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French Long Duration Balloon Activity :
- The InfraRed Montgolfiere (MIR)
- The Superpressure Balloon (BPS)

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FRENCH LONG DURATION BALLOON ACTIVITY:
- The InfraRed Montgolfiere (MIR)
- The Superpressure Balloon (BPS)

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Abstract

Since 1971 (EOLE project), the Centre National d'Etudes Spatiales (CNES), the French space agency has supported a stratospheric long duration programme for the French scientific community.
The purpose of this paper is to present the two long duration vehicles, the MIR and the BPS, and their performances during several campaign.
After more than 40 flights, the MIR (hot air balloon) has demonstrated its capability for long duration scientific flights during tropical and Ecuador campaigns.
In addition to long duration flights, the MIR may take vertical soundings of the atmosphere between 18 and 30 kilometres twice a day with 40 to 80 kilograms of payload.
Since 1997 this vehicle was used to perform circumpolar winter flights with on-board scientific experiment for the study of the dynamic and the ozone chemistry of the stratospheric polar vortex.
Concerning the Superpressure Stratospheric Balloon (BPS), CNES has developed an observing system based on the use of isopycnic drifting balloons, flying at constant density levels from 18 to 20 kilometres (spherical shape of 10 meters diameter).
Tests have been made from Aire sur l'Adour in France. The system including the gondola and the ground section has been qualified with six launches which took place from Ecuador in August / September 1998.
A scientific project called Lagrangian Experiment is organised in January/February 1999 to study the Arctic polar vortex in terms of dynamics and chemistry.
Main results from these experiments are presented

1- Long duration flight using the InfraRed Montgolfiere

1-1 The vehicle and its principle

The starting point to use the montgolfiere concept to perform long duration balloon flights in the stratosphere was an idea forward by Service Aéronomie (Aeronomy department) from CNRS (Centre National de la Recherche Scientifique) in 1977 (Ref.1).
From this idea, the balloon division of CNES (Centre National d'Etudes Spatiales) developed and qualified in flight a vehicle called MIR (Montgolfiere InfraRouge).
The MIR is a very light hot-air balloon absorbing its energy from its radiation environment: it is heated by upwelling infrared fluxes during night-time and by the direct and reflected solar fluxes during daytime.
The figure1 below shows the MIR radiative budget:

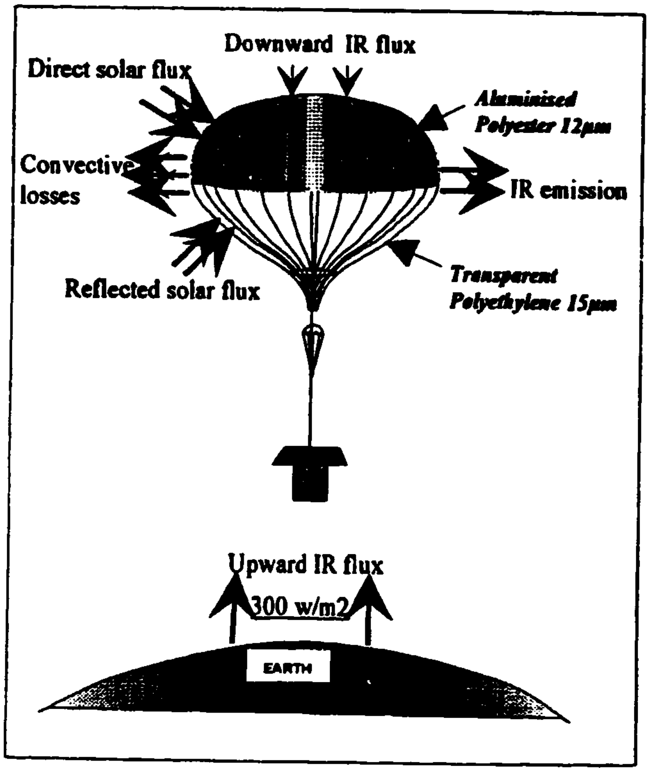

Figure1: MIR radiative budget

At the present time, the volume of the MIR is 45 000 m3 with natural shape which requires an over temperature inside the balloon of 10/15 degrees at night to keep a balanced float level. For over temperatures less than 10 degrees, the MIR descents slowly at low level and stops at sunrise to re-ascend during daytime.

The MIR envelope is composed of two different hemispheres with materials which offer a good compromise between thermo-optical properties (for the captation of infrared fluxes) and weight budget. The lower part is made of 15um linear polyethylene, a material transparent to infrared radiation and resistant to cold ambient conditions (-80°) met by the balloon during its flight. The upper part is made of 12um aluminised mylar, a material which allows the absorption of infrared radiations and avoids its re-emission to the outside.

An example of a MIR vertical profile is shown on figure2:

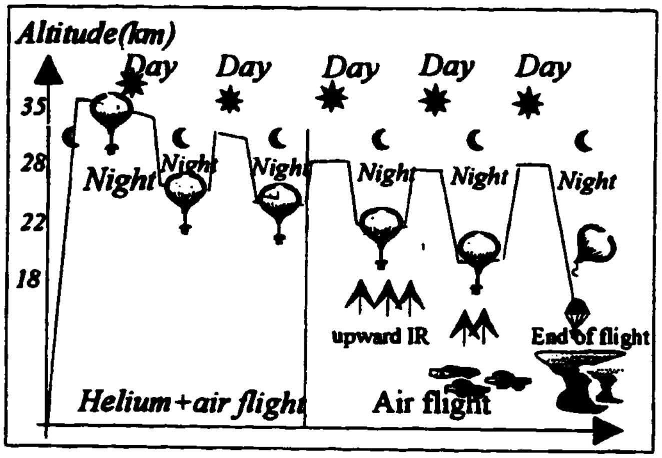

Figure 2: MIR flight profile

The first ascent from the ground is carried out with the helium as aerostatic gas. After 2 or 3 days the helium is completely evacuated and the MIR flies only with the hot air. With 60 Kg payload, the MIR in long duration flight flies at an altitude around 28 Km slightly dependant on albedo by daytime and between 17 and 22 Km at night depending on the amount of infrared flux coming up from the overflown area and on ambient temperature profile at flight level.

