# Inflatable Re-Entry Technologies: Flight Demonstration and Future Prospects

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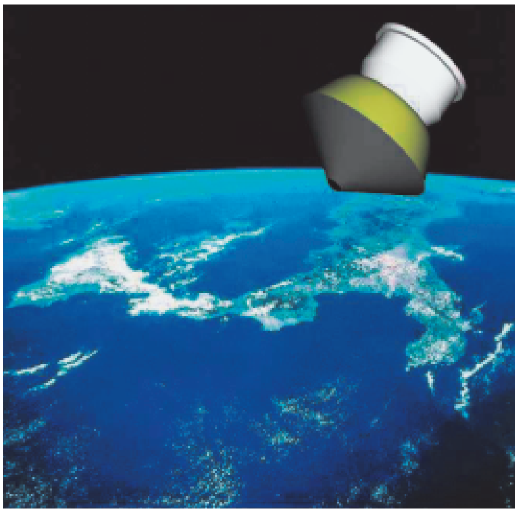
**In cooperation with Astrium-I (formerly DASA), NPO Lavochkin and the European Commission, ESA has developed and launched a capsule that re-entered the Earth's atmosphere protected by an inflatable heat shield. During the same mission, the newly developed Russian Fregat upper stage was also returned to Earth using the same technology. The last phase of the descent in both cases was performed with no parachute, allowing substantial savings in launch volume and mass. Obvious future applications for this new re-entry technology include International Space Station sample return, the delivery of networks of small stations to the Martian surface, and the return to Earth of launcher upper stages.**

## An innovative concept

The first qualification flight of the Soyuz Fregat launcher took place from Baikonur in Kazakhstan at 4.20 AM on 9 February. On board was a small capsule, the IRDT (Inflatable Re-entry and Descent Technology) demonstrator, destined to enter the Earth's atmosphere and land without recourse to a parachute or a conventional heat shield. In place of these heavy and cumbersome items, the IRDT deployed an inflatable envelope able to withstand the extreme hypersonic flight environment before re-entry (Fig. 1). The newly developed Fregat upper stage was also to be returned to Earth using the same re-entry technology.

Such a flexible inflatable shield had been developed earlier by Lavochkin in the framework of the MARS-96 project for the entry and descent of a penetrator into Mars' atmosphere. However, this mission was lost due to a launcher failure, and the inflatable technology had therefore never been tested previously.



The inflatable technology offers great advantages due to its low volume and mass and is therefore of interest to many potential users, ranging from the Space Station to planetary science, and even possibly launcher or technology developers. ESA therefore decided to investigate the potential of this advanced concept further.

## A new programmatic approach

There are at least three aspects of the IRDT project that made it unique. Firstly, the programme was conducted, from initial assessment study to flight, for less than 2 MEuro, including the experimental payload. This low cost was achieved thanks to the maturity of the concept (due to Lavochkin's earlier work), to the simplification of the design and manufacturing, and of course to the availability of the comparatively inexpensive Soyuz Fregat qualification flight.

Secondly, the capsule's development and launch was completed in less than a year, the programme even being shortened by three months along the way in order to benefit from an earlier launch opportunity. Even so, some new experiments could still be incorporated at the last moment. A preliminary concept feasibility assessment was performed between December 1998 and March 1999, and the programme was officially kicked-off on 1 May 1999. A Critical Design Review was performed in July 1999, and integration and testing took place from August to November 1999. The launch took place on 9 February 2000, and the capsule was recovered on 14 February, five days after its landing. The final presentation of the results took place at ESTEC on 6 April.

Thirdly, there was real co-operation between ESA, DASA, Lavochkin and the European Commission, both in terms of funding and at the working level. The total cost of the project was 1.95 M$. Under a contract with the International Science and Technology Centre (ISTC), ESA contributed US$ 650 000, the European Commission provided US$ 600 000, DASA provided US$ 500 000, and Lavochkin US$ 200 000. In addition to funding and evaluating the project, ESA, Lavochkin and DASA actively participated together in its technical definition and assembled the payload.

**Figure 1. Artist's impressions of the various IRDT in-flight configurations**

### A flexible, re-configurable heat shield

During its entry into the Earth's atmosphere, a capsule relies on the surrounding air for braking. The gas molecules impinging on its surfaces convert kinetic energy into heat, most of which is carried away by the air flow. However, a huge amount of heat still enters the capsule itself. To moderate the resulting temperature increase inside the capsule, heavy thermal protection systems are traditionally used, with a fixed size and shape. In addition, a dedicated system (parachute, parafoil or retro-rockets) is necessary to provide proper landing conditions and stability, and sometimes a floatation capability.

