UK TECHNICAL ACTIVITIES ASSOCIATED WITH THE RETURN TO EARTH OF THE MIR SPACE STATION

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ABSTRACT/RESUME

The British National Space Centre (BNSC) acts as the focus in the United Kingdom (UK) for space-related activities. With the anticipated return to Earth of the Mir space station, BNSC established a group of technical experts to consider the associated implications for the UK, and to address both national and international activities relating to the planned de-orbit. In particular, the risk to the UK of an uncontrolled re-entry was considered in contingency planning and the means for the provision of accurate information to the public and media were established to ensure balanced view of the potential hazards that Mir posed to persons and property on the ground. The Mir de-orbit was exemplary, both in terms of the technical activities of the Rosaviakosmos and the safe disposal of Mir in the Pacific, and in relation to the open and effective communication between agencies and the positive reporting by the media.

1. INTRODUCTION

The Mir space station was launched on 20 February 1986 with a planned operational life of five years. When it returned to Earth on 23 March 2001, it had completed over fifteen years in orbit and more than 86,000 revolutions of the Earth. Mir became temporary home to over 100 cosmonauts from more than 11 nations.

Mir's mass in orbit was in excess of 130 tonnes. Mir consisted of a number of elements: the Mir core module which acted as living quarters; Kvant 1, a laboratory bay and astronomical observatory; Kvant 2, used for biological research as to provide access to the outside of the station; Kristall, housing a materials processing facility; Spektr, used for remote sensing of the Earth; Priroda, again a remote sensing module; and the Progress supply ship which ultimately drove the Mir station to the atmosphere. By the beginning of 2000, Mir achieved its mission objectives so at the end of 2000, the Russian Prime Minister signed a decree authorising the controlled disposal of Mir in the Pacific Ocean.

A controlled re-entry was considered necessary to minimise the hazard to persons and property on the ground posed by the estimated 30 tonnes of debris that would survive Mir's fiery re-entry through the atmosphere. The disposal location was the Pacific Ocean region, chosen because it represented a region of low population density.

A final Progress supply ship was launched on 24 January 2001 and docked successfully with Mir 3 days later. This supply ship brought with it the 2.7 tonnes of fuel needed to bring Mir back safely to Earth. Mission controllers had determined the threshold altitude below which Mir must pass, under the action of natural atmospheric drag forces, in order to ensure a safe and controlled re-entry manoeuvre with the available fuel budget. During February and March 2001 solar activity was less than expected, so that the initially planned de-orbit date was postponed. Finally the 220 km altitude threshold was reached and during the early hours of March 23, 2001, the Mir and Progress engines were fired for the final time to bring Mir safely back into the atmosphere. Planning in the UK had started in 1999 when the

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de-orbit was first proposed by Rosaviakosmos and related activities continued until the safe return to Earth of Mir had been finally confirmed. This paper outlines those activities that were conducted in the UK and coordinated by BNSC.

2. BNSC's Role

2.1 Background

The de-orbiting of the Mir space station was the responsibility of Rosaviakosmos and its operating centres. BNSC's role was to consider the risks that the return of Mir to Earth might pose to the UK and to ensure that national government departments, the public, and the press had access to the most accurate and up to date information.

The risks posed by a fully controlled de-orbit, a partially controlled de-orbit, and an uncontrolled de-orbit were considered as the proposed return date of Mir approached.

In the case of a fully controlled de-orbit, there was effectively no impact risk to the United Kingdom associated with Mir's return as the Pacific Ocean had been selected and this was effectively on the other side of the world to the UK.

In the case of a partially controlled de-orbit, effectively latitude of impact controlled but longitude uncontrolled, again the UK was considered to be at minimal risk. The target latitude was in the southern hemisphere and provided that the latitude of perigee was achieved as planned, the likelihood of Mir falling at the UK latitude of 51.6N, the maximum northerly excursion of its ground track, was negligible.

The uncontrolled orbit case covered a number a scenarios:

- Failure to re-acquire control of the Mir complex
- Failure of Progress to dock with Mir complex
- Failure to maintain attitude and thereby permit manoeuvring of the complex as planned

In all these cases the outcome would have been the same, the station returning to Earth purely under the influence of aerodynamic drag. Although the likelihood of an uncontrolled re-entry was considered very small, the possibility had to be considered a part of the associated contingency planning.

2.2 Uncontrolled Re-entry Considerations

In the case of an uncontrolled re-entry the first issue to consider is the remaining orbital lifetime. If the time of re-entry can be estimated to within several days, than a range of ground tracks can be determined and regions of the Earth that are not exposed to an impact risk can be identified. If the time of re-entry to within several hours, then one or two ground tracks can be identified along which the object will fall. If the time of re-entry can be predicted to within several minutes then the area along a ground track where an object will fall can be determined.

