An update on CNES balloons operational campaigns 2019-2024

Vincent Dubourg[a]*, Stéphane Louvel[a], Stéphanie Venel[a], Isabelle Zenone[a], Frederi Mirc[a], Frédéric Thoumieux[a], Laurent Tessariol[a]

[a] *CNES, Centre National d'Etudes Spatiales, Toulouse, France*
* Corresponding Author

Abstract

The French Centre National d 'Etudes Spatiales (CNES) goes on supporting a significant balloon program and infrastructure, for scientific and technological purposes. The CNES balloon systems and operation means are mobile; they can be deployed and operated worldwide, at several latitudes, in compliance with safety and environmental rules.

The extended range of vehicles and payload gondola support provided by CNES allow addressing several kinds of missions such as atmospheric physics and chemistry, stratospheric and tropospheric meteorology, and astronomy. In particular, CNES provides a very high performance pointed gondola service.

Since the last presentation of CNES balloons to SPACE OPS 2018, CNES conducted several operational campaigns with varied types of balloons and from varied sites in the world:

- 6 scientific campaigns of heavy Zero Pressure Balloons (ZPB) were carried out, 4 from Timmins, Ontario, in partnership with the Canadian Space Agency and 2 from Esrange, Kiruna, Sweden, hosted by the Swedish Space Corporation. In particular, a transatlantic flight was operated for the first time from Kiruna to northern Canada in June 2024.
- In the field of long duration balloons, CNES conducted 2 flight campaigns of super pressure balloons (SPB) from the Seychelles Islands for the STRATEOLE 2 project, for the study of the low stratosphere in equatorial regions, in link with the climate change survey and stratospheric air transport modelling. The observing system is based on the use of fleets of small super pressure balloons (SPB) flying up to 3 months each, carrying payloads of 25 kg at 18 to 20 km in altitude. The last scientific campaign is on schedule for late 2025.
- CNES also performed yearly 30 to 40 flights of light sounding balloons (SB), from its historical French operation site of Aire sur l'Adour. The balloon flights completed airborne and ground measurements of greenhouse gases and aerosols, to calibrate observation satellite instruments.

This paper gives a synthesis of the launch campaigns of the past five years emphasizing the operational challenges achieved in the fields of ZPB and SPB. The contributions of balloons in favour of sustainable development will be highlighted. Finally, the prospects for the coming years are also mentioned.

Keywords: Balloons, operations, stratosphere, aerostats, flight monitoring, sustainability.

Acronyms/Abbreviations

Centre national d'études spatiales (CNES)
Esrange Andoya Special Project (EASP)
Sounding balloon (SB)
Super pressure balloon (SPB)
Telemetry and remote control (TMTC)
Zero pressure balloon (ZPB)

1. Introduction

The CNES balloon department currently conducts yearly stratospheric balloon flight campaigns for science and technology purposes. From 2018 to 2024, not less than fifteen launch campaigns were performed from several places in the world:
Among them, seven were carried out using light SBs, from the French historical launch base of Aire sur l 'Adour, for a total of more than 200 flights.
In addition, six scientific campaigns of heavy ZPBs took place, four from Timmins, Ontario, in partnership with the Canadian Space Agency and two from Esrange, Kiruna, Sweden, hosted by the Swedish Space Corporation, in the framework of the EASP. In particular, a transatlantic flight was operated for the first time from Kiruna to northern Canada in June 2024. A total of 24 ZPBs flights were performed.

In the field of long duration SPB, CNES conducted two launch campaigns from the Seychelles Islands for the STRATEOLE 2 project, for the study of the low stratosphere in equatorial regions. 25 balloons were operated, cumulating 1312 days of flight. Also a maiden flight of a steerable balloon, the BALMAN, was achieved from French Guyana in October 2024, paving the way to long duration persistent stratospheric platforms.
The paper gives, for each kind of balloon, ZPB, SPB and SB, a description of the on-board and ground systems, a synthesis of the launch campaigns carried out, and an overview of the operational challenges achieved. The contributions of balloons in favour of sustainable development will be highlighted. And finally, the prospects for the coming years are also mentioned, including an overview of the steerable balloon project (BALMAN), an innovative system currently in development at CNES, with the French HEMERIA AS company.

2. The typical CNES balloon operation phases

CNES process to organize a balloon launch and operation campaign is basically the same whatever the kind of balloon system deployed.

Regarding safety, CNES imposes both qualitative and quantitative criteria: For heavy balloons, the risk to touch a person at landing must remain under 3 x 10^{-5} for the whole flight, and the quantitative criterion imposes that all the critical functions will be duplicated on-board and on ground, through the use of totally independent command chains, hardware and software, or critically developed and tested software in case of common source.

Once the “go” for launch preparation is given at the meteo briefing on site, all the flight items are installed on the launch pad, and then the system operations can be decomposed into four phases: The assembly and test phase on the tarmac, the balloon inflation, constituting the negative chronology until the take-off, then the flight phase (ascent and float, with or without piloting the altitude profile) until separation (commanded flight termination).

Thirdly, comes the burst and/or descent of the balloon envelope and the descent of the flight chain under parachute. The fourth step are the recovery (except for small very long duration balloons lost at sea), and reconditioning of the equipment, instruments and gondolas for the next flight (envelope excepted).