The demonstrator deceleration system consists instead of a small ablative nose (Fig. 2), and a flexible envelope inflated in two stages. First the flexible entry shield is deployed, increasing the capsule diameter from 80 cm to 2.3 m. This flexible shield consists of an internal network of rubber hoses pressurised with nitrogen, covered by an insulating layer (Multi-Layer Insulation)

**Table 1. IRDT initial mass budget**

| | |
|---|---|
| Rigid nose | 17.0 kg |
| Instrument container | 8.5 kg |
| Filling system | 21.0 kg |
| Inflatable shell | 40.0 kg |
| Search system | 2.5 kg |
| Sensor package | 13.0 kg |
| Miscellaneous<br>(damping, harness, etc.) | 10.0 kg |
| Total mass | 112.0 kg |

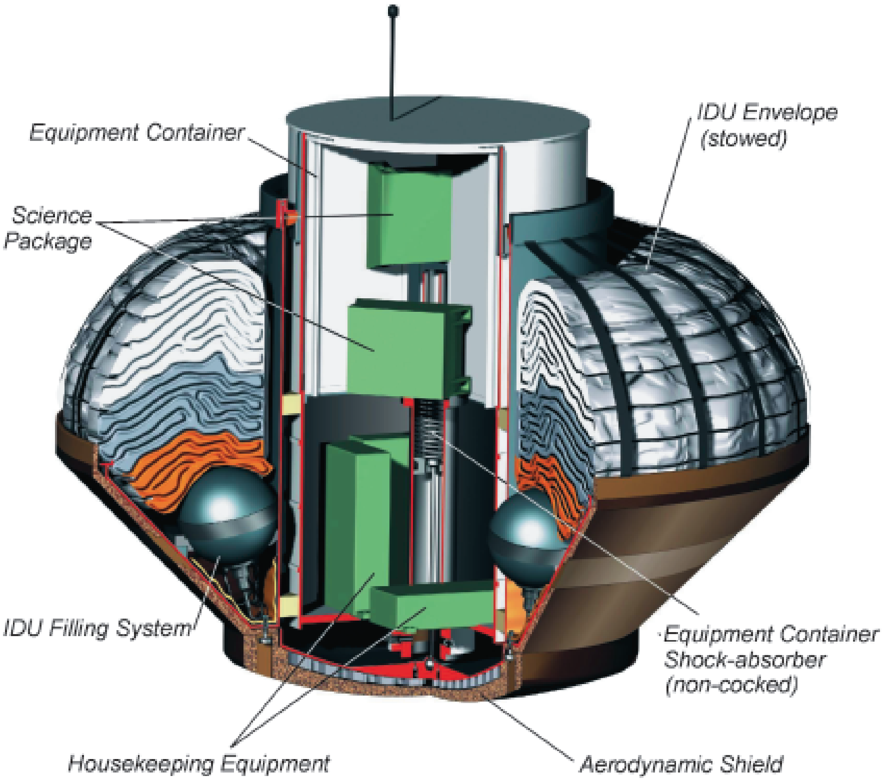


**Figure 2. The IRDT in stowed configuration**

protected by a silica-based fabric impregnated with an ablative material. As its temperature increases, this ablative material decomposes, absorbing heat and thereby limiting the heat input to the capsule's interior. The thickness of the material, i.e. number of layers, is designed to cope with the expected atmospheric-entry heat loadings with some margin. Then, in place of a parachute system, a second cascade is opened, further increasing the capsule's diameter to 3.8 m (Fig. 3) and slowing the demonstrator down to achieve a nominal landing velocity in the order of 13 -15 m/s.

