IRDT 2R MISSION, FIRST RESULTS

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ABSTRACT

Under ESA contract to EADS-ST in cooperation with Lavochkin (Russia), a new concept of heat shield, based on an inflatable braking device, has been developed and tested. This paper presents the main characteristics of IRDT and reports the results of the last flight, performed on 7/10/05.
IRDT combines the classical elements (heatshield, parachute, landing gear) of a re-entry and landing system into a single inflatable system providing a lightweight, re-configurable re-entry system.
After a first IRDT flight in suborbital entry conditions in 2000, the present flight has been performed in close to orbital entry conditions. This paper presents a first account on the mission, the initial interpretation of flight data and conclusions on the capability of the inflatable heat shield.

1. INTRODUCTION

The inflatable technology was developed in Russia for Mars96 Penetrators and for Moon lander airbags. This technology, combining the functions of an entry heat shield and a parachute into a single inflatable system, was considered as promising also for Earth entry, and the return of payloads from the International Space Station was identified as a direct application after a proper demonstration: The Inflatable Reentry and Descent Technology (IRDT) demonstrator has been developed and flight-tested to serve this purpose.

The main advantage of this technology is the small volume required for decelerator subsystems usually cumbersome. In addition, the concept is relatively lightweight and can easily be scaled up.

The IRDT demonstration programme has been developed under European Space Agency (ESA) and International Science and Technology Center (ISTC) contracts to EADS-ST and Lavochkin Association's Babakin Space Centre. For the demonstration, two test flights have been performed. In a first flight, the IRDT-1 Demonstrator launched in a sub-orbital trajectory has been subjected to entry conditions similar to the ones encountered during a Martian entry. This mission launched on a Soyuz-Fregat in 2000 provided useful data for the development of the IRDT-2 mission, to be performed in close to orbital entry conditions.

IRDT-2 configuration is similar to IRDT-1, but improved taking into account the results of the first test flight. IRDT-2 has also been adapted for another launch vehicle, Volna, and for more severe entry conditions.

Two launch attempts in 2001 and 2002 resulted in failures of launch vehicule (2001) and of the interface with the launcher (2002).

In 2002, it has been decided to proceed with the IRDT-2 substantially redesigned, and a new Volna interface. The new project was named IRDT-2R. The test flight subject of this paper took place in October 2005. Its initial results have been reported in an earlier paper [1]. Here, the flight data and preliminary analyses results are presented.

2. MISSION AND SYSTEM

IRDT and IRDT-2 have been already presented in earlier publications [,2]. Here, the main features of IRDT will be briefly recalled, and the modifications and specific aspects for the latest flight described.

2.1 IRDT-2 mission

The demonstration flight of IRDT-2R has been fulfilled in accordance with the profile shown in Fig. 1. The IRDT-2R consists of the PC (Payload compartment) cover of the VOLNA launch vehicle (LV) and of the D-2R reentry vehicle. The mission profile comprises the following phases:

Lift-off from Submarine in Barentz Sea, near Severomorsk;
D-2R injection into an open ballistic trajectory (altitude at apogee H = 258.2 km) by means of "VOLNA" LV;
D-2R turn into a "neutral" direction;

