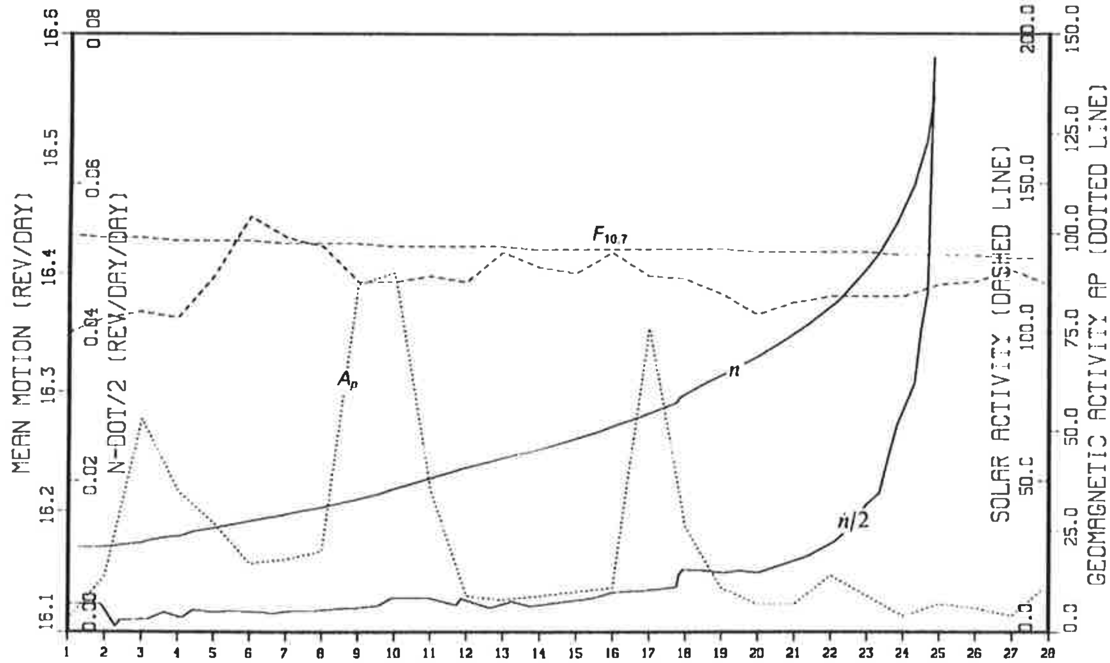

Figure 4. The orbital decay of Pion 5 was strongly coupled with the solar and geomagnetic activity

3.2 Atmospheric conditions

In Figure 4 solar and geomagnetic activity are plotted. The dashed line shows a very smooth solar activity between 100 and 139× 10^4 *Jy*. The mean solar activity averaged over 162 days (6 solar revolutions) was smoothly dropping from 133 to 126. However, the geomagnetic A_p index reveals three peaks: one medium-sized peak on 3 September, a two-day peak of up to 90 on 9-10 September, and a third peak on 17 September.

A correlation between the last magnetic storm and the mean motion of PION 5 is apparent. Even more apparent is the correlation with the first time derivative of the mean motion, generally called *n-dot*. $\dot{n}$ is directly proportional to the atmospheric density, which itself is strongly influenced by magnetic storms.

Due to the very quiet conditions after 17 September the reentry predictions of PION 5 and 6 were very accurate during the last week of their orbital lifetime.

3.3 Orbital Evolution

The release of the second sphere was announced for the 2nd of September, but due to bad observation geometry in Wachtberg-Werthhoven PION 6 was not observed before 11:15 UTC the following day. Due to its radar transparent spherical shell, and due to its radar reflective internal structure (corner reflector), FGAN could not confirm that the observed object was PION 6. In the course of the next days, as more and more data were gathered, it could be verified that PION 5 was in a leading position, with PION 6 trailing some seconds behind. Initially, the PION 5 decay rate was 1.2 km/d, and the PION 6 release orbit at 221km x 226km was slightly above the descended PION 5, with an on-orbit time separation of about -30 sec behind. This time separation gradually built up to -100 sec within 13 days after the release of both spacecraft. At that time, the larger decay rate of PION 6 had compensated for the initially larger orbital period, and PION 6 started to accelerate towards PION 5. On 21 September, 19 days after the release, PION 6 moved ahead of PION 5 towards an earlier decay date.