Figure 3. The IRDT fully deployed

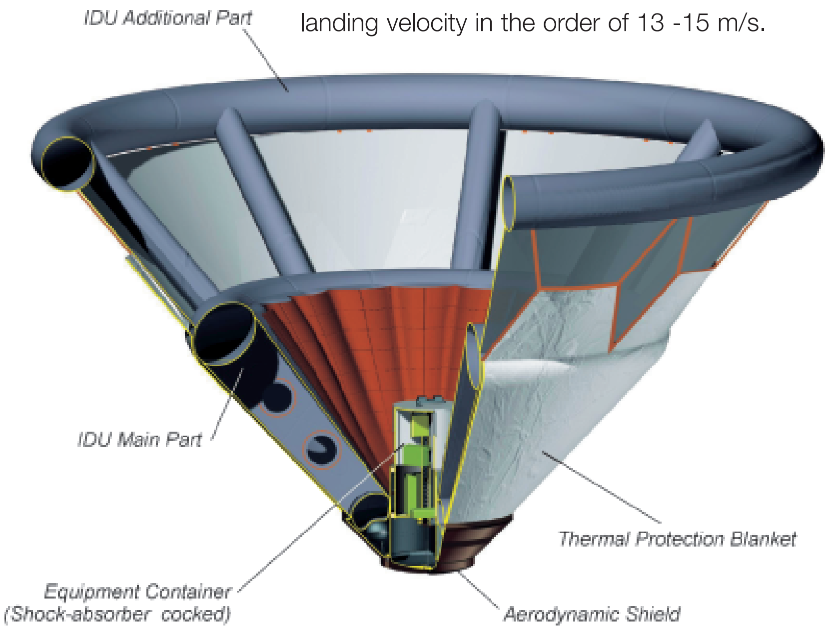
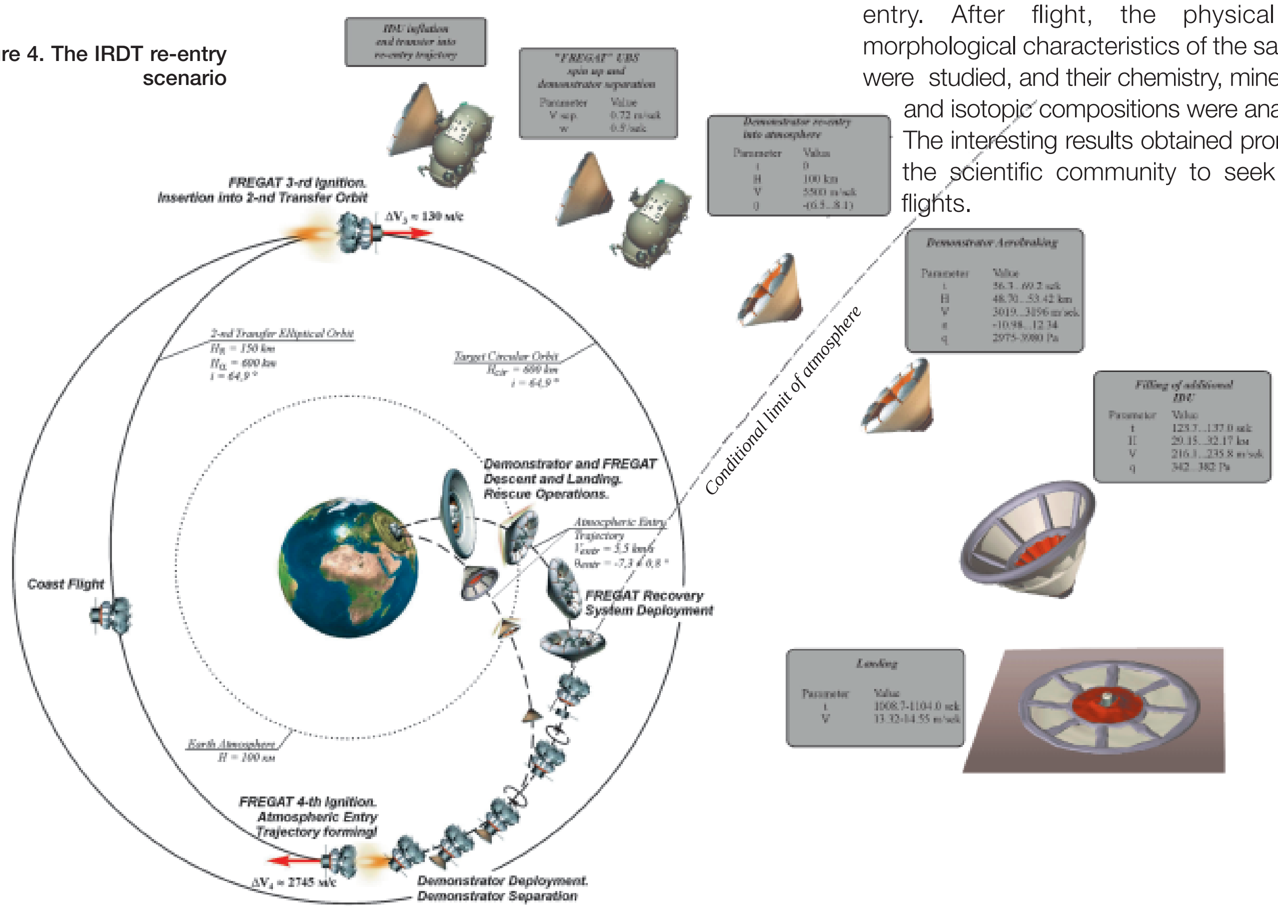


Figure 4. The IRDT re-entry scenario



The inflation process is triggered by the sequential firing of a series of pyro-valves, which progressively empties of a set of 13 nitrogen bottles into the envelopes, at different stages of the mission. To ensure adequate stability during all phases of re-entry and provide proper deceleration, a sphere-cone shape, with a nose radius of 0.61 m and a cone half angle of 45° has been selected.

## An advanced payload

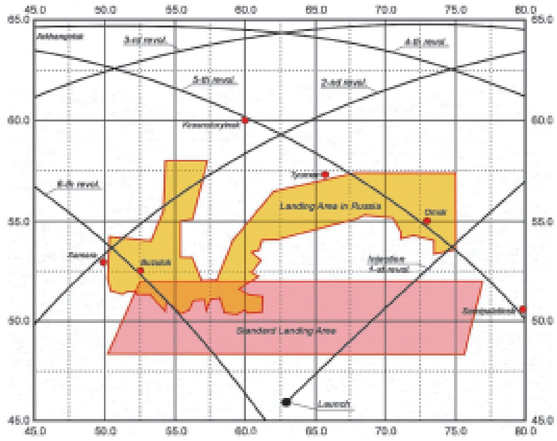
The payload consisted of two scientific experiments:

- *The FIPEX sensor:* Developed by IRS Stuttgart for measuring atomic oxygen in the upper layers of the atmosphere, this instrument also provided pressure measurements allowing the altitude history of the demonstrator in the stable phases of its flight to be derived.
- *The STONE experiment:* STONE, an artificial meteorite experiment proposed by Prof. A. Brack (CNRS, Orleans), was intended to study the physical and chemical modifications affecting sedimentary rocks falling through the Earth's atmosphere. The first experiment of this kind had been conducted on Foton-12, flown in September 1999 (see ESA Bulletin No. 101 and 'On Station', Issue 1, December 1999). Three pieces of terrestrial rock were embedded in the Foton capsule's ablative heat shield and exposed to the rigours of atmospheric re-entry. After flight, the physical and morphological characteristics of the samples were studied, and their chemistry, mineralogy and isotopic compositions were analysed. The interesting results obtained prompted the scientific community to seek more flights.