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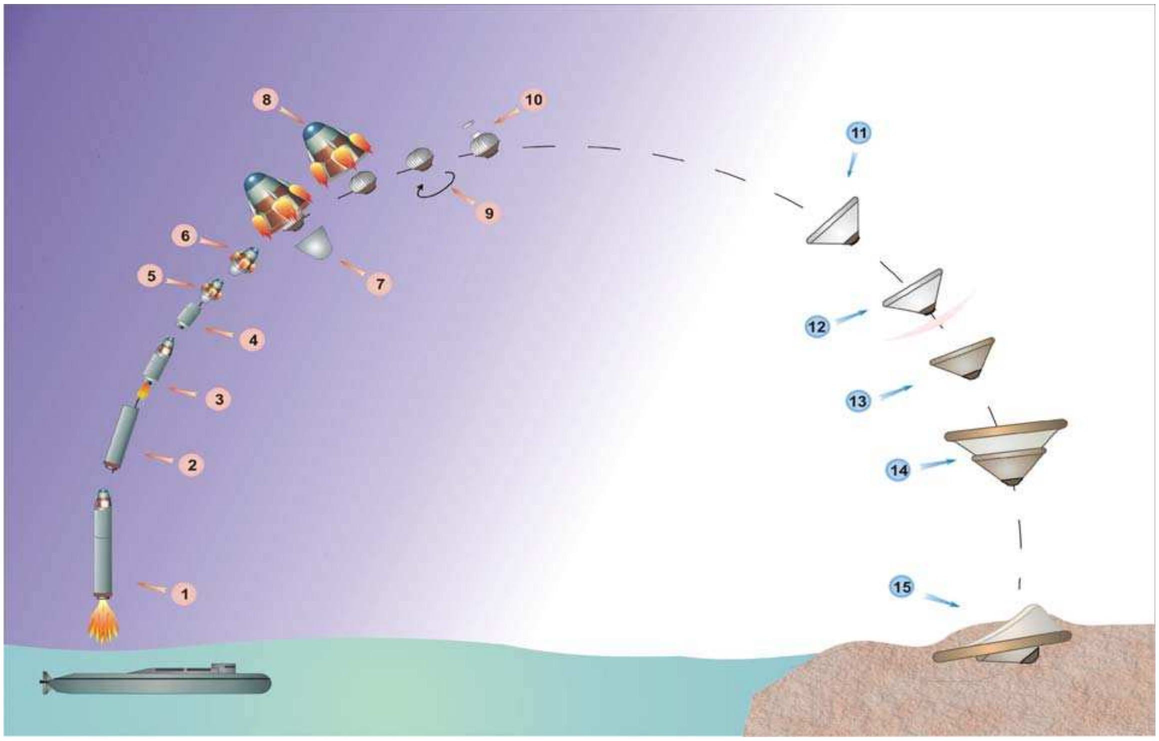


1 –«Volna» LV Take off
2 – Separation of 1st stage
3 – Ignition of PS of 2nd stage
4 – Separation of 2nd stage
5 – Ignition of PS of 3rd stage
6 – Venting of pressure from the PC
7 – Separation of PC cover
8 – Separation of D-2R
9 – Spin-up of D-2R
10 – Arming of the EC, platform separation
11 – Beginning of inflation of D-2R MIBD
12 – Re-entry
13 – Aerobraking
14 – Deployment of D-2R AIBD
15 – Landing of the D-2R

Fig. 1: IRDT mission profile

PC cover separation from the 3rd stage of the "VOLNA" LV;
D-2R separation from VOLNA" LV 3rd stage;
D - 2R spin-up;
Arming of the EC (separation of jettisonable platform);
Main IBD (MIBD) inflation ;
D-2R re-entry into the atmosphere (altitude = 100 km);
D-2R braking in the atmosphere;
Additional IBD activation (AIBD);
D-2R landing in Kamchatka;
D-2R search and recovery.

The most important parameters corresponding to the main phases of the mission are reported Table 1: In this table, H indicates altitude in km, V is the velocity in m/s, V_{rel} the relative velocity in m/s, Q the dynamic pressure in Pa, ω_x is the angular velocity (spin) in °/s and θ the path angle.

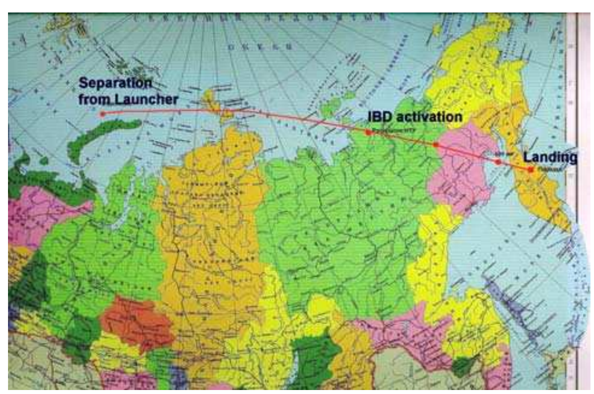
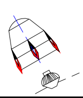
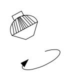
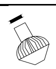
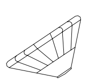
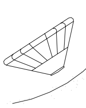
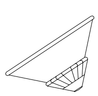
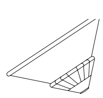


Fig. 2: IRDT-2R mission, ground track

To specify the date and time of the launch (within the launch window) the following factors have been taken into consideration: Illumination along flight route, TV camera sun exposure, landing during daylight period. Furthermore, local weather conditions (at launch and at landing sites) have also been taken into account for the launch go-ahead.