1-2 The gondola and the flight train

The arrangement of the various gondola and sub-systems below the balloon is shown in figure 3 for a standard flight train and presented here after:

- *Air safety and end of flight devices* :

. One pyrotechnic cutting device commanded from the service gondola, coupled with a barometric system to put an end of flight as soon as the low altitude limit is reached

. A parachute for the descent after cut down

. A passive reflector and a radar transponder if required for the detection of balloon by planes

. One flashlight for visual detection of the flight train from 0 to 18 Km in altitude

All the balloon borne security devices described have been tested qualified and operationally used in CNES long duration campaigns and in agreement with ICAO regulations.

The weight of these devices including straps and cables is around 10/15 Kg depending on the length of the flight train

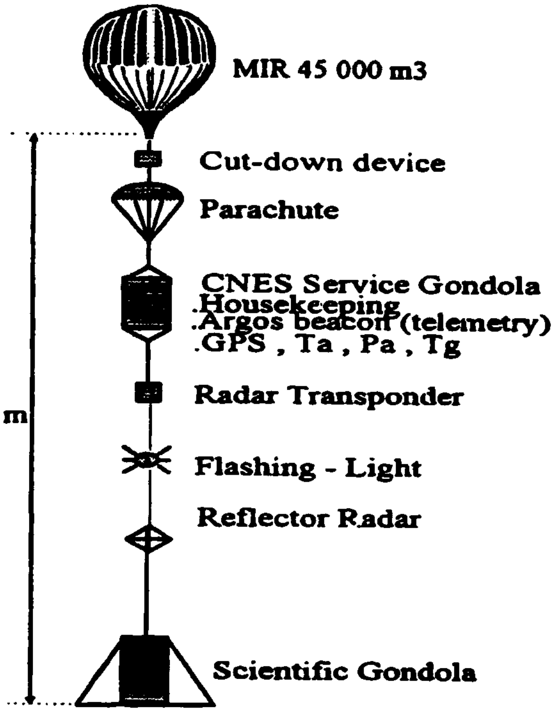

Figure 3: MIR flight train

- *Service gondola* :

The gondola is composed of a platform in polystyrene adapted for insulate containing lithium batteries and telemetry system (ARGOS), localisation system (GPS), various sensor and electronic cards.

The role of the service gondola is to allow the monitoring of the flight. This gondola called SAMBA has been developed by the CNES balloon division for long duration flights and has to insure the following tasks:

. Management of the power supply for GPS receiver, ARGOS beacon, thermodynamic sensors (pressures, temperatures).

. Acquisition and treatment of thermodynamic sensors.

. Acquisition of 3D GPS location.

. Transmission to the ground via ARGOS satellites of all technological and thermodynamic parameters concerning the balloon flight (altitude, location, atmospheric pressure, atmospheric and gas temperatures, equipment temperatures, status of flight)

. Elaboration and activation of an end of flight command thanks to an onboard automaton if the balloon goes out of a pre-programmed flight domain in the following cases:

-Detection by the onboard GPS receiver of a drift of the trajectory down a limit in latitude;

-Detection of the altitude threshold below the standard altitude for the air traffic;

-Detection by an onboard timer of flight duration more than the maximum duration pre-defined before the flight;

-Detection by GPS of an entry in a pre-programmed area for cut down in view of a possible payload recovery.

The total weight of payload of the service gondola is about of 11 Kg including batteries for one month of flight duration.

Generally the scientific payload is situated at the end of the flight train around of 25 or 50 meters below the service gondola depending of scientific requests.

1-3 The performances of the InfraRed Montgolfiere

The standard vehicle, which is now used for long duration flight, has the characteristics described on the following table:

Flight domain ⇒ low and middle stratosphere

Volume ⇒ 45 000 m3

Flight altitude ⇒ Daytime : 29 / 27Km
Night-time : 23 / 17Km

Payload at hook ⇒ 40 / 70 Kg

Flight duration ⇒ max:2 months / 2 revolutions around the globe

Flight area ⇒ Tropics , Equator, Arctic

The level in altitude of the MIR can be determined by the following relation:

$$(Roa - Rog)*Vol - Ms = 0 \Rightarrow$$

$$Roa = 287.0856*Ms*Tg/Vol/(Tg - Ta)$$

where Roa : air volumetric mass
Rog : gaz volumetric mass (air inside the MIR)
Tg : MIR internal temperature
Ta : air temperature
Ms : amount of solid masses

An study of performances of a 45 000 m3 MIR versus various payload at hook for different over temperatures corresponding at radiative conditions over flown by the MIR (clear et cloudy sky) is presented on the figure 4:

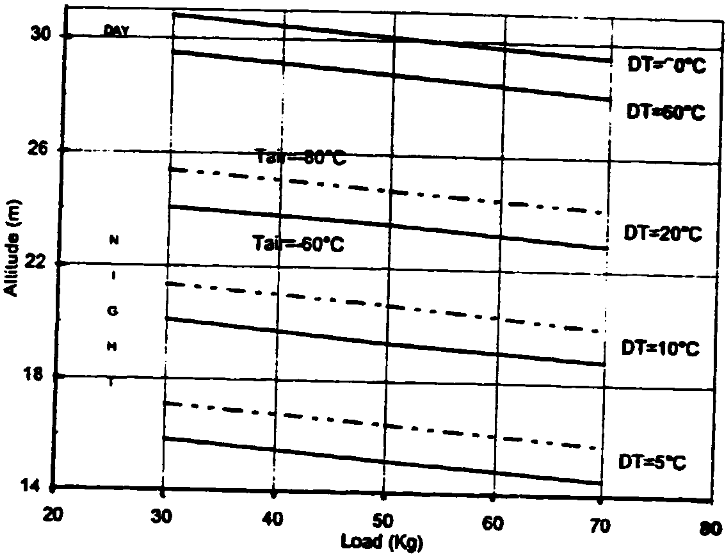

Figure 4: MIR performances

Obviously, the behaviour of a MIR depends closely on atmospheric parameters. The stability of the flight level, especially at night, is very sensitive to the atmospheric temperature profile and, of course, to upwelling infrared fluxes at the flight level and the probabilities of balloon fall depend on these two parameters. Moreover, the time constants of the thermal exchanges are such that a static analysis of a 'frozen' state of the MIR could introduce a misinterpretation of in-flight measurements. That is why an numerical model (Ref.2) which takes into account all the dynamic and thermal parameters such that radiative and convective heat transfer, mass transfer, aerodynamics, inertia, temperature profile, incoming and outgoing fluxes, with their variability has been developed and validated with measurements of several real flights (figure 5). This model allows predicting the performance of an Infrared Montgolfiere for a defined set of environmental parameters (temperature profile, albedo, IR flux, load balloon size, period, latitude).

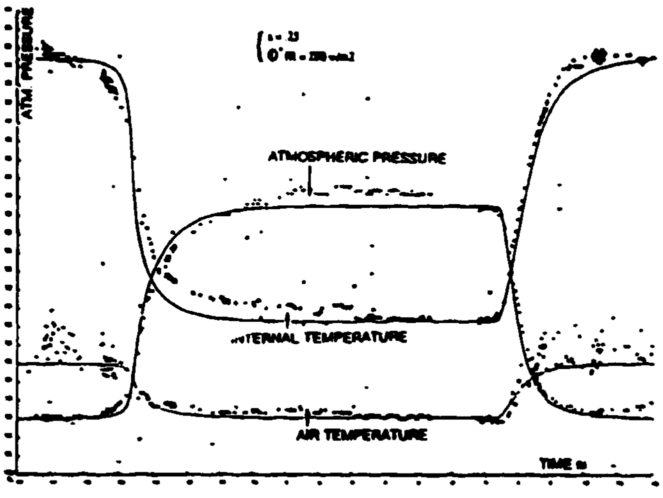

Figure 5: Comparison of simulation vs. experimental data

The parametric analysis in figure 6 with different upward infrared fluxes shows clearly that there is a limit around 140 w/m2 below which there is no possible stabilisation of the balloon during the night.

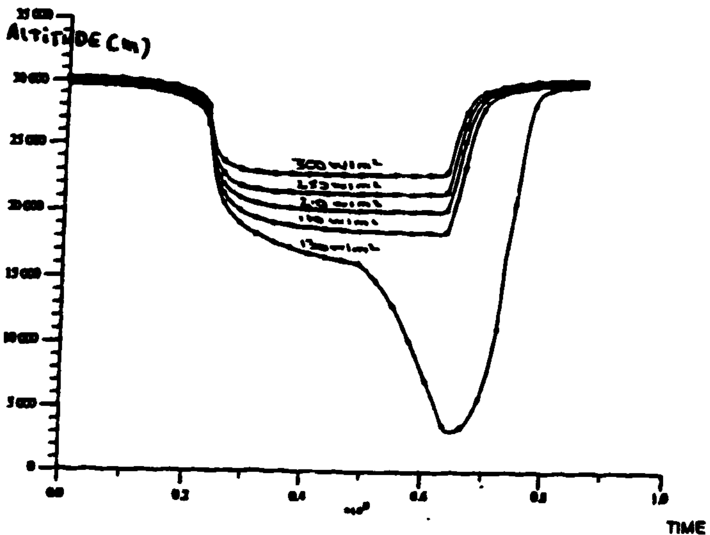

Figure 6: Simulation for various IR upward fluxes

The statistic study (figure 7) realised with the data of the upward infrared fluxes from SCARAB satellite during 5 years (1994-1999) compared at the computed IR flux curve sufficient to stabilise the MIR at low level for a season and latitude given, shows that the least favourable conditions are encountered primarily in the middle and higher latitudes, as a result of the combined occurrence of dense clouds formations and relatively high temperatures in the lower stratosphere. The favourable period and ideal zone is found at latitude of about 25° in austral summer and 15 ° in austral winter.

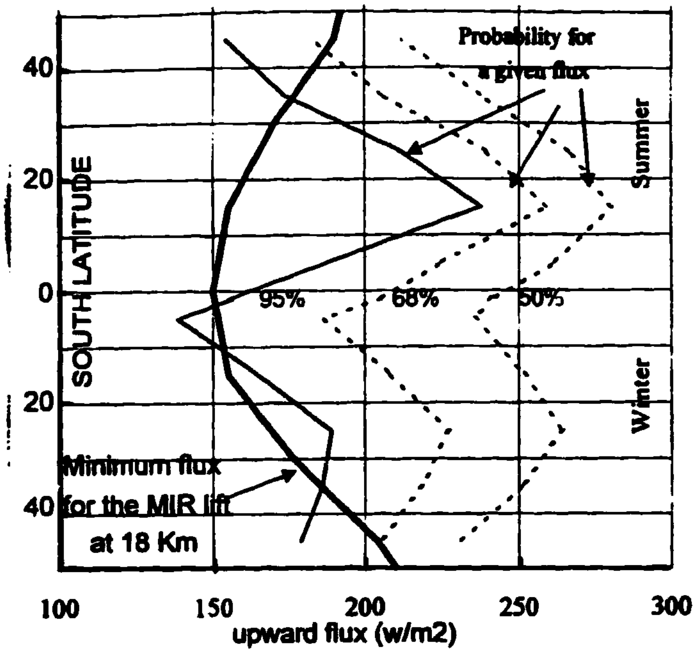

Figure 7: MIR flight domain

1-4 Results of long duration MIR campaigns

1-4-1 Statistics of MIR lifetime

After more than 40 flights launched from different places (France, South Africa, Scandinavia), the MIR has demonstrated its capabilities for long duration flights. The figure 8 gives a summary of the scientific flight durations for the last fourteen years. The best average duration (3 weeks) of a flight is encountered in tropical latitude confirming the analysis on the domain flight MIR presented above.