ESA supported the installation of three more rock samples (designated 'STONE 2') on the nose of the IRDT demonstrator, to endure the hottest re-entry conditions. The samples were glued onto the ablative heat shield, whilst on Foton they had been attached to the capsule's outer surface by special holders. The new fixing method was verified by analysis and validated with both thermal and vibration/shock tests in Lavochkin's laboratories.

To facilitate post-landing recovery, a beacon similar that on the Soyuz capsule was installed. In addition, a dedicated sensor package developed by Astrium-I monitored and recorded the flight parameters:

- a three-axis accelerometer (Triade B-290) and three gyroscopes developed by LITEF
- a three-axis accelerometer from NPO Lavochkin, for system operations (house-keeping equipment)
- 15 temperature sensors (thermocouples) placed at various points on the internal structure, and 8 in the payload container.
- 81 CIMTs (Crystal Indicators of Maximum Temperature), within the ablative front shield at depths of 3, 6 and 9 mm. These silicon-carbon (SiC) or diamond (C) crystals contain defects artificially created in their crystalline network by a neutron beam. The exponential decay of the defects can be related to the maximum temperature encountered by the crystal, as well as its duration of application. X-ray measurements performed later on the ground, combined with adequate heat-transfer analysis methods, allow the maximum temperature experienced to be derived. Such crystals can measure temperatures up to 2000ºC.



## The mission

The launch took place from Baikonur Launch Site Number 6 at 4.20 AM (to provide optimum visibility during IRDT search operations after landing) on the first of the two Soyuz-Fregat qualification flights for ESA's Cluster project. The capsule performed five orbits attached to the Fregat upper stage, at 600 km altitude. After two upper-stage burns and separation of the Fregat dummy payload representing the two Cluster satellites, the third burn lowered its trajectory perigee to 150 km. A large fourth burn then injected Fregat and the IRDT into a Earth return trajectory (Fig. 4).

Then, the probe inflated the first cascade of its deceleration device acting as a heat shield. It separated from Fregat without spinning, and began re-entry at the conventional altitude of 100 km at an absolute velocity of 5.52 km/s, at an entry angle of –7.69° above the Earth's sphere, at an azimuth of 134.4ºN. The longitude was 49.67ºE, the latitude 53.7ºN. The second cascade, replacing the parachute, opened

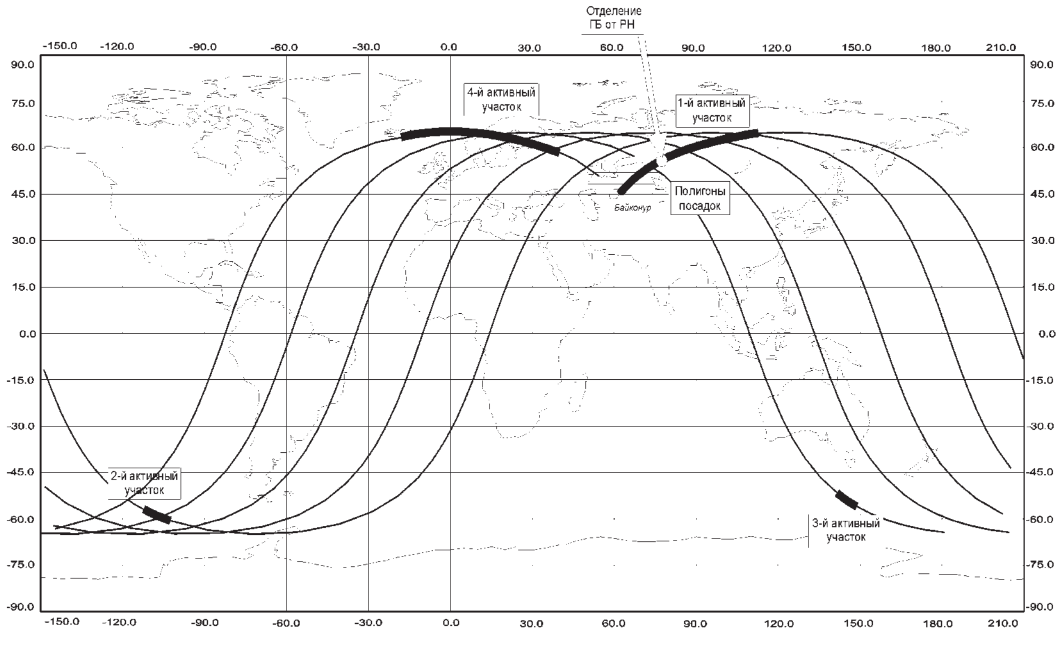


**Figure 5. Ground track of fire orbits of the IRDT-Fregat upper stage, with the four burns highlighted. Above, a map of the launch and landing region**

around Mach 0.77, at an altitude of approximately 32 km. The command was correctly issued, but the opening was not provoked by the pyrotechnic firing, probably due to a malfunction related to non-nominal events during re-entry.