During assembly, flight and descent phases, the monitoring of the system is assured by the control centre. The system is designed to guarantee a continuous monitoring and control of the aerostat even in case of one critical failure.

The flight termination is decided in coordination with the experiment principal investigator, and the local authorities. During the descent phase, the balloon and the flight chain are monitored by the control centre, and land in a safe area. The recovery team then will find and carry back the flight train and envelope to the launch base, in coordination with the control centre.

3. The ZPB system and recent operation campaigns

3.1. The ZPB system

The ZPB system currently operated today relies on the NOSYCA system (New system for the command of aerostats) developed by CNES almost fifteen years ago. The leading concepts of this system are based on compliance to mission safety and performance requirements:

Regarding mission performances requirements, the NOSYCA system provides a 1.5 Mbits/s rate for the payload telemetry downlink, and an IP link to operate the payload from the ground.
A quick view of the CNES ZPB system is given below, firstly the housekeeping on-board and ground systems, and secondly, the payload gondola services provided to the users’ community.

3.1.1 The ZPB housekeeping system

The ZPB flight segment overview is given in Fig. 1 below:

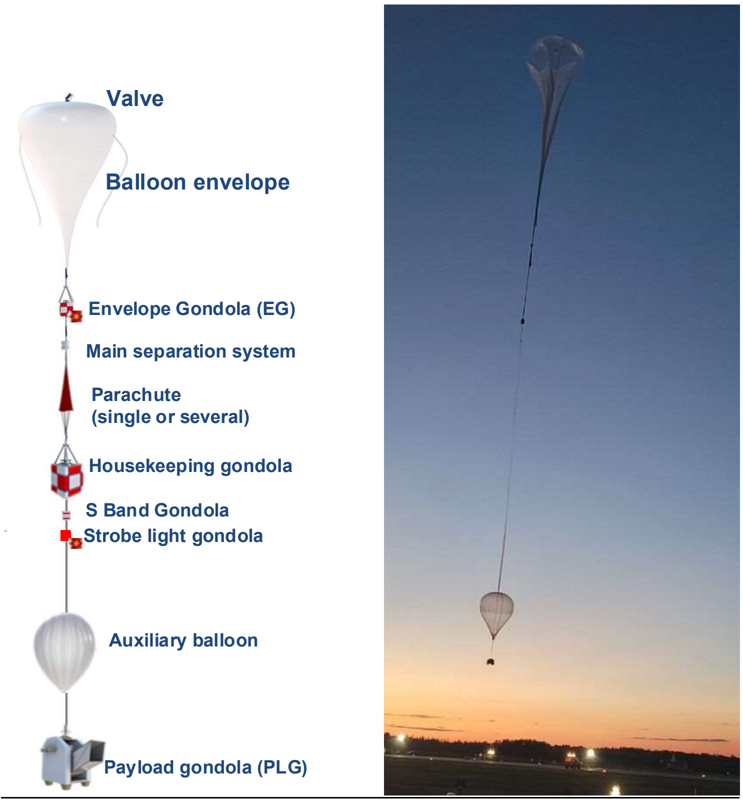


Fig. 1: The CNES ZPB flight segment

The balloon envelope is made of polyethylene; its volume can vary from 3000 m3 (106 kcft) to 800 000 m3 (28,25 Mcft), depending on the payload mass and the ceiling altitude required.
The valve is installed at the top of the envelope. It is fail safe, using 3 flaps and 3 gear motors.
An envelope gondola (EG) is suspended at the hook of the balloon, and will give its location during the descent after flight termination and when landed. It comprises an Iridium short burst data modem, an Argos/GPS beacon, a mode S radar transponder emitting ADS B data, with a 65 kft encoder, and a strobe light for visual detection of the envelope when crossing the air traffic corridors. The EG weighs 15 kg.
Below the EG, is located a fail-safe pyro separation device, that will implement the flight termination by separating the flight train from the balloon, and induce the destruction of the envelope, activating a fail-safe halyard system and tear panels on the envelope.
After separation, the whole flight train descends under parachute, situated in line in the flight train.
For the heaviest payloads up to 1,1 tons, CNES uses a single 30 ft. parachute, and a system of three smaller parachutes for medium size payloads.
The house-keeping gondola is suspended under the parachute, it is the Operational Gondola (OG) that allows communication with the ground control centre: It operates on-board actuators to release either gas or ballast to control the flight level of the balloon by two independent ways: S-band link (named ITAC) and Iridium& Inmarsat modems (named ULIS link).
The OG has a mass of 150 kg for the electronic cases, plus 280 kg of stainless steel balls ballast.
ITAC is the nominal command chain, it comprises
The nominal on-board computer (OBC1), a GPS receiver, an S Band transceiver (TM 1,75 Mbits/s, TC 95 kbits/s, an IP router and a WiFi modem.
ULIS is the backup link, composed of the OBC2, another GPS receiver, Iridium and Inmarsat modems, for low rate TM/TC.
The ballast tank is equipped with 3 valves.
The OG also comprises a mode S radar transponder emitting ADS B formats under FL600 (about 18 km), and separate battery packs for ITAC, ULIS and the pyro separation device.