The IRDT Demonstrator ground track, extending over most of Russian territory, is shown in Fig. 2

Table 1: Operational sequence of IRDT flight

Flight stages		Time from start T, s	Time from separation T_0, s	features
Config.	Name			
	D-2R separation from LV	306	0	H=203
	D-2R spin-up	308.7 (+0.7, -0.5)	2.6 +0.7,-0.5	ω_x=21
	EC arming, Platform separation	312	6	
	start of MIBD filling	662	356	H=238
	Entry into the atmosphere	906	600	H=100 V_{rel}=6870 θ=-6.84 °.
	AIBD deployment	1211 … 1216	905… 910	H = 12 - 14 V=55 Q=390
	D-2R landing	1742 … 1900	1436… 1594	V=15

Two stations have been selected for reception of telemetry data: Norilsk near Severomorsk and Kluchi, in Kamchatka.

2.2 IRDT-2 demonstrator

The purpose of the demonstration is to assess the availability of the inflatable reentry technology for future ESA missions. The heart of the demonstrator is therefore its inflatable decelerator, also named Inflatable Braking Device (IBD). The inflatable heat shield is based on a flexible thermal protection system (TPS), consisting in several silica cloth layers each coated with a silicone ablator and covering a series of kapton sheets separated by glass fiber spacers, constituting a Multi Layer Insulation. Then, supporting the TPS, a regulated pressurised system relies on a series of fiber-reinforced airtight toroidal structures and insures the inflation and stability of the shield during all phases of the flight.

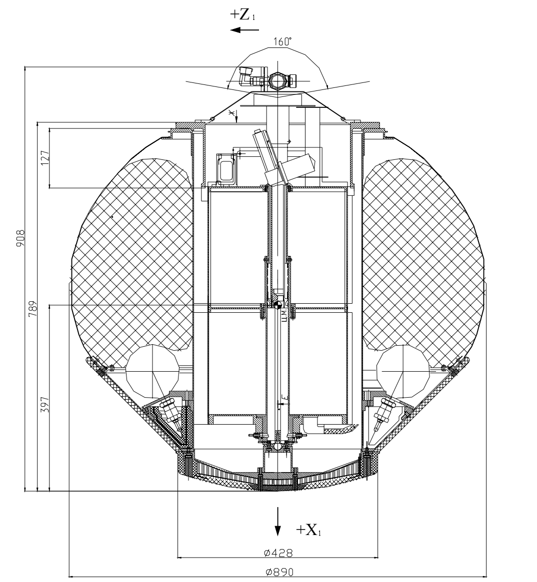


Fig. 3: IRDT-2 demonstrator in stowed configuration

As for the former demonstrators, the IRDT-2 capsule has a diameter of .89 m and a height of .908 m when stowed in the launch vehicle (Fig. 3). Two different configurations correspond to a first (partial) deployment of the Main Inflatable Braking Device (MIBD) before hypersonic entry, the IRDT reaching a diameter of 2.34 m, and followed by a full deployment, the Additional Inflatable Braking Device (AIBD) bringing the diameter of the vehicle to 3.8 m after hypersonic flight, during descent until touch-down (Fig. 4). A damping system has been added to the payload container, to alleviate the landing shock. The mass of the vehicle varies from 141 kg after separation from Volna, down to 122 kg at landing. The aerodynamic shape during entry is a blunted-cone, with a nose radius of .61 m, and a 45° half cone angle.

With respect to its predecessors, the latest IRDT-2 demonstrator contains a number of changes. The main ones are reviewed here:

Firstly, the interface with the launcher has been redefined. Pyro-locks have replaced pyro-bolts, and the responsibility for the interface management has been clarified. The new interface has been fully qualified with a number of mechanical tests including a large scale one involving the launcher's second and third stages.