Lavochkin was responsible for operations at the landing site, with the support of the local military authorities and their radars. Two days before the landing, ESA and DASA representatives joined the Lavochkin engineers and specialists in Orenburg, a city close to the Kazachstan border some 1500 km southeast of Moscow. The recovery operations were directed from the Russian military airfield of Chebinky, some 50 km northeast of Orenburg, where a squadron of Mil-Mi 8 and Mil-Mi 6 helicopters is based (the same squadron usually involved in the recovery of manned capsules returning from the Mir space station; it had also participated in the recovery of the Foton-12 descent capsule two months earlier).

The separation of the two payloads occurred as planned, and the radar stations detected two objects falling with different trajectories within the nominal zone. The Demonstrator landed at 12.40 local time, 4 min 51 sec after re-entry, at 50º 56 min North, 53º 43 min East, just inside the Kazakhstan border (Fig. 5). This was about 50 km behind nominal point, but within the dispersion ellipse. The velocity at touchdown was estimated at 60 m/s, which resulted in some damage to the lower part of the IRDT demonstrator containing the housekeeping equipment, the radio transmitter and the locator beacon.

Figure 6. The Demonstrator at the recovery site

Bad weather (snow and fog) and poor visibility hampered the recovery operations, which had to be carried out with a single low-altitude helicopter flight each day. It was not until 14 February, five days after the landing, that one of the helicopters finally picked up the IRDT demonstrator (Fig. 6).

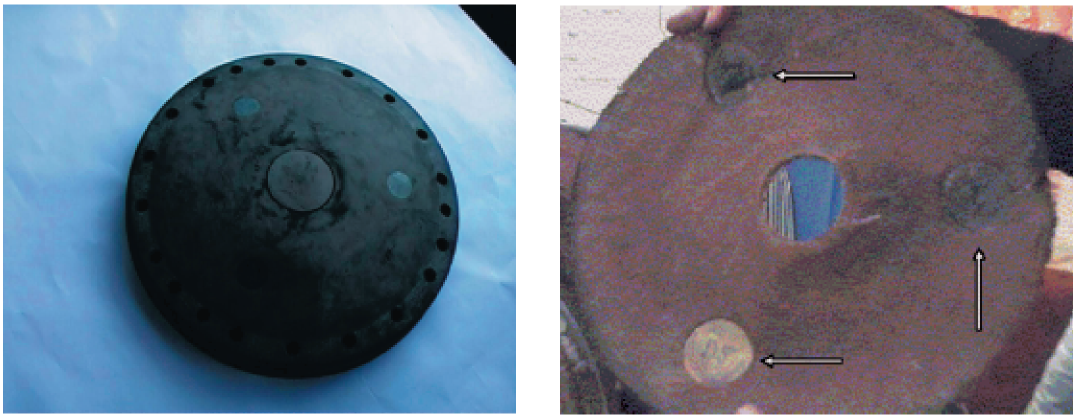
Unfortunately, the high heat load experienced by the Demonstrator shield during its high-speed descent had almost completely ablated the protective layer (9 mm against the 2 mm foreseen), and the STONE samples were not recovered. The Demonstrator hardware was returned to Moscow for post-flight evaluation, including detailed inspection and data retrieval. This inspection confirmed the mechanical damage due to too heavy a ground impact, but no thermal burning effects were visible. Flight data from the Demonstrator and sensor package on-board computers could be retrieved perfectly. The nose of the heat shield showed greater ablation than expected, and the three STONE samples were missing (Fig. 7). The inflatable heat shield was damaged, but was 80% intact.

## Flight evaluation

After the capsule's recovery, all sensor data were retrieved, downloaded and made available to the various teams involved for detailed evaluation and discussion. A formal flight-evaluation review then took place at ESTEC in Noordwijk (NL) on 4 and 5 April 2000.

The accelerometers and gyroscopes indicate a sharp increase in IRDT acceleration and rotational rates 37.4 s after its separation from Fregat (Figs. 8a,b). The Demonstrator's tumbling motion is attributed to a collision between the IRDT and its Fregat interface adapter jettisoned shortly after the Demonstrator's separation.

Figure 7. The nose shield before and after re-entry. Note the locations of the three STONE samples



The accelerometer and thermocouple data show that the Demonstrator's stability was restored during the beginning of the re-entry and that the inflatable structure survived the peak heat-flux (350 kW/m$^2$) and g-load (15 g) conditions intact, but partially collapsed later. This resulted in unstable flight conditions, as indicated by the accelerometer and gyroscope measurements, and in a local increase in temperature. This failure could be related to the earlier impact with the adapter having locally weakened the thermal protection, to defective pressure regulation, or to insufficient thickness of the thermal protection. A significantly larger mechanical load and ablated thickness on the rigid nose element was observed afterwards, and this provoked the loss of the STONE experiment and of all but six of the CIMTs.

The temperature inside the Demonstrator increased locally by 200ºC, but the internal temperature of the payload container was almost unchanged (Figs. 9a-c).