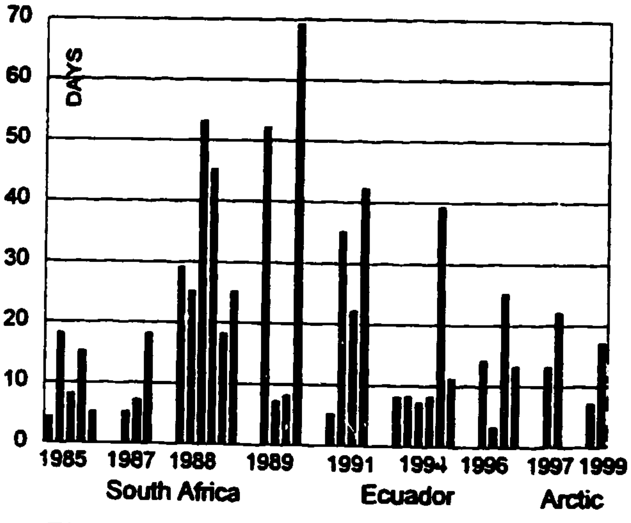

Figure 8: MIR lifetime (1985-1999)

1-4-2 Tropical Flights

About 30 MIR have been launched in seven scientific and technologic campaigns of 3 to 8 each between 1981 and 1989 from Pretoria in South Africa.

The scientific experiments concerned mainly gravity waves measurements (Ref.3) and water vapour measurements (Ref.4, 5) for the benefit for two French institutes of CNRS: LMD (laboratoire de Meteorologie Dynamique) and SA (Service Aeronomie).

The average duration of a flight is about 20 days and the record duration was achieved during a flight of 69 days with a balloon launched in December 1989 which flew 2,5 times around the earth with 57 Kg of payload (Figure 9)

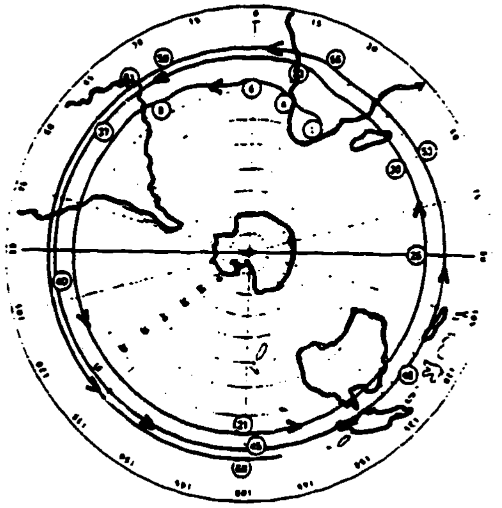

Figure 9: MIR flight trajectory, December 1989

During the previous campaign in December 1988, another flight lasted 53 days with 41 Kg of payload and circled the globe 2 times (Figure 10)

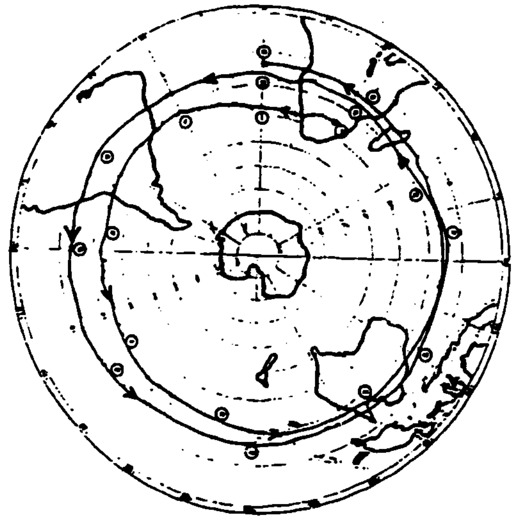

Figure 10: MIR flight trajectory, December 1988

The majority of end of flight was encountered when the MIR over flown regions with highly convective clouds zones above African and South America continents that brought down the MIR under the safety level of 18/17 Km where it was self destroyed.

1-4-3 Equatorial flights

At the request of the scientific team from LMD in the frame of AMETHYST project, 3 long duration campaigns took place in March 1991,January 1994 and April 1996 from Latacunga (latitude = 1°S, longitude = 78°W) in Ecuador.

The goal of AMETHYST project was to study the stratosphere-troposphere exchanges in the very active convective zones around Indonesia and the water vapour balance in equatorial zones. During these campaigns the ALBATROS experiment (measurements of earth magnetic field to investigate the link between magnetic anomalies and plate tectonics) of IPGP (Institut de Physique du Globe de Paris) and the SAOZ experiment (measurements of profiles of ozone, NO2, O2 and O4) flew under MIRs. In total 15 scientific flights was carried out with durations of 10 to 42 days and payloads of 50 to 70 Kg.

A trajectory and vertical profile of one flight realised in 1996 is presented in figure 11 and 12.