An S-band gondola is suspended below the OG, with an antenna ensuring the link with the ground station for remote control and science telemetry.
A strobe light gondola, dedicated to visual detection by air traffic, and including an Iridium short burst data modem is located below the S band gondola.
An auxiliary balloon (BAX) is integrated in the flight train to lift the scientific payload during take-off.
At the bottom of the flight train, the payload gondola contains the scientific experiments, and the PASTIS interface module for communication with the house-keeping gondola through a Wi-Fi connection.
The IP link from board to ground has a high bit rate of 1.0 Mb/s of which 0.95 Mb/s are dedicated to real time science telemetry and the independent remainder flow allows monitoring and controlling from the ground the balloon. The ground segment includes a nominal control centre connected to the S-band station via IP protocol and to an Iridium modem via RS232 asynchronous protocol with in parallel an emergency control centre connected to an Iridium modem.
An OBC testbed allows preparing and testing the house-keeping configuration before each flight. A scientific host interface for TM/TC remote control of the on-board experiments is also available for configuration tests and real time monitoring.
All the Nosyca system is mobile; the control centre and the telemetry station are installed into 20 ft. sea containers to be easily transported and operated anywhere in the world.

The ground segment architecture, shown in fig.2, is composed of:

- The nominal control center (CCB), in permanent link with the ITAC and ULIS modules of the OG. The CCB ensures all the monitoring and piloting of the aerostat. The nominal control center (CCB) uses 2GHZ link to communicate with the ITAC module, and an Iridium link module to communicate with the ULIS module. The CCB manages independently the command control of ITAC and ULIS modules. In case of failure of one chain, piloting the aerostat by the other chain is possible.
- In case of a transatlantic flight, the nominal control center (CCB) uses also an Iridium link to communicate with the ITAC module, and an Inmarsat modem to communicate with the ULIS module.
- The safety control center (CC-SVG) that uses only the Iridium link with the ULIS module and allows to pilot the aerostat as well. It is used only in case of a CCB failure.
- The EG TM computer monitors the envelope gondola localization.
- The power supply of the CCB and CC-SVG is designed to be fail-safe.
- The 2 GHz terminal ensures the link communication with ITAC module using 2GHz. In case of failure on this terminal, the CCB may pilot the aerostat by iridium link with NSO ULIS module.
- Internet network is used to receive localization of NEV gondola and meteorological data. It is also used for the communication with remote TTC station when needed.
- Internet network is also used for an additional telecommunication link in Inmarsat for the transatlantic flight
- "Meteo externe" is a computer dedicated to the trajectory forecast as a back-up to the CCB

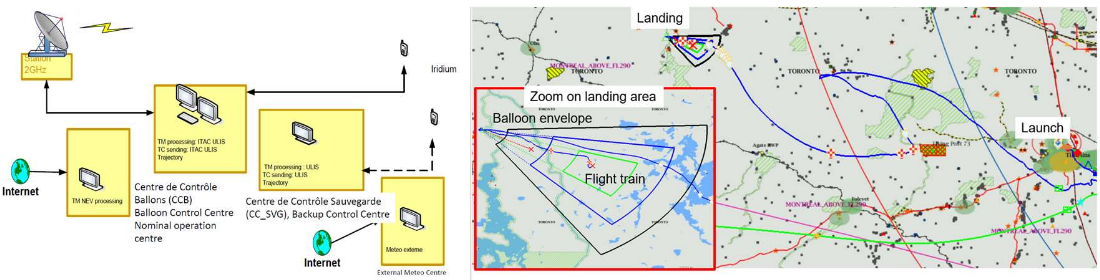


Fig.2: The ZPB ground segment, and the flight monitoring cartography

The ground segment architecture is fail-safe due to the two control-centers: CCB and CC-SVG. They can control and command the aerostat independently with independent software or critical software.

For the negative chronology, lasting about 4 hours, and the launch operations on the launch pad, a team of 9 persons is mobilized. Their functions are launch manager, controller, release vehicle driver, video technician, two payload operators, two inflation technicians, and housekeeping gondola operator.

The control centre is until now installed in line of sight of the launch pad to monitor the negative chronology and the whole flight. It is operated by an operation manager (or pilot), assisted by a meteo expert and an on-board / ground interfaces engineer. The whole campaign, and the flight operations, are under the responsibility of the CNES mission manager. During a ZPB campaign, up to 180 people (CNES staff, local staff, scientific teams) participate on site.

3.1.2. The ZPB payload gondola services:

We give below a description of the generic gondolas that CNES can provide to users wishing to fly instruments on ZPB flights.

The HELIOS gondola, shown in fig.3, is built from steel struts and balls can carry equipment on the floor or in the walls of the structure. It weighs 90 kg and can carry payloads of up to 180 kg. It measures 2.06 m x 1.43 m x 1.44 m and is designed for easy integration of medium-sized instruments.