Figure 5 shows the separation time history. From 4 September (day 248 of the year) onwards, also IKI orbital data were available which were in perfect agreement with FGAN time offsets. The explanation for PION 6 to catch up with PION 5 is its higher atmospheric drag. Determination of the ballistic coefficient ($BC = \frac{1}{2} c_D A/m$) by fitting four TLEs of PION 5 and five TLEs of PION 6 (the epochs of the TLEs are within an interval of 24 hours on 22-23 September) renders considerable differences:

PION 5: 0.00173 m^2/kg
PION 6: 0.00181 m^2/kg

The Russian scientists deduced somewhat lower values: 0.00163 for PION 5 and 0.00169 for PION 6. These values, however, are below the theoretical values of 0.0019 to 0.0020 which were provided by IKI for both spheres.

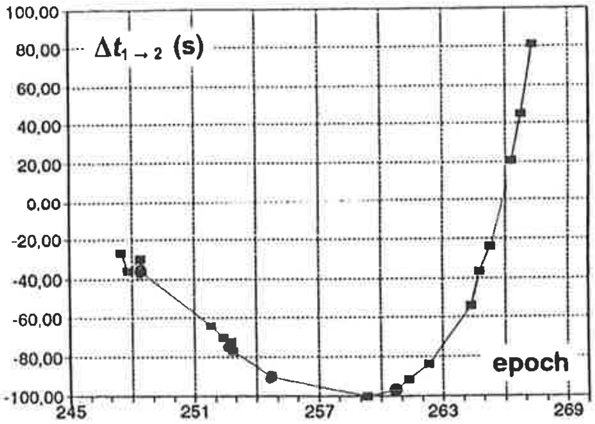

Figure 5. Separation time history between PION 5 and 6 (squares: FGAN, circles: IKI).

4. REENTRY PREDICTIONS

Reentry predictions for both PIONs were started at ESOC on a regular basis 3 days before the expected decay, on 21 September. For PION 5, which had considerably more orbit determination data than PION 6, a 4-day arc of the observed decay history was used to perform an RMS retro-fit to the history of the semimajor axis by adaptation of the drag coefficient c_D.

ESOC Orbit Determination from FGAN Tracking Data		ESOC Lifetime Prediction from Combined Orbital Data		
Epoch (UTC)	c_D	**Epoch (UTC)**	c_D	**Reentry (UTC)**
15-Sep-92 09:08	**1.700**	–	–	–
16-Sep-92 08:45	**1.726**	–	–	–
20-Sep-92 19:05	**1.799**	–	–	–
–	–	**21-Sep-92 18:31**	**1.937 (**)**	**25-Sep-92 00:44**
23-Sep-92 08:22	**1.965**	**23-Sep-92 06:50**	**1.948 (**)**	**24-Sep-92 23:58**
24-Sep-92 07:45	**1.972**	**24-Sep-92 07:41**	**1.961**	**24-Sep-92 23:38**
–	–	**24-Sep-92 13:20**	**1.970**	**24-Sep-92 23:54 (*)**
24-Sep-92 18:15	**2.051**	**24-Sep-92 18:15**	**1.960**	**24-Sep-92 23:52**

Table 2. Determination of drag coefficients for PION 5.
(*) last reentry prediction by DoD/IKI (at 13:20) → 23:58 UTC, (**) c_D of DoD/IKI → 1.885 - 1.955 (on 22 September).

Table 2 summarises drag coefficient estimates from a numerical orbit determination program (left columns), and from a semi-analytical reentry prediction program (right columns), with results sorted in ascending epochs. It can be noted that the numerical c_D results are slightly larger than the semi-analytical ones. This may be explained by the use of different density models (MSIS-77 and Jacchia-Lineberry, respectively). The secular increase in c_D (particularly noticeable in the numerical orbit determinations) is most likely the consequence of density model deficiencies as altitudes approach the turbopause (at 120km). While there are aerodynamically founded effects of c_D increase during re-entries, these will only take place below altitudes of 120km (transition region).

The semi-analytical results of c_D for PION 5 (Table 2) were very consistent over the time span of reentry predictions (21 to 24 September). This consistency is also reflected in the predicted reentry times (accuracy of better than 1 hour, 3 days before decay). The epochs given in Table 2 are times at which an altitude of 30 km is passed. The final prediction for PION 5, using a state vector from 24 September 18:15 UTC, resulted in a reentry epoch of 24 September 23:52 UTC, at a location near the 180° meridian in the Bering sea (Figure 7). This result matches well with the last available Russian forecast of 23:58 UTC (using a state vector from 13:20 UTC). Figure 6 shows the final descent arc of PION 5.