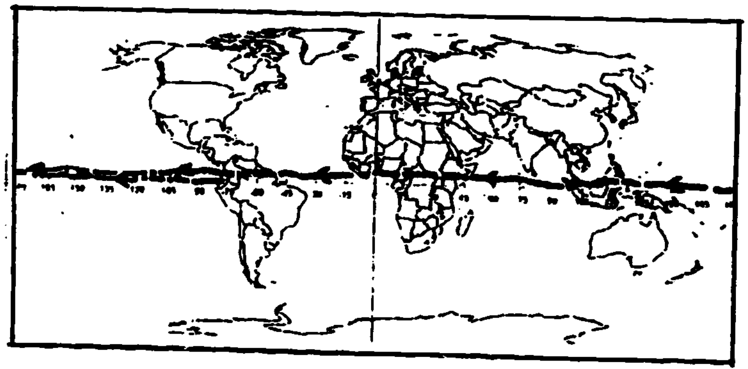

Figure 11: MIR flight trajectory
5/04/1996-28/04/1996

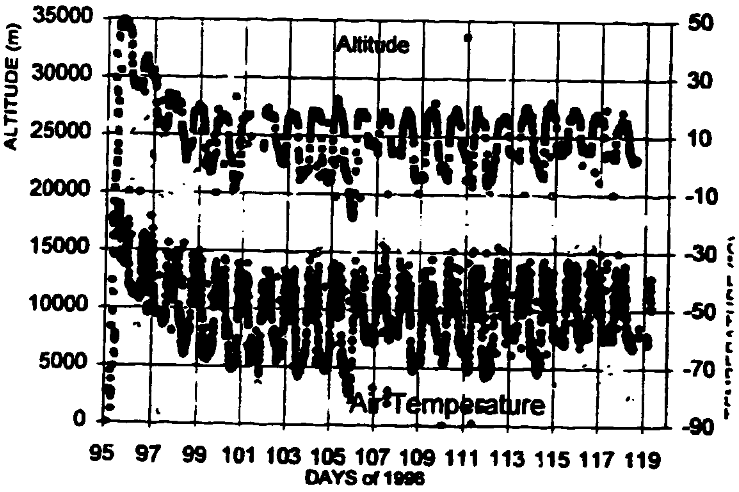

Figure 12: MIR vertical profiles
5/04/1996-28/04/1996

The longest flights lasted 45 days in 1991, 39 days in 1994 and circled the globe twice before felling above the Amazonian forest known to be a highly convective region (low infrared fluxes).

One of difficulties to fly with a MIR in equatorial zones is to cross by night areas of high convective cloud concentration (ITCZ: InterTropical Convergence Zone) such as for example Micronesia (Pacific ocean). In 1994, 6 balloons out of 7 fell over this region after crossing the ocean Pacific.

Another problem to launch a MIR from Ecuador is the direction of the wind in the stratosphere depending on the QBO (Quasi Bienal Oscillation): the flow must be easterly in order to avoid the Amazonian region dangerous for long duration MIR flight and to start the flight above the Pacific ocean.

1-4-4 Arctic flights

Since 1997 the scientists wished that long duration flights be carried out during winter in the Arctic to inject a MIR into the polar vortex .The scientific objective was the study of the daily evolution of the stratospheric ozone concentration within the polar vortex, where temperatures are very low and massive destruction takes place. The study of the dynamic processes of the polar was also an important objective.

The CNES balloon division had to study the less unfavourable period to perform long duration MIR flights because it is not easy to fly with a MIR in winter or early spring owing to night durations and poor infrared fluxes (< 150 w/m2) coming up from frozen regions such as North Siberia and Greenland. However a cold stratosphere temperature (-80°C/-70°C) is favourable to the flight of the MIR: this situation is encountered in January – February and when the polar vortex is very cold. The compromise is to fly the balloons between mid-February and mid-March where medium infrared flux in cold areas combined with low stratospheric temperature profile and period of sunshine sufficient can be met.

Because safety reasons and limitation of balloon performances as well, the flights were limited inside the vortex and automatically terminated if the balloon was drifting south of 55°North or below 150 Hpa; moreover the flight duration was limited at 28 days maximum and the possibility to terminate the flight above Scandinavia after 22 days of flight in view of recovery the payload was controlled thanks an onboard automaton pre-programmed at ground.

With these considerations, 2 scientific campaigns with 2 MIR each was carried out from ESRANGE, the facility of the Swedish Corporation at Kiruna (68°N, 21°E) during the winters 1997 and 1999.

A summary of principal characteristics of flights is presented on the following table:

N°	Experiment Laboratory	Load at hook	Date	Flight duration	End of flight
1	SAOZ SA/CNRS	61 Kg	24/2/97	13 days	Greenland
2	SAOZ SA/CNRS	61 Kg	17/03/97	22 days	Norway
3	Lagrangian Experiment SA/NPL/CAO	70 Kg	18/02/99	7 days	Siberia
4	Lagrangian Experiment SA/UCAM/ CNR	45 Kg	19/02/99	17 days	Labrador coast

ILAS campaign, winter 1997:

The first MIR launched within the polar vortex on February 24,1997 flew 13 days performing 3 circumpolar rotation at latitude above 60° N. Given its rapid trajectory towards the East, this MIR has flown during 16 solar days and 17 nights. The end of flight occurred above Greenland due to an erroneous order of cut-down delivered by CPU and the payload was not recovered. The trajectory and the altitude of the balloon and the atmospheric temperature are displayed in figure 13 and 14.

As expected the MIR remained inside the vortex, and after one and half day and the lost of additional helium for the first ascent, the daytime flight level becomes stable about 25 Km. During night-time, it varies from 20-22 Km at cold temperature (-80°/-75°) to 15 Km at two occasions at warmer temperature (-65°) above Labrador and at low upward infrared fluxes (<140 w/m2) above Southern Greenland.