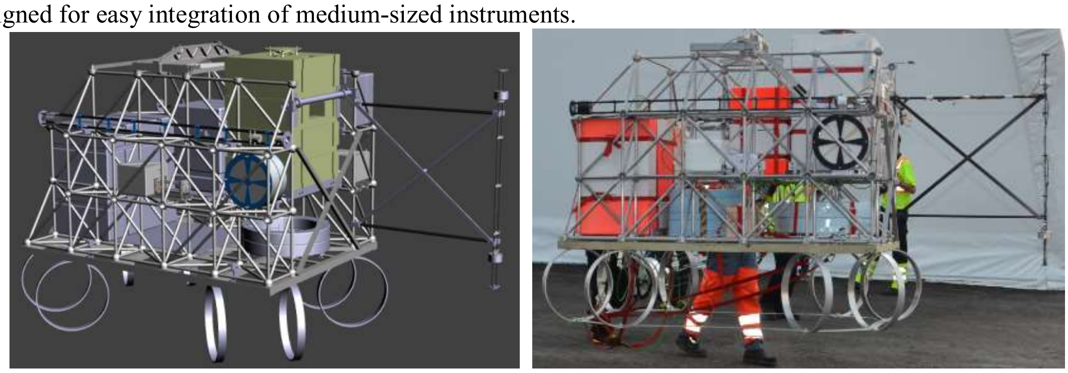


Fig. 3: The Helios gondola

The CARMENCITA gondola, shown in fig.4, is also constructed from struts and balls. It weighs 190 kg and is able to carry payloads of up to 410 kg. It measures 2.45 m x 1.85 m x 2.20 m and its upper metal beam is able to include a pivot for azimuth pointing.

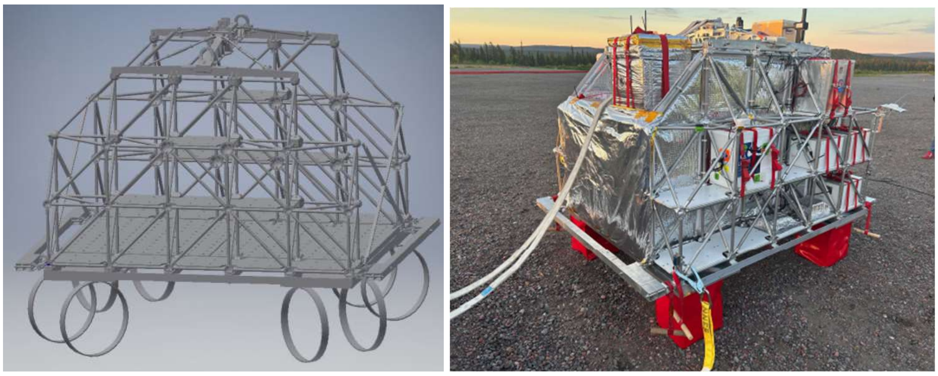
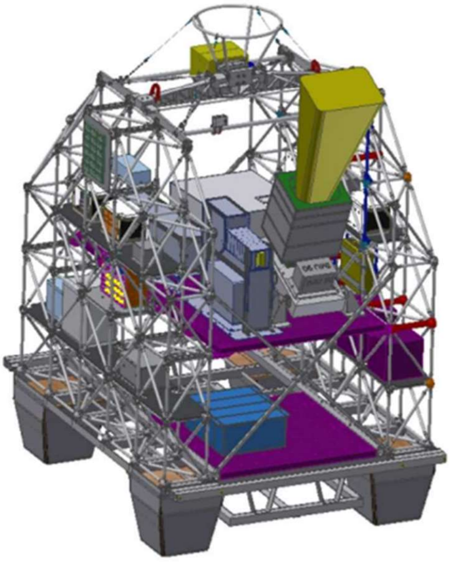


Fig.4: The Carmencita payload gondola

The CARMEN gondola, shown in fig.5, is suitable for larger payloads (total capacity of 4.7 m^3). This structure of struts and balls is particularly appropriate for experiments requiring pointing. With a size of 2.45 m x 1.85 m x 3.0 m and weighing 210 kg on its own, it can carry payloads for a total of 700 kg.



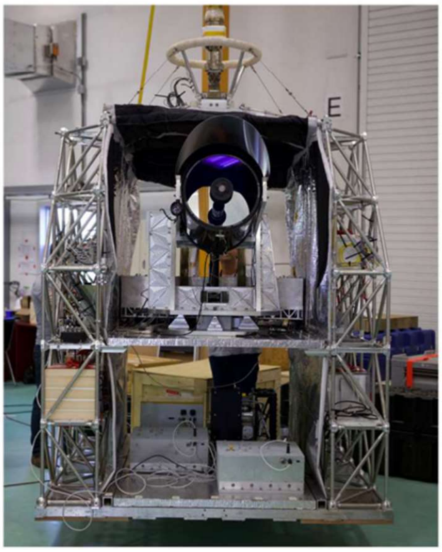


Fig. 5: The CARMEN payload gondola

CNES payload gondolas provide varied services to the on-board instruments, such as
- Power supply, through Li-ion batteries (32V, 25V, 1000 W), rechargeable via on-board solar cells panels
- Thermal control
- Axis command, control in position and velocity, elevation primary pointing with10 arc minutes' accuracy, field derotation, opening and closure of doors and covers on-board
- Sensors like an inertial measurement unit (IMU) including accelerometers and fiber optics gyros (FOG) to measure the accelerations and angular velocity of the platform and stellar sensors for fine attitude restitution. CNES has developed the ESTADIUS stellar sensor to measure the platform attitude even during daytime in the stratosphere.
- Azimuth orientation and pointing of the gondola, using a pivot, a gyro and a magnetomer, yielding a 1 arcminute stability
- Fine pointing, 2-axis orientation and stabilisation of the payload, using fine pointing actuators (inertia wheels, gyro) and sensors (ESTADIUS, instrument camera in line with the instrument). The pointing accuracy obtained is better than 1 arcsec.
- Providing mission parameters to the scientific team, to ease their operations, like sharing the date, location, of inertial or solar pointing, piloting of the payload attitude.