For PION 6, tracking data and orbit determinations were less numerous than for PION 5. The time span for an RMS retro-fit of c_D thus had to be extended to about 1 week. Due to the higher drag coefficient of PION 6 (assuming similar mass and geometry), its decay was earlier than for PION 5. Predictions from 22 September, using a state vector at 16:01 UTC, resulted in a reentry on 24 September at 13:50 UTC. The final prediction, with a state vector from 24 September 11:47 UTC, led to a reentry at 13:21 UTC, on an ascending pass above the Gulf of Mexico (see Figure 8).

5. CONCLUSIONS

The 1992 PION experiment was used at ESOC and FGAN to test reentry prediction capabilities. Since the reentry objects were spheres the accuracy of the reentry prediction mainly depends on availability of orbital data.

Since FGAN supplied data for at least 3 passes per day, sufficient data was available to allow very accurate reentry predictions.

Russia added a lot of useful orbit and mission related data (via IKI), including some design information about the PION spheres. During the first two weeks also NASA Two-Line Elements were available. For similar experiments in the future, CNES (France) will try to provide data as well.

6. ACKNOWLEDGEMENTS

We gratefully acknowledge the assistance of Natan Eismont and Sascha Sukhanov of IKI, Russia for their support in data transmission.

7. REFERENCES

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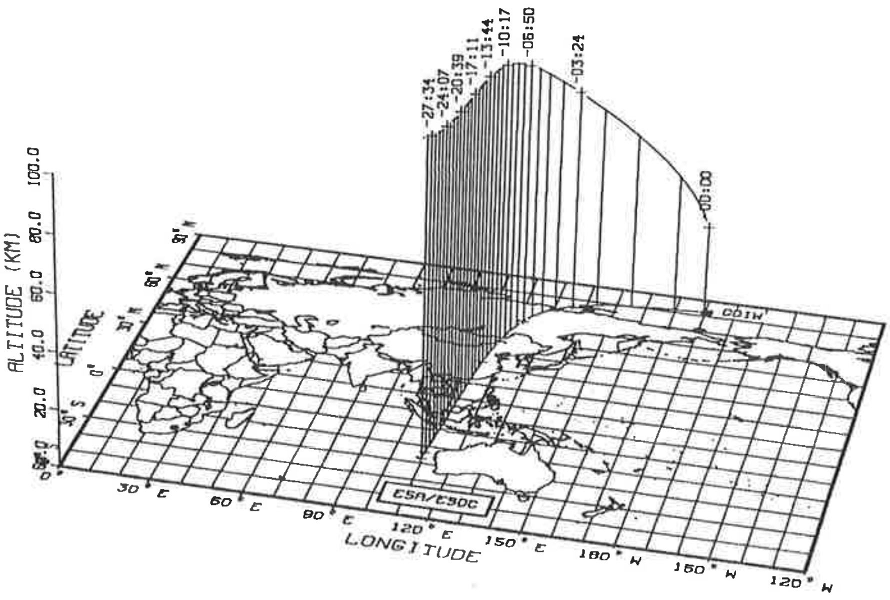