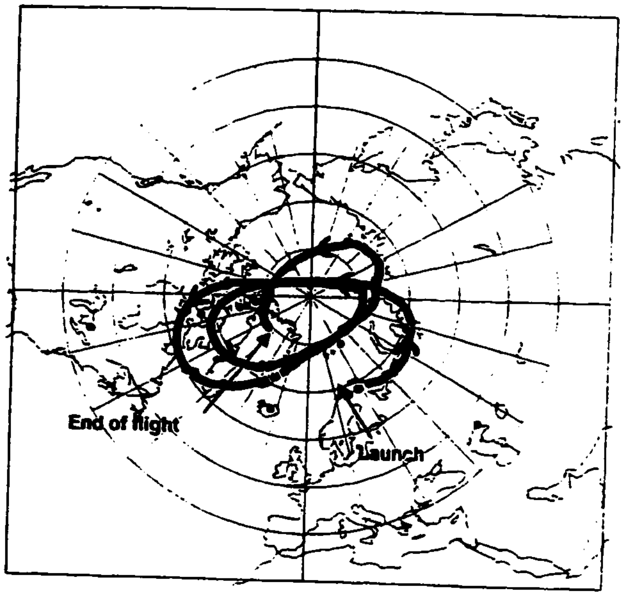

Figure 13: MIR flight N°1 trajectory 24/02/1997-09/03/1997

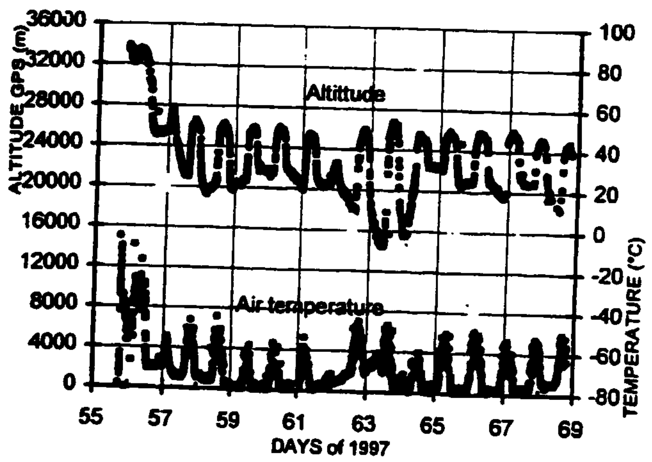

Figure 14: Flight N°1 profiles 24/02/97-09/09/97

The second MIR of this campaign was launched on March 17,1997 one week after the end of the first flight at the inner edge of the vortex. It lasted 22 calendar days (26 solar days and 27 nights) and Circled 5 times around the earth between 57° N and 78° N (Fig.15, Fig.16). The end of flight occurred above Scandinavia by automatic cut down of the gondola: this system was armed, as planned, after 20 days of flight. The scientific payload landed safely on 8 April near Trondheim in Norway where it has been recovered on the following day.

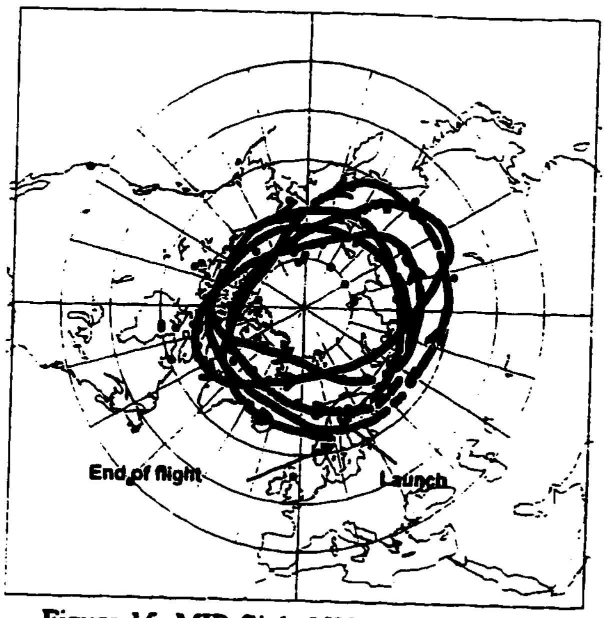

Figure 15: MIR flight N°2 trajectory 17/03/1997-08/04/1997

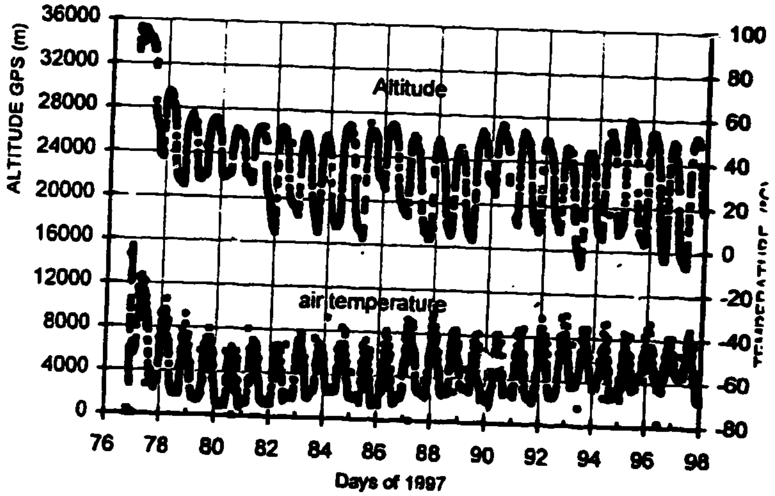

Figure 16: Flight N°2 profiles 17/03/97- 8/04/1997

As the first flight, the MIR remained inside the relatively large but undisturbed vortex north of 60°N in average. The progressive warming of the late vortex resulted in a progressive lowering of the night-time altitude, partly compensated by the shorter duration of the night, but always far from the limit level of cut-down at 150Hpa.

THESEO campaign, winter 1999:

The MIR campaign started as planned in February but since the stratosphere was already warm and the vortex very weak, the conditions have never been favourable. However, two MIR were launched in the late and elongated vortex on February 18 and February 19. The first flight carried the Lagrangian payload (SAOZ UV visible: spectrometer of Service Aeronomie, CH4 TDL: sensor of methane of National Physical Laboratory, FLASH-B: hygrometer of Central Aerological Observatory) and the second carried English and Italian experiments (Ozone sensor of University of Cambridge, LABS : Laser BackscatterSondes of Intituto per Fisica dell'Atmosphera). These two flights lasted respectively for 8 and 17 days. The trajectories and the altitudes of MIRs and the atmospheric temperatures are shown in figures 17, 18, 19 and 20.