3.2 Some recent CNES ZPB operation campaign

From 2018 to 2024, CNES carried out 6 ZPB operation campaigns, involving each 3 to 5 flights. Also see [5]. The table 1 below gives the summary of the content of these campaigns:

Table 1: CNES ZPB campaigns from 2018 to 2024

Year	Launch Base	Number of ZPB flights	Flight names	Launch dates	Volume of balloons (m3)	Number of payloads	Helium used (m3)
2018	Timmins, CAN	5	CLIMAT, SPECIES, CABUX, AIRBUS, FAST	August 10, 16, 19, 22, 25	1 x 100.000 m3, 3 x 150.000 m3, 1 x 400.000 m3	26	16000
2019	Timmins, CAN	4	CABUX; LIFE, SUPER BIT, PILOT	August 26, September 1, 20, 24	1 x 100.000 m3, 2 x 400.000 m3, 1 x 800.000 m3	15	21000
2021	Kiruna, SWE	4	HEMERA 1, XENON, HEMERA 2, SUPER CLIMAT	August 12, 16, 22, 23	3x 150.000 m3, 1 x 400.000 m3	21	13000
2022	Timmins, CAN	4	CALASET, SOLAR, HEMERA 3, IFTS	August 12, 17, 21, 23	1x 150.000 m3, 3 x 400.000 m3	25	13500
2023	Timmins, CAN	4	COMICSn BESAFE, HICIBAS, Pré-TRANSAT	August 8, 15, 22, 27	2x 150.000 m3, 2 x 400.000 m4	19	13371
2024	Kiruna, SWE	3	SAPHERALLER, TRANSAT, ATMOSFER	August 12, 22, 27	1 x 100.000 m3, 1 x 800.000 m3, 1 x 150.000 m3	27	10093

The payloads weighed from 1 kg to 550 kg. The heaviest payload gondola was the one of the PILOT submillimetre telescope, with 1060 kg, launched in 2019.

The two main mission profiles that can be provided to users are a constant level flight, with a specific duration, or a piloted slow descent from the float altitude to the lower stratosphere (typically from about 37 km down to 13 km). CNES can also provide a combination of constant level flights at several levels and slow descent in between.
Some examples of the mission profiles are provided in fig. 6, 7, 8 below:

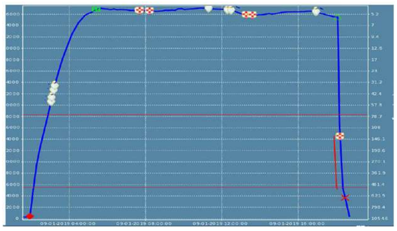


Fig.6: LIFE 2019, constant level flight around 37 km

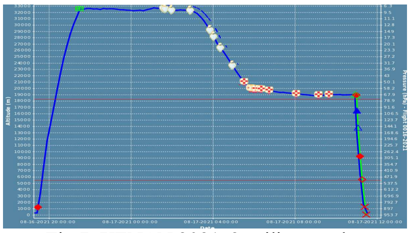


Fig.7: XENON 2021, 2 ceilings and a piloted slow descent

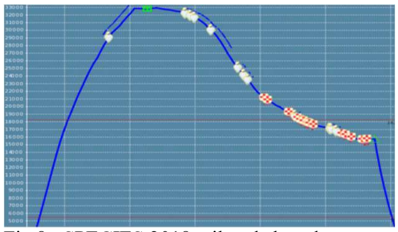


Fig.8 : SPECIES 2018, piloted slow descent

3.3. The ZPB TRANSAT 2024 flight

CNES decided to organize its first ZPB transatlantic flight in 2024 to demonstrate the capability to extend the flight duration of the ZPB up to several days, to comply with the scientific requirements of some astronomy missions like BISOU, currently in phase A study.
The objective was then to launch from the Esrange site in Kiruna Sweden, 68° North, and to fly at a constant level around 40 km in altitude at least 3 to 4 days, with a 1-ton range payload gondola, and to smoothly recover all the flight items in northern Canada.
Due to flight physics constraints for an open balloon, this ZPB configuration could only fly at constant level on such long duration at the summer solstice period. That is why the CNES TRANSAT operation campaign was scheduled on June 2024, all the more so as at that time of the year, the stratospheric winds blow from East to West.
Two other short ZPB flights were performed by CNES for scientific purposes, during the Transat campaign, namely SAPHERALLER (4 instruments for aerosols and particles measurements), and ATMOSFER (14 instruments, hygrometers, particles and radiations), but we will detail more deeply the transatlantic flight.