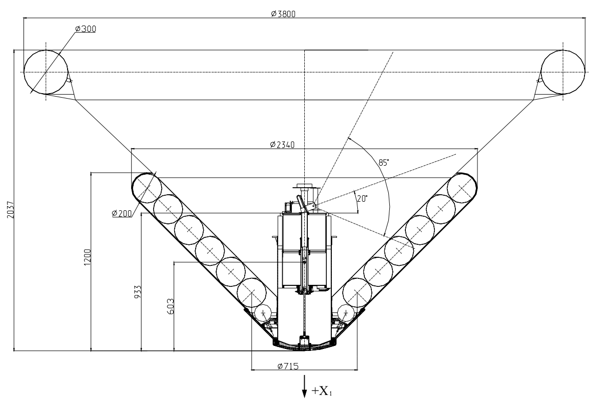


Fig. 4: IRDT-2 demonstrator in fully deployed configuration

Secondly, the telemetry has been enhanced for the launch phase, but also after separation: Two payloads have been included in IRDT-2. On the one hand, housekeeping and monitoring equipment set and on the other hand dedicated test equipment, to provide data on the flight environment and on the main parameters of the inflatable system and of its payload. The latter comprises a video camera and its recorder, accelerometers and gyroscopes, and two different GPS systems. Data from housekeeping equipment, including accelerometers and gyroscopes, IBD pressure sensors, atmospheric pressure sensors, temperature sensors, as well as a recording of voltage and discharge current of batteries and of issued commands are stored on- board. The list of issued commands and their actual execution time as well as the flight parameters (provided by a second set of accelerometers and gyroscopes and a GPS) are stored in the telemetry system memory and sent to ground continuously when communications are available, through a 219-MHz antenna integrated into the ablative nose. Furthermore, all available telemetry data are sent at 9 specific moments of the mission, before entry and during descent. The selection of the emission periods has been performed taking into account engineering estimates of black-out period.

Thirdly, recovery operations have been improved, as summarized in Fig. 5: Two beacon systems (114 and 121 MHz) have been implemented. Their antennas emitted tracking signals in all directions around the vehicle. In addition, flight data were made available to the search teams a few hours after landing. Two helicopters participated to search operations.

3. FLIGHT RESULTS

3.1 Search Operations

On 7/10/2005 at 1:30 AM Moscow time, the IRDT has been launched on a Volna rocket from a submarine stationed near Severomorsk in the Barents Sea. The separation with the launch vehicle has been confirmed within nominal time, and telemetry has been received before and after black-out phase, that started at 1:45:40 Moscow Time. At 1:46:13 Moscow Time, telemetry was recovered and faded out progressively at 1:48:00 Moscow Time.