The accuracy of current orbital lifetime predictions vary between 10 and 20% of the remaining orbital lifetime. Thus if there are estimated to be 10 days remaining in orbit, the accuracy is between 1 and 2 days either side of the nominal predicted re-entry epoch. Orbital lifetime prediction for uncontrolled objects is accomplished either by employing special perturbations or general perturbations techniques. Within the UK general perturbation techniques are generally used to estimate the orbital lifetime of uncontrolled objects. In most cases this approach is based on the theory of King-Hele[1]. The approach uses observed changes in the orbital elements of a tracked object in order to infer the influence of the aerodynamic characteristics of the object and the specific neutral density of the atmosphere upon its trajectory. Accordingly this approach can be used when the mass, area and drag coefficient of an object are not know and when no direct measurements of neutral density are available. The technique assumes however that the ballistic coefficient (product of the profile area and drag coefficient divided by the mass) remains constant between the observed period and the prediction period. Further it assumes that the atmospheric conditions remain relatively constant over the same period. Thus the limitation of the approach is that any significant change in the mass of the object, or its orientation (affecting both the drag coefficient and the profile area) will lead to incontinuities and at least two observations post- any change in the ballistic coefficient are required for a reliable prediction. Further any manoeuvre conducted will also negate the use of this technique until two consecutive impulse-free observations are achieved. Finally any changes in the trend or profile of the atmospheric density will result in errors in prediction, such fluctuations normally being caused by sudden increases in solar activity or geomagnetic activity. The approach relies upon access to up-to-date state vector information, in particular the mean motion and rate of change of mean motion that are normally derived from the NASA two line element sets.

From King-Hele[1], the remaining orbital lifetime L of an uncontrolled object moving within an atmosphere is given by:

$$L = \frac{en}{\dot{n}} F(e) \qquad (1)$$

- e is the orbital eccentricity
- n is the mean motion
- $F(e)$ depends on the orbital phase

In its simplest form, for a circular orbit, the lifetime is given by:

$$L = \frac{3Hn}{2a\dot{n}} \qquad (2)$$

- H is the density scale height
- a is the semi-major axis

In addition it is necessary to account for the effect of oscillations in perigee height caused by odd zonal harmonics, atmospheric oblateness, semi-annual variation in air density, and the effect of the solar cycle on the atmospheric density. King-Hele[1] again derives correction factors which depend upon the argument of perigee ω, right ascension of ascending node Ω, inclination i, and the period within the 11 year solar cycle that is being considered.

Klinkrad[2] has derived an expression for the probability that an object will fall over a particular latitude and longitude band. This is given by:

$$P_i(\phi, \Delta\lambda) = \frac{\Delta\lambda}{2\pi \cos i} P_i(\phi) \qquad (3)$$

- $\Delta\lambda$ is the longitude interval
- $P_i(\phi)$ is the probability of impact as function of latitude

where:

$$P_i(\phi) = \Phi(\phi) - \frac{1}{\pi} \arcsin\left(\frac{\sin(\phi - \Delta\phi/2)}{\sin i}\right) \qquad (4)$$

if $i \geq \phi + \Delta\phi/2$, then:

$$\Phi(\phi) = \frac{1}{\pi} \arcsin\left(\frac{\sin(\phi + \Delta\phi/2)}{\sin i}\right) \qquad (5)$$

if $\phi - \Delta\phi/2 \leq i \leq \phi + \Delta\phi/2$, then:

$$\Phi(\phi) = \frac{1}{2} \qquad (6)$$

This tells us that the probability that an uncontrolled object will fall within a particular longitude band is directly proportional to the size of that longitude band. The likelihood that an object will fall within a particular latitude band is again dependent upon its size but also will be greater at latitude bands closer to the northerly and southerly extent of the latitudinal excursion in the ground-track, which itself will be bounded by the orbital inclination. As the orbital inclination of Mir relative to the equator was 51.6^0, then there was a significant probability that Mir would fall along the 51.6^0N or 51.6^0S latitude bands, the former running across the Southern UK.

2.3 Controlled Re-entry Considerations

The planned controlled re-entry of Mir into the Pacific effectively ruled out any possibility of debris fragments from Mir landing in the UK. As the Russian Space Agency Rosaviakosmos was responsible for the controlled disposal strategy and execution of the proposed manoeuvres, BNSC's role was to monitor the situation to ensure that everything was going according to plan. The final manoeuvres were planned for the early hours of the morning of the 23 March 2001. A series of impulses would first alter the shape of the orbit to fix the argument of perigee over the target latitude band in the Southern Hemisphere and then lower that perigee further when a ground track offering an impact point at the appropriate longitude point was available.

Table 1 Mir Final Disposal Events

Planned Event	Time (GMT)	Outcome
1st Correction Burn	23 Mar 01, 00:32	9.3 m/s impulse
2nd Correction Burn	23 Mar 01, 02:00	10.4 m/s impulse
3rd Burn for Deorbit	23 Mar 01, 05:08	28.0 m/s impulse
Entry in atmosphere	23 Mar 01, 05:44	aerocapture
Splashdown	23 Mar 01, 06:00	impact

The manoeuvres are summarised in table 1. The first burn effected a change in orbit altitude from 231 x 213 km to 219 x 188 km. The second burn further reduced this to 219 x 158 km fixing the latitude of perigee over the southern hemisphere close to 40^0 S. The final burn produced a terminal arc that resulted in a longitude of the final impact point over 160^0 W. The resulting debris dispersion footprint was estimated to be 3000 km along track and 200 km cross track.

3. CONCLUSIONS

The successful controlled disposal of Mir demonstrates that even a large and complex system such as a space station can be de-orbited safely. The return of Mir will act as a testimony to the professionalism of the Moscow mission controllers, and as an exemplar for addressing the risk posed by future large risk objects. As the number of the objects in space increases and the need to remove redundant systems from orbit becomes more urgent, the number of controlled re-entries will increase. Exploiting the lessons learnt from the Mir experience will help us to minimise such future risks.

4. REFERENCES

1. King-Hele, D.G, *Satellite Orbits in an Atmosphere,* Blackie & Sons, London, 1987.

2. Klinkrad, H., Evolution of the On-Ground Risk during Uncontrolled Re-entries, *IAA-99-IAA.6.7.05*, 1999.