The current ZPB system configuration described above had to be adapted for the Transat flight as follows:

- To cope with the range limit of the ITAC S-Band link, a ground station was settled down in Greenland (Kangerlussuaq) to complement the one in Kiruna. It guaranteed a housekeeping link coverage for the populated areas of the south west of Greenland, and to give the scientific users a high rate real time telemetry link to download their data without waiting for the end of the flight and the recovery.
- The housekeeping gondola was the same as usual but had two more communication links (Iridium in the ITAC module and Inmarsat in the ULIS module); The nominal control centre (CCB) used thus also an Iridium link to communicate with the ITAC module, and an Inmarsat link module to communicate with the ULIS module.
- The Inmarsat antenna was installed on the tore of the 100 ft parachute.
- Two Infrared measurement devices were added for flight physics purposes, to confirm the need to ballast in very cold conditions cases.

The TRANSAT flight segment was composed of an 800 000 m3 balloon envelope, the flight train and operational gondola described above, and was carrying a 900 kg payload gondola, including 9 instruments from 4 countries, France, Sweden, Canada, and Germany.
The list of instruments was the following, mainly dedicated to atmosphere study measurements:

- For France, Species, an absorption spectrometer for greenhouse gases (CNRS LPC2E), Comcube, a Compton telescope (CNRS-IJCLab), a GNSS receiver, and CERBUS, for radiation tests on electronics substrate.
- For Sweden, NLC/Infrasound, for the study of noctilucent clouds and infrasounds
- For Canada, Calaset, a laser spectrometer, and Osiris-3, an optical spectrometer
- For Germany, Gloria-lite, a pointed Fourier transform spectrometer, for atmospheric components measurements (Karlsruhe Institute of Technology)

The CAD view of the CARMEN gondola is given in fig.9 below, as well as a picture of the real hardware, on the launch pad in Esrange.

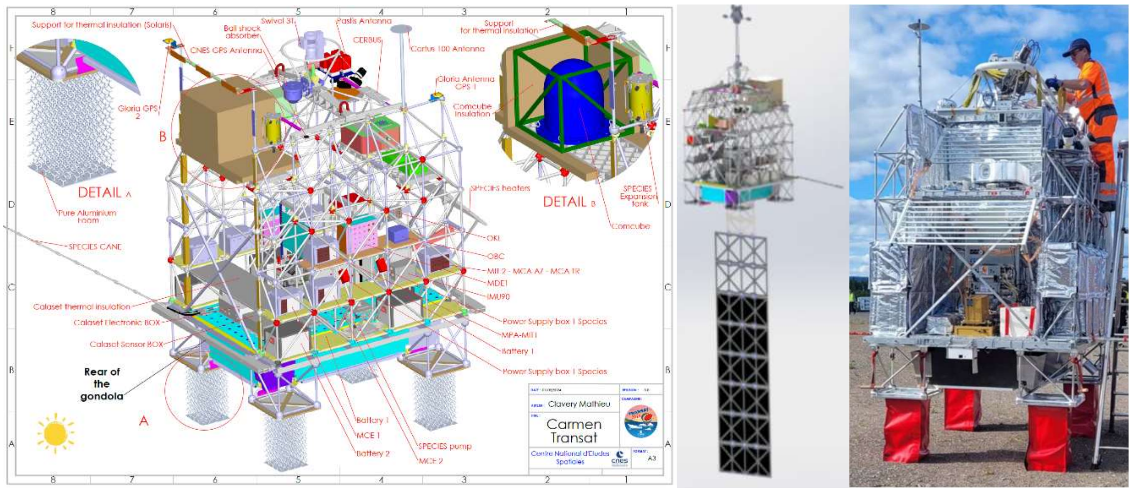


Fig.9: The CARMEN Gondola CAD, details, with MEDOR solar panel deployed, and on the launch pad
(Credit R. Gaboriaud, Prodigima, 2024)

The flight authorizations for Transat were obtained from the varied countries involved: In France, the CNES operator's country were the balloon was matriculated, the CNES Safety department and the DGAC representing the European authority EASA, gave the exploitation authorization. Also SSC (Swedish Space Corporation, site authority in Esrange) coordinated the flight authorization from Sweden, Norway, and Finland. French Foreign Affairs ministry helped getting the authorization from Iceland, and Denmark for the overflight of Greenland, and our partners of the Canadian Space Agency (CSA) assisted to get the flight and landing authorizations in Canada.

The launch, operated by CNES, took place from Esrange, in the framework of the EASP PAC agreement of ESA, on June 22nd, 2024.

The 3 days and 17 hours' flight was successful, as well as the recovery in the Baffin Island, at 71 °North, on June 27th, coordinated by the CSA.