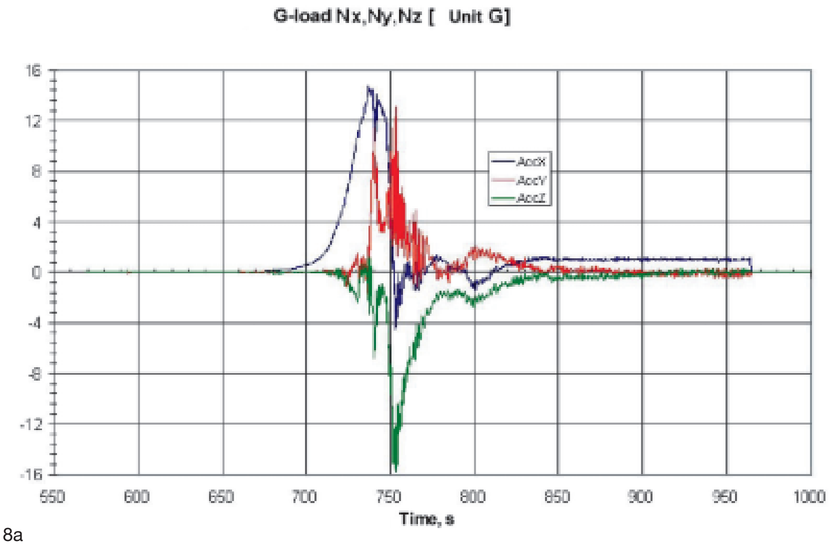
The second cascade opened nominally (at close to Mach 0.8), but did not inflate. The final descent was therefore faster than nominal, leading to a touch-down velocity of around 60 m/s (corresponding to the free fall of the rigid core body), instead of the 13 m/s design value. Consequently, the total descent time was shorter than nominal.

The beacon system was damaged during touch-down, and its antenna was covered precluding signals from being acquired during the recovery operations.

## Potential future applications

### *ISS payload download system*

The first practical application envisaged for the IRDT is as a payload downloading system for the International Space Station (ISS), with an ATV or a Progress spacecraft as the carrier



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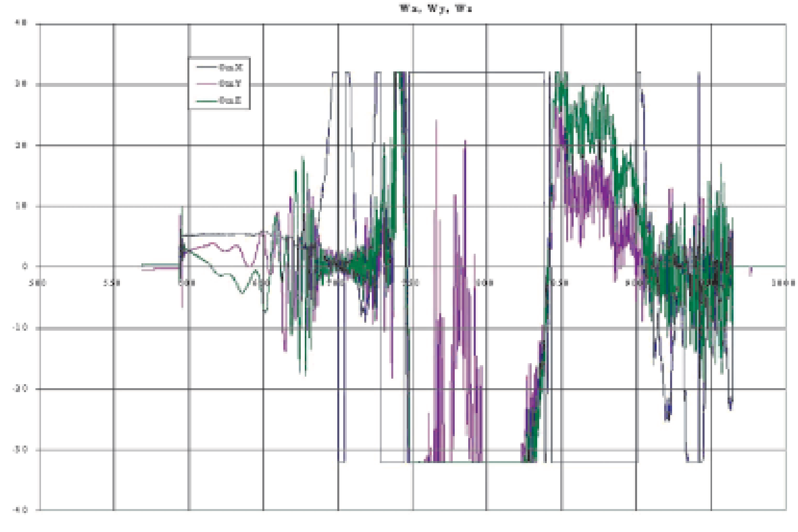

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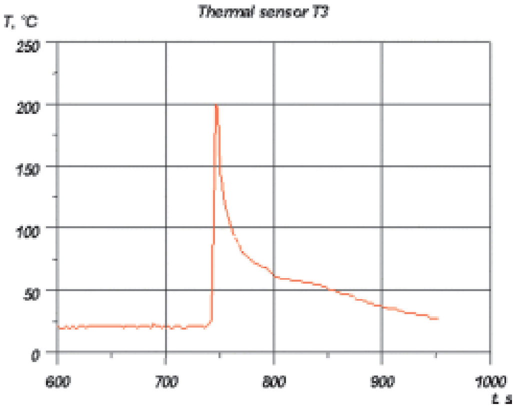
Figure 8a,b. Acceleration and angular-velocity components during re-entry



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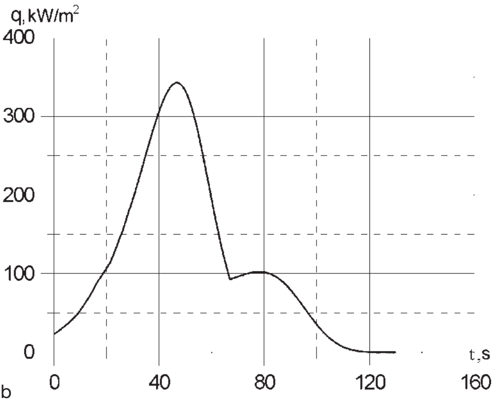