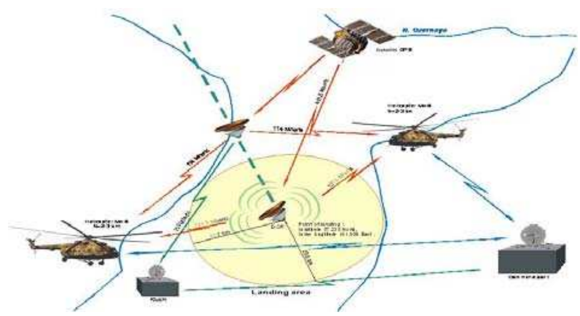


Fig. 5: Scheme for search operations

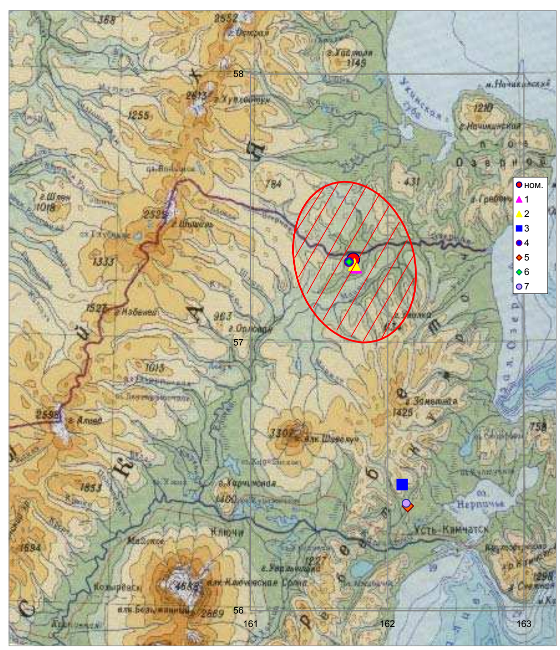


Fig. 6: Landing zone, search areas

Search operations started immediately after expected landing time, at 10:00 AM Kamchatka time (2:00 AM Moscow time). Two helicopters searched the nominal landing area, represented in Fig. 6. No reception of beacon signal was reported. In the afternoon, the search was extended to non-nominal landing areas (points 3, 5 and 7) without success. In the evening, preliminary telemetry data were made available, covering the period before but also after black-out.

Two days later, a new attempt was made to retrieve the demonstrator. The life expectancy of the beacon batteries was exceeded, and search activities relied mostly on visual inspection of a zone joining the nominal and non-nominal landing areas. Unfortunately, due to local bad weather, a mountainous area located in the middle of the search area was not investigated.

3.2 Flight data rebuilding

Before and after blackout, the telemetry system has provided data to the ground. Amongst the data, of particular relevance were the measurements of acceleration, angular motion and GPS coordinates. Unfortunately, the latter were not exploitable.

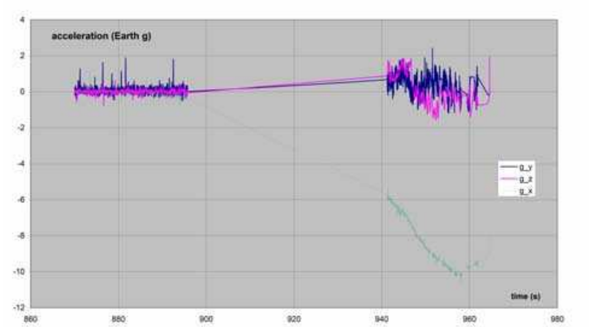


Fig. 7: accelerometer measurements during IRDT-2R demonstrator entry

The initial analysis of the telemetry confirmed the correct separation and spin-up of the demonstrator, the activation of the video camera, the full deployment of the main Inflatable Braking Device, and the arming of the payload container damping system. All events occurred according to schedule.

Based on telemetry data, the reconstruction of the IRDT-2R demonstrator re-entry has been performed, in order to understand the flight events. The focus here has been the rebuilding of accelerometer data for the entry phase. Fig. 7, the evolution of the three components of acceleration measured during entry is plotted versus time since launch (actually, time since the telemetry timer has been started, 32.6 s after launch). At ESTEC, two different codes, developed by FGE, have been adapted to the IRDT entry: 3-degrees of freedom (DOF) code named traj3d and 6- DOF one named traj6d. The main data available for rebuilding is the axial acceleration (g-load).

A first step has consisted in verifying the calculations, by comparing two independent assessments. Both computations of Babakin Space Centre and ESA/ESTEC have been performed starting from the separation with the launcher, with the same state vector, i. e. the initial position and velocity provided by the launcher authorities (Table 2).

Table 2: Initial point for the reconstruction (t=306.18s from take-off), geocentric coordinates

	Position (m)	Velocity (m)
X	859 236	-6 669.60
Y	1 322 691	-147.36
Z	6 368 346	1 437.54

An excellent agreement is observed between traj6d and Babakin Space Centre results, in terms of trajectory parameters as shown Fig. 8, where the evolution of altitude, expressed in meters, is plotted versus time (in seconds) from separation from the launch vehicle at t=0, until touchdown. The resulting predicted entry conditions for IRDT-2R also concurred.

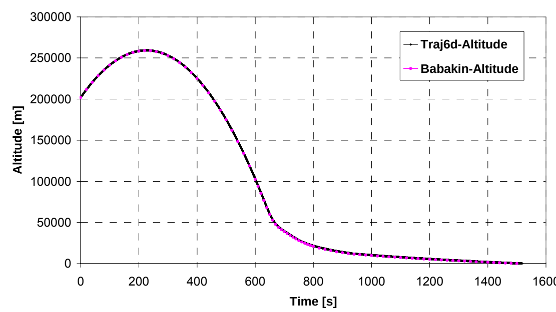


Fig. 8: IRDT-2R 6 Degrees of Freedom trajectory analysis results

The same agreement has been found for the entry phase between 3 degrees of freedom and 6 degrees of freedom analyses.