Pictures of the launch, of the flight, and a synoptic view of the trajectory are given in fig.10, and picture of the recovery are given in fig.11 below:

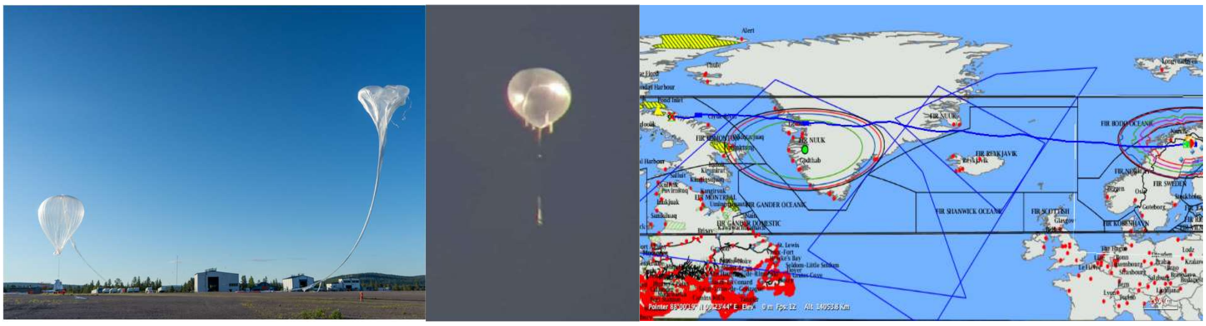


Fig. 10: Launch (Credit R. Gaboriaud, 2024) and balloon at ceiling (40 km), and synoptic of the flight trajectory

Fig. 11: CARMEN gondola and flight train recovery in Baffin Island, Credit N. Bray, CNES, 2024

4. The SPB system and the STRATEOLE 2 operational campaigns

For missions requiring long duration flights, CNES has developed a super pressure balloon vehicle, and all the related on board and ground system, allowing flights of 25 kg payloads in the lower stratosphere for up to 3 months.

The system is currently used for the STRATEOLE 2 programme, led by French LMD of CNRS, with the participation of US payloads founded by the NSF (National Science Foundation). The project is aiming at the study of the equatorial air masses content and transport in the lower stratosphere in relation with climate change.

We present below the observation system, and the main results of the two operational campaigns already achieved in 2019 and 2021, see more in [1], [3], [4], [6]. One last scientific campaign is in process of preparation at CNES and CNRS, scheduled for late 2026, with 22 flights.

4.1 The SPB system

4.1.1. The SPB vehicle

Super Pressure Balloons are sealed spherical balloons, typically up to 13 meter in diameter. The closed and stiff envelope of these balloons means they rise and expand to their full volume where the gas density matches the density of the surrounding air, and drift with the wind along constant density surfaces, roughly speaking at constant altitude.

Pending a high quality manufacturing process, (no pinhole accepted!) and carefully handling and conditioning for ground transport, these small balloons can fly during typically 2 to 3 months, carrying an overall 40-50 kg suspended load, and flotilla of 20 to 25 balloons can be deployed. They thus allow "quasi Lagrangian" observation of the lowermost stratosphere and are acting as observation platforms for remote sensing of the troposphere.

Being far smaller than the ZPB, they need mobile and lighter launch infrastructure and staff, as shown in fig.12 below:

Fig.12: SPB ready to launch, Credit: R. Gaboriaud, Prodigima, 2019

4.1.2. The SPB system

The CNES SPB system meets the same safety standards as the above described ZPB system, since the SPB is considered as potentially lethal for ground populations. This means that it shall fully meet the criteria that no single point failure might lead to potentially catastrophic event and the compliance with that criteria shall be extensively documented. Thus, the on-board software is developed with "safety critical validation rules", like on ZPB. A secondary flight control command is implemented through a dedicated telecom link, using Inmarsat SBD for Strateole-2. Also the flight Control Centre is redeveloped, meeting the above failure tolerance criteria and using Iridium RUDICS service as the nominal communication link.

Lessons learned from previous SPB campaigns like Concordiasi 2010, showed that several electronic components (RAM…) are sensitive to the atmospheric radiation environment, causing many transitory or permanent interruptions of the control boards for power or payload management (once per week…). The new design implements more radiation tolerant electronic components, software protection for critical data, and equipment are validated in radiation chambers. On several Concordiasi flights we also experienced loss of solar power slightly before the specified 3-month duration. New more enduring (UV) solar panels, and with a better power/weight ratio were qualified. These solar panels and the energy management system, developed by CNES, are used both for the EUROS operational gondola, and ZEPHYR, the payload gondola.

On the ZPB system, reusability was the main design driver, whereas on the SPB system, special care has been given to minimizing the mass with an overall suspended weight at hook target of 42 kg, with a 10 kg mass allocation to scientific instruments.