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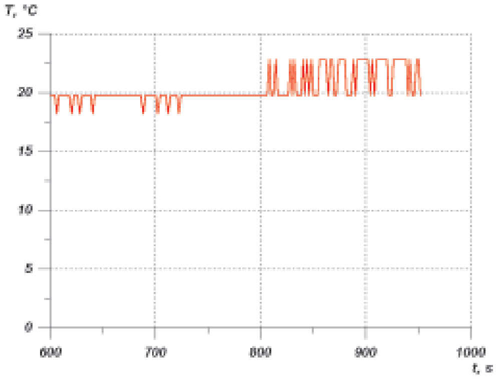

9c

Figure 9a-c. Shield temperature, nose heat flux (flight rebuilding) and payload-container temperature logged during re-entry

Figure 10. ISS download scenario with the ATV

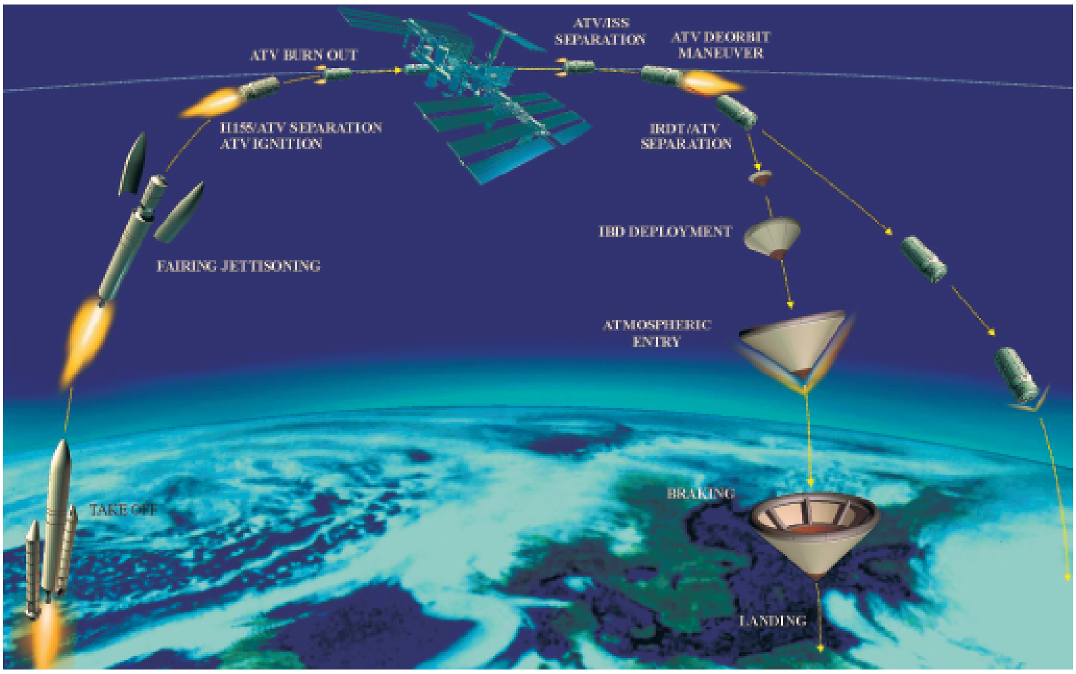

Figure 11. The Netlander scenario

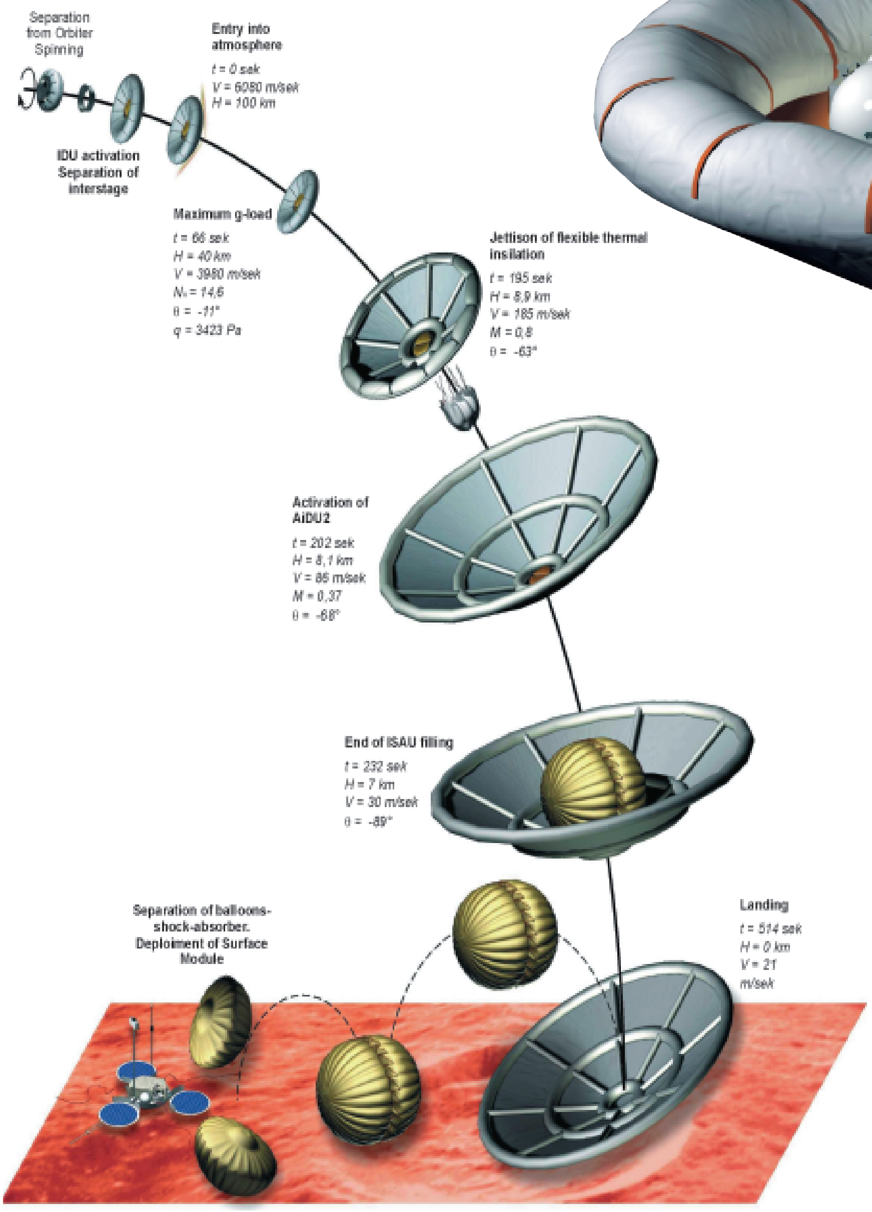

Figure 12. Fregat upper stage entry configuration with IRDT first cascade deployed

(Fig 10). ESA's own download needs are estimated at 600 kg per year. As for the Russian Raduga system, a small capsule would be installed inside the carrier whilst docked with the ISS, and would then be jettisoned after the de-orbit burn of the spacecraft. Each flight of such a vehicle could return 200 – 250 kg of payload to Earth. A first analysis indicates that the costs would be competitive with today's options for providing such a service, for example using the Space Shuttle.

### *Marsnet landers*

A second possible application of the IRDT could be for Mars landers. Its potential high payload/mass ratio and small size is an advantage for accommodating several probes on a spacecraft to Mars. Lavochkin has already studied its potential for a CNES/NASA co-operation on the Mars Sample Return mission, with the aim of delivering four Netlander descent vehicles and surface stations to the planet's surface (Fig. 11). The system consists of a descent module and a surface module with a total mass of 60 kg, of which 20 kg is available for the surface module payload.

*Recovery of launcher upper stages*

The Fregat upper stage was also returned by an IRDT system as part of the first flight demonstration, using 8 and 14 m diameter inflations of the two cascades (Fig. 12). This demonstartion served as a good example of IRDT applications in the areas of reusable and expendable launch-vehicle stage return, their safe disposal, and aerobraking.