Fig. 9 presents the 3 DOF computations results in red (Babakin Space Centre) and blue (ESTEC, traj3d). The flight data are plotted in black. Here, axial g loads (along the axis of symmetry of the demonstrator) are reported versus time from beginning of entry (when the demonstrator reached the altitude of 100 km). The two branches of the curve for the flight data correspond to the axial g-loads before and after the communication black-out that occurred during Earth atmospheric entry.

The two independent analyses present a good match with each other. However, they do not agree with flight data. A sensitivity analysis, performed with traj3d, indicated that changing the lift or the ballistic coefficient of IRDT over the whole trajectory, or the atmosphere model, the entry angle or the entry velocity did not improve the agreement with the flight data.

A discontinuous evolution of the ballistic coefficient has then been introduced in the 3 degrees of freedom model.

This was to analyse the case where the inflatable decelerator in the course of the entry would have become suddenly partially or totally ineffective, for example due to its deflation.

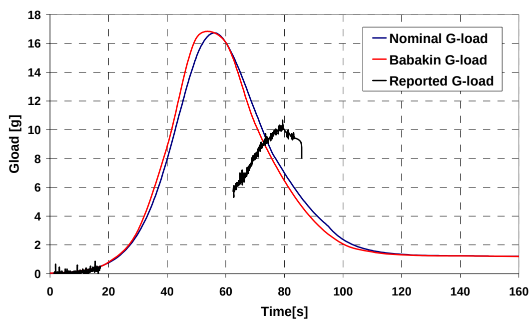


Fig. 9: Axial G-loads comparison between flight data and analysis results for nominal trajectory

The best match with flight data was obtained assuming that the inflatable shield was almost fully deflated, its surface being reduced to 0.95 m^2 (A fully deployed IBD offers 4.15 m2 frontal surface, whereas the stowed configuration provides only 0.62 m^2) abruptly 55s after entry (Fig. 10).

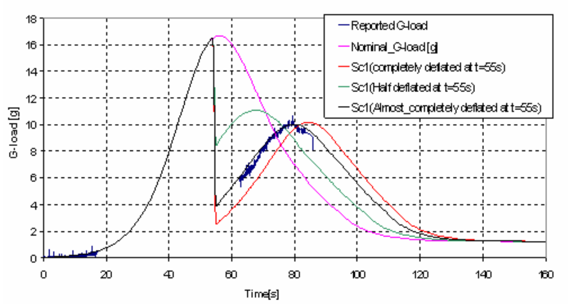


Fig. 10: sensitivity analysis: 3 Degrees of Freedom trajectory analysis for various degrees of variation of ballistic coefficient at t= 55s.

Fig. 11, the results of a 6 DOF analysis are reported in terms of axial loads versus time elapsed since separation (entry occurs at t=600.9 s approximately). Here again, the analyses, and also later comparisons with IRS results [3] showed a satisfactory agreement with the axial acceleration evolution measured during flight. Babakin Space Centre came independently with a similar interpretation of flight results that agreed again with the ones presented here.

So far, the entry analyses have been limited to the axial acceleration data. Gyroscopes also provided data, but they could not be interpreted quantitatively: due to their high sensitivity to the temperature of their environment, unknown: it was therefore not possible to calibrate their results. Lateral loads interpretation requires further efforts.

A comparison between nominal and expected flight trajectory has then been performed in terms of heat flux, and of electron density represented versus time since entry Fig. 12.

The heat flux is a direct output of the trajectory code, estimated with a Dedra-Kemp-Riddel correlation. For the electron density, non-equilibrium flow field calculations have been performed with an engineering code developed by FGE, named PMSSR. From the electron density, as in the earlier work performed by Reynier[4], the plasma frequencies have been determined, and the black-out start time and end time resulting from this simulation has been compared with the observed ones, indicated as dashed vertical lines in the figure. The analyses predict a much longer black-out period than observed, for the UHF band (219 MHz telemetry frequency). The flight data would better correspond to S-band communication black-out, and remain unexplained. Otherwise, for the scenario envisaged, the higher total heat input at the time when the communication was lost could have provoked an earlier ablation of the front shield, in front of the telemetry antenna.