For Strateole-2, it has been decided to fully segregate the flight control system from the payload system:

The CNES flight control system is composed of the EUROS gondola, two control centers located in Toulouse and in Aire-sur-l'Adour, France, the CNES operational staff.
The Science Payload System is composed of the ZEPHYR gondola, the ZEPHYR Mission Control Centre in Paris, and scientific laboratories operational staff.
The flight segment is shown below in fig. 13:

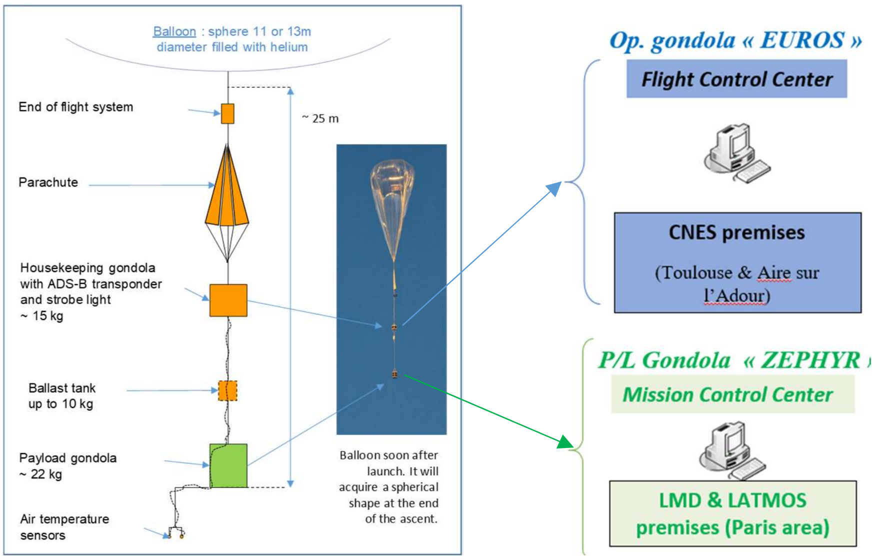


Fig.13: The STRATEOLE 2 flight and ground segments

4.2 The STRATEOLE 2 project and the 2019 and 2021 flight campaigns
4.2.1 The STRATEOLE 2 observation system:
Table 2 below gives the list of the instruments participating in the STRATEOLE 2 observing system:

Table 2: The STRATEOLE 2 scientific instruments

Instrument name	Measurement
GPS	Wind at balloon flight level
TSEN	Air pressure and temperature at balloon flight level
RACHuTS	Vertical profiles of air temperature, water vapour and cloud detection, up to 2000m below the balloon
FLOATS	Vertical profiles of air temperature, up to 2000m below the balloon
BOL-DAIR	Upwelling infrared flux
SAWfPHY	Water vapour, through "frost point" technique, at balloon flight level
pico-SDLA	Water vapour and carbon dioxide, through laser absorption, at balloon flight level
B-Bop	Ozone concentration at balloon flight level
LOPC	Cloud aerosol counter at balloon flight level
LOAC	Cloud aerosol counter at balloon flight level
BeCOOL	Cloud detection by Lidar, up to a few kilometres below the balloon
ROC	Atmospheric sounding through GPS Radio-Occultation
VATA	Wind speed
BIS	Infrasounds
X-STORM	High energy particles
RIP	Electrical field

4.2.2. The STRATEOLE 2 2019 and 2021 flight campaigns
A validation campaign was conducted, with the dual purpose of validating the CNES system and the science system. A unit of each one of the flight configurations was flown. The launch campaign took place in 2019, from Mahé, in the Seychelles Islands. This flight validation campaign was a great success: The 8 balloons, launched from

November 11th to December 6th 2021, achieved a total of 680 days of flight, an average of 85 days per balloon, and a record of 107 days for the longest duration!
Circling the world, the balloons overflew 63 countries among the 96 possible on their track.

Both the housekeeping system and the payloads were validated, pre-STRATEOLE 2 data were used by ESA to calibrate the AEOLUS satellite wind lidar measurements, several publications were issued, and the system was declared qualified for te scientific campaigns.

The 1st scientific Campaign of 2021 began in Mahé, Seychelles, on September 23rd by the installation of two tents for balloons and gondolas preparation and 5 offices, and the preparation of all the ground means for AIT and the control centres. The first SPB was ready to fly on October 11.

We had to cope with the 4 to 5 night slots per week given by the Victoria airport authority, that lasted between 1,5 and 8 hours depending on the day and the month (according to the number of aircraft, that increased towards the end of the year). 17 launches were carried out from October 19 to November 25, i.e. an average of 3 launches per week as foreseen, thanks to 5 “double launches” during a launch window given by the airport.

Regarding the weather at ground, we experienced a “dry” season compared to usual climatology, but 50% of the airport slots could not be used mainly because of surface winds. Among the 17 flights, some balloon envelope failures occurred quite early during the campaign, and balloons were then (partially) controlled on the launch table before launch. The failures proved to be due to a degraded quality in the manufacturing and conditioning processes of the three-laminated envelope material. The rest of the system, ground and onboard, and the operational procedures functioned perfectly.

To give figures, the balloons yielded a total of 632 days of flight, an average of 42 days per balloon. The longest flight lasted 71 days. See the trajectories in fig.14.

The fact remains that this campaign was a scientific success despite the shorter average durations of flights, as unique data were retrieved regarding the winds, the greenhouse gases concentrations, the air temperature and pressure, in the lower equatorial stratosphere. In particular, temperature and pressure data could be assimilated in real time in the MeteoFrance Arpege model, and the results are quite promising.

Also the fine air pressure variations measurements with the onboard ultra-accurate barometer allowed to detect the impact of the Hunga Tonga volcano activity during the period, paving the way to detection of seismic activity from the stratosphere (see Work by Garcia and Al., ISAE).