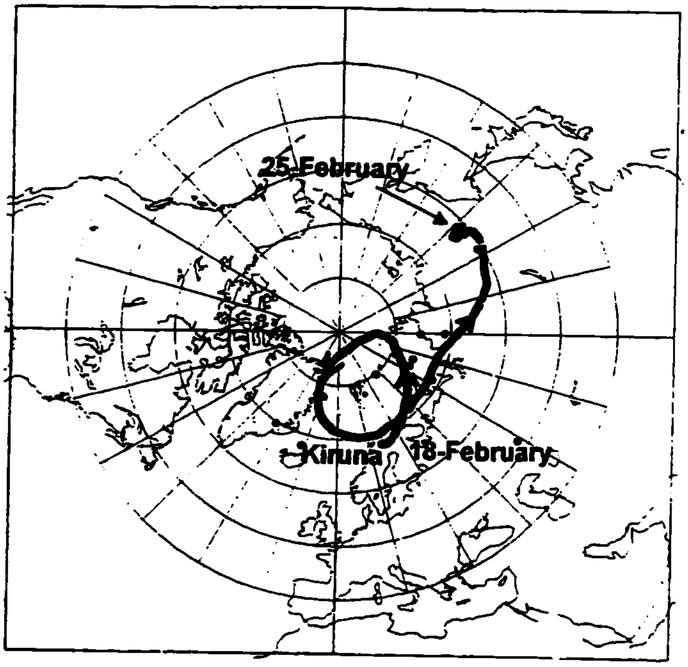

Figure 17: MIR flight N°1 trajectory 18/02/1999-25/02/1999

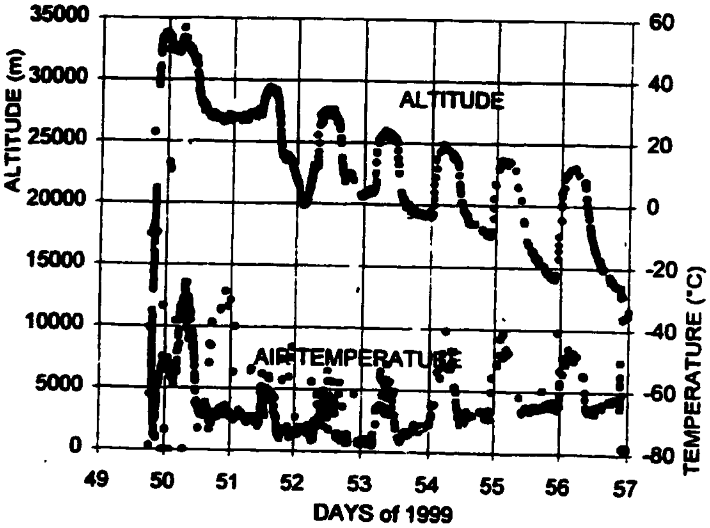

Figure 18: Flight N°1 profiles 18/02/99-25/02/99

The first flight was cut-down at its minimum altitude about 13 Km above Siberia (frozen region, infrared fluxes: 150 w/m2) and the second at its southernmost acceptable latitude of 55°N near the Labrador coast of Canada after the breakdown of the vortex.

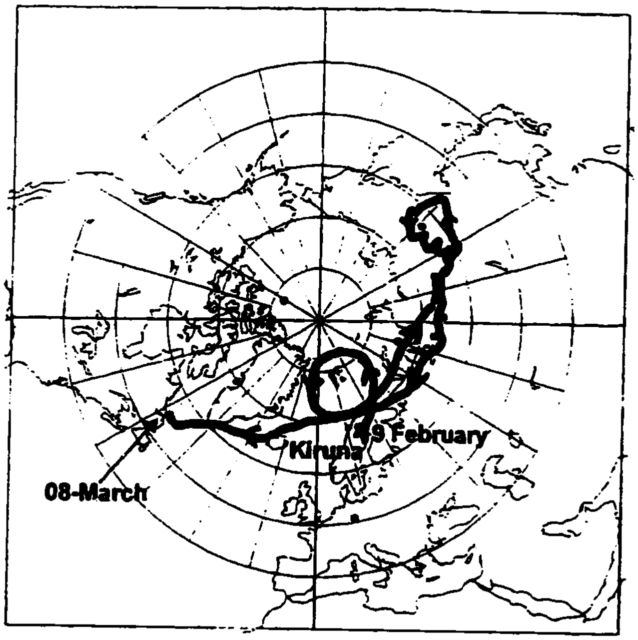

Figure 19: MIR flight N°2 trajectory 19/02/1999-08/03/1999

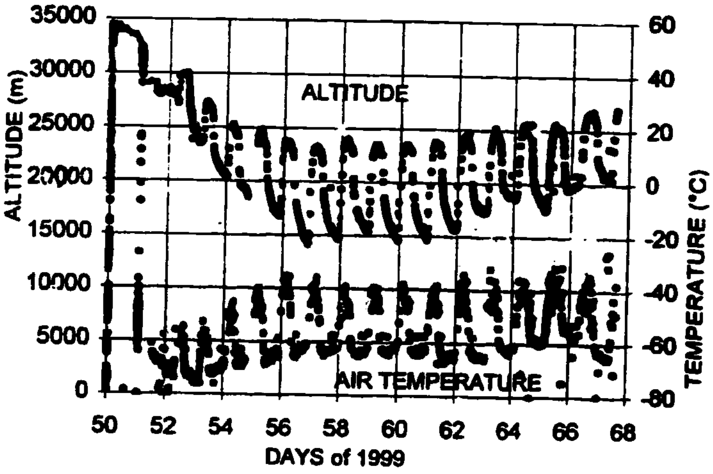

Figure 20: Flight N°2 profiles 19/02/99-08/03/99

Because of the adverse meteorological situation, a third MIR could not to be launched, but the two flights carried out allowed to better understand the limits of the system .The load at the hook of the balloon seems to be an important parameter in unfavourable atmospheric conditions (warm temperatures and low infrared flux) and had to be optimise between 50 et 60 Kg.

Lessons learned from arctic flights:

From an operational point of view, the MIRs have proved their effectiveness during ILAS and THESO campaigns. The following points have been demonstrated:

- feasibility and ability to fly for more 2 weeks in winter conditions with best chances when the vortex is cold and well-formed
- injection into the polar vortex
- possibility to recover the experiment in a pre-programmed area
- good control problems linked with the safety of these long duration flight in North hemisphere

From a scientific point of view, the success of Arctic campaigns opens up a new experimentation tools for chemistry and dynamic processes in the Arctic stratosphere. The significant results (Ref.6, 7) are the best proof.