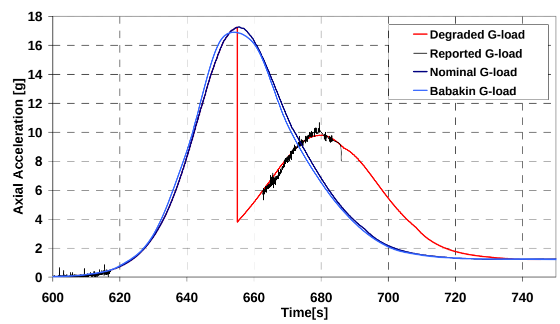


Fig. 11: 6 degrees of freedom analyses: rebuilding of flight data

Finally, all analyses agreed on the predicted landing point location of the demonstrator based on telemetry data, shown in yellow Fig. 13: The expected location is right in the middle between the nominal landing area, represented in red, and the landing area corresponding to a flight without IBD inflation, represented in blue square, pink circle and orange diamond near the city of Ust-Kamchatka. This remote area, mountainous, was unfortunately not explored during search operations due to weather conditions improper for helicopter flight.

4. CONCLUSIONS

The IRDT-2 demonstrator has been developed and tested in flight in October 2005. The demonstrator has provided useful flight data before and after black-out, but it has unfortunately not been recovered yet. The present interpretation of flight data is that the inflatable shield may have achieved a significant part of its mission, but experienced a failure near peak deceleration. The last phase of the demonstrator trajectory was therefore non-nominal, and its landing site appears to be in a region that was not searched by the recovery teams. The recovery of the IRDT-2 demonstrator would provide a number of data missing presently, and would certainly allow concluding on the actual performance of the system and on its possible improvements. The inflatable entry technology, though no demonstrated yet, appears to be promising for future Earth and planetary entry missions.

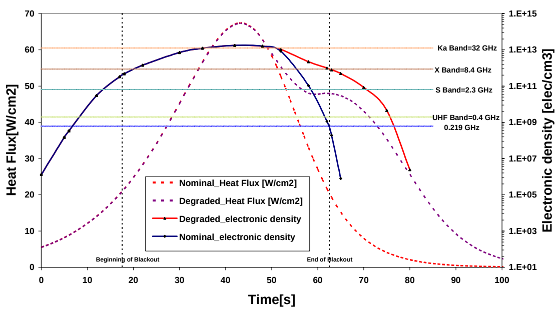


Fig. 12: Evolution of heatflux and of electron density, IRDT-2R entry

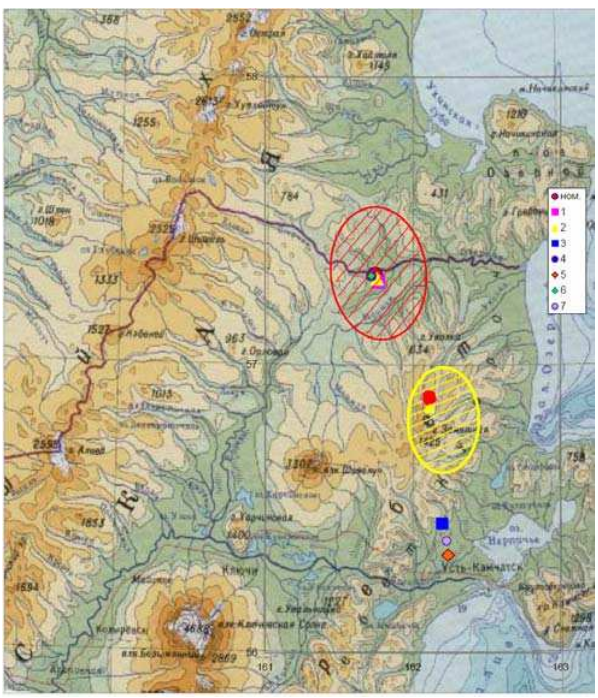


Fig. 13: IRDT-2R landing site location

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