Figure 6. PION 5 final descent altitude profile

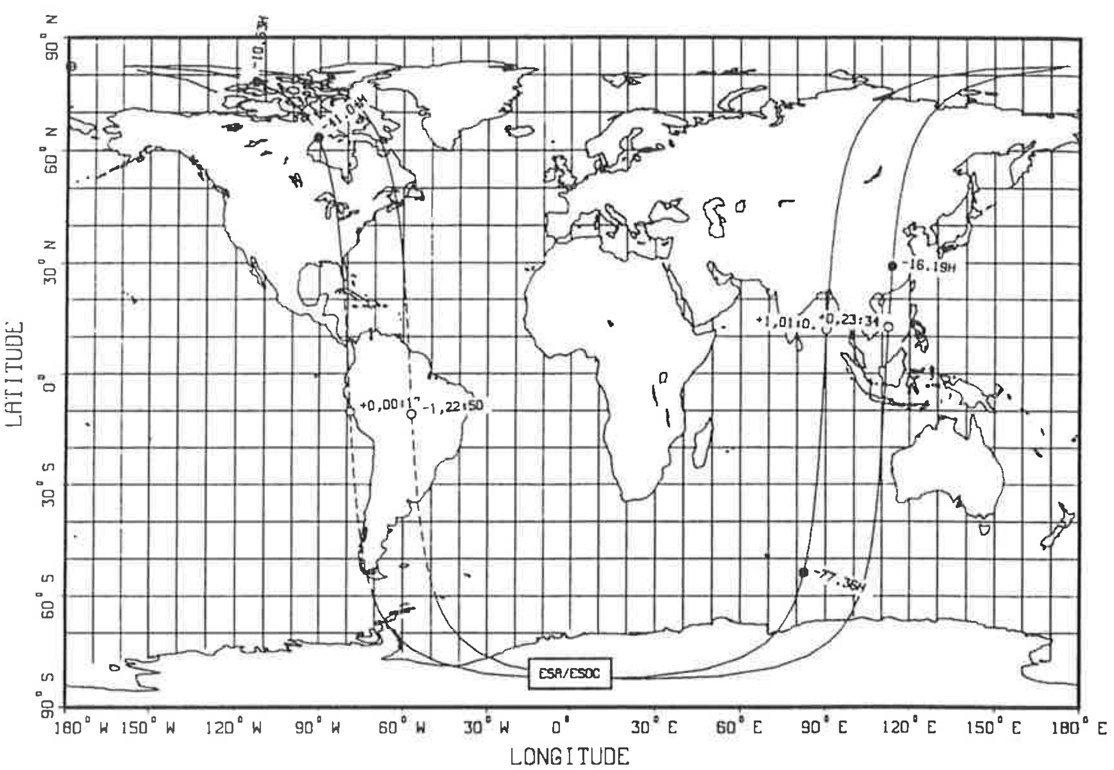

Figure 7. Predicted groundtracks on reentry day of PION 5

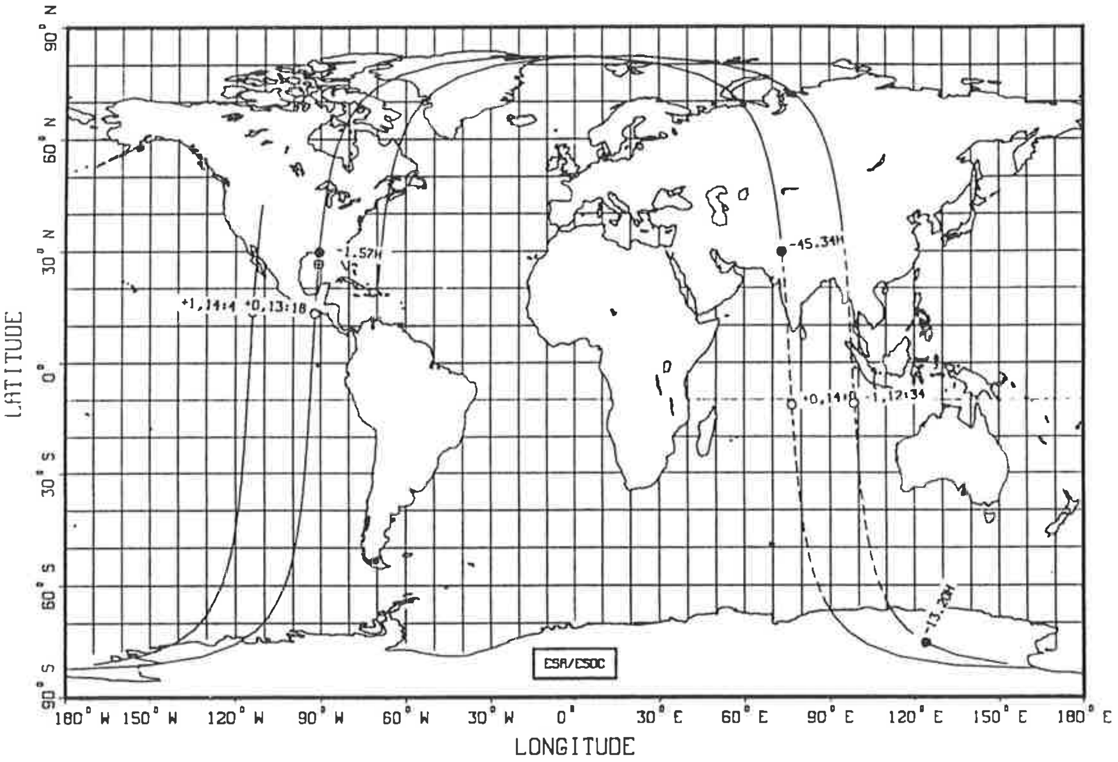

Figure 8. Predicted groundtracks on reentry day of PION 6