### Conclusion

For the first time, an inflatable heat shield has been deployed in space and has successfully performed a flight experiencing maximum thermal and mechanical entry loads. Despite some non-nominal conditions and partial damage to the envelope, the flight hardware and data were successfully recovered. The sensor payload worked perfectly and provided a rich mission database. The FIPEX instrument was space-qualified.

This new concept allows both mass and volume savings compared to conventional technology, and is easily reconfigured. Improvements and adaptations are now being prepared to suit the requirements of future space missions. In particular, its application to the return of samples from the International Space Station (ISS) requires extension and demonstration of the IRDT's capabilities for orbital re-entry conditions. A second verification flight with more extensive instrumentation is felt necessary, to incorporate the lessons learned from the first flight and the new requirements emanating from the ISS downloading system. The pressure regulation system and the launcher interface will be improved, and the heat shield will be strengthened. Telemetry and navigation systems allowing better descent monitoring and more efficient recovery operations will also be introduced, and a camera will provide images of the various stages of deployment.

Among several longer-term improvements to the capsule, it is foreseen to increase the payload/mass ratio and offer soft-landing capabilities. In addition to the ISS sample-return project, a number of other applications have already been identified, and will be more thoroughly investigated.

### Acknowledgement

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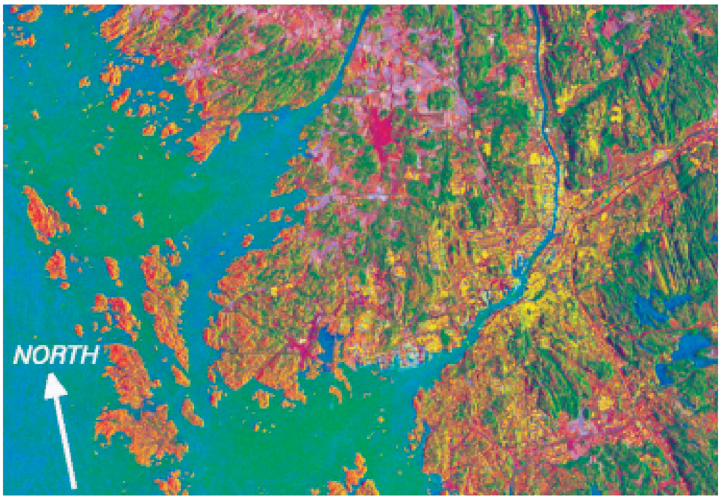

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