2-The Superpressure Balloon (BPS)

CNES is currently developing a stratospheric observation system based on the use of long-lived isopycnic drifting balloons able to fly at constant density levels from 15 to 20 kilometers carrying about 20 kilograms at hook.

2-1 The BPS system

The balloon technology is a 10 meters diameter spherical pressurised balloon (BPS). It is an extension of the EOLE balloon (1970) which was 3,7 meters diameter, for studying tropospheric dynamics. Lessons learned from the EOLE experiment drove the design of the envelope, the main effort being put on industrialisation and quality control of the manufacturing company. Due to the dimension, special packing procedures and items were developed to minimise damage for the balloon envelope during packing and shipping. Several balloon tests are conducted in Toulouse.

The flight train equipment is composed of all the security devices and the electrical and mechanical links between the balloon and the gondola. Its length is of the order of 15 meters. Emphasis is put mainly on weight (cut-down device, radar transponder...).

The design of the gondola may be left to the scientific group. However there are unavoidable functions which have to be fulfilled in any case such as security, end of life, telemetry of balloon sensors.... CNES has developed a standard gondola called SAMBA. It can host other scientific equipment under specifications. This development was necessary for the flight experiments.

Basically, as for the MIR but with emphasis on reduction weight, SAMBA provides onboard energy, telemetry throw the ARGOS system, acquisition and processing of sensors (pressure and temperature), 3D GPS localisation, end-of-flight in pre-programmed domain (latitude, longitude, altitude), management of the scientific passengers.

All the data can be made available automatically to the scientific community on a computer file (Internet for example) within a few hours, depending on which part of the earth is the balloon.

2-2 State of the art of the BPS system

2-2-1 The qualification phase

A " float level qualification " took place during winter 1997/1998 from Aire sur l'Adour in France. Three over four balloons succeeded to reach 60 Hpa level (around 19 km). The flight duration was ended by telecommand after one hour of ceiling.

A " long duration qualification " was performed from Ecuador (Latacunga) in August/September 1998. Six BPS flights were attempted. A brief summary is given in table 1 concerning the main characteristics of these flights.
Three flights gave CNES encouragements to go on, with flight duration of 21, 47 and 24 days respectively, but all of them ended their life over Micronesia (over extremely low infrared upwelling fluxes: around 150w/m2). See figure 21 for the trajectories.

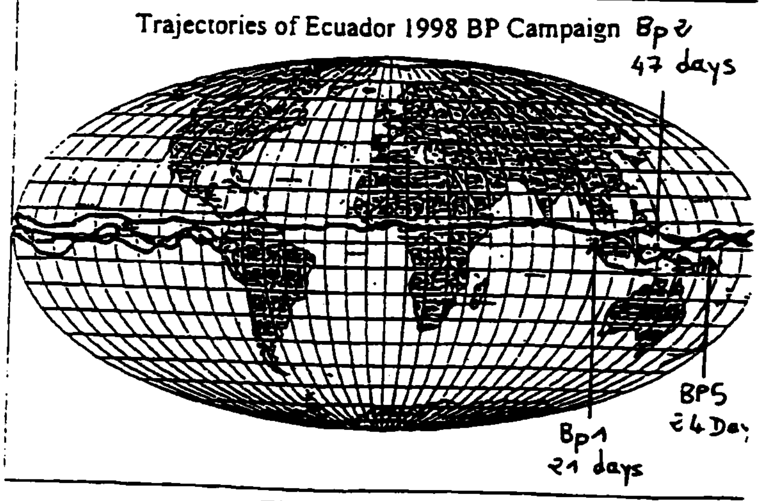

Figure 21

During these two phases, some slight improvements were brought to the BPS system, but the launch and operations were very much conservative due to time constraints. However it was decided to go on the next phase, in spite of this relatively limited success.

	BP1	BP2	BP3	BP4	BP5	BP6
Date of launch	25/08	01/09	01/09	04/09	07/09	11/09
Free Lift (%)	10	10	10	10	7	7
Weight at hook	21	21	26,6	21	25	25
Ballast (Kg)	1	1	1	1	0	0
Surface wind (m/s)	1	1	1	2	2	1
Ascent	1H30 ok	1H30 ok	1H30 ok	1H50 Slow	1H35 ok	1H35 slow
Gondola	SAMBA CNES	SAMBA CNES	SAMBA CNES	LMD1	SAMBA CNES	LMD2+ SAMBA
First ceiling (Hpa)	60 ok	60,4 ok	65,4 ok	62,1 ok	65 ok	63,8 ok
2nd Ceiling (Hpa)) after ballast	58,7 ok	59,5 ok	64 burst	62,1 ok	65 ok	63.8 descent
Air Temp. (°C)	-61 to -75	-67 to -71	-60 to -67	-63 to -69	-63 to -70	-66
Tropopause Temp.(°C)	-81,5	-77,5	-78,4	-76,9	-80,8	-76,6
Max.DeltaP (Hpa)	15	15	14	11	15,5	4
Flight Duration (Days)	20,5	47	0,1	>4	24	0,1
End of life	Cold night	Cold night	Over pressure	?	Cold night	Leak 1cm

Table 1

2-2-2 The demonstration plan

In order to improve and finalise the BPS system and as experimental facts are needed when dealing with balloons developments (even sophisticated computer simulations are still very difficult) a demonstration plan with scientific objectives was undertaken.

The risks have to be shared of course; for the scientific community, it has the advantage of reducing the cost of the experiment, but the drawbacks for the technical group are the scientific requirements and the bad impression induced on the BPS system in case of failure.

In the framework of the Lagrangian Experiment of the THESEO campaign, besides the two MIR here above mentioned 3 BPS flights took place from Kiruna airport carrying SAMBA gondolas with passengers.

A summary of the flights is given in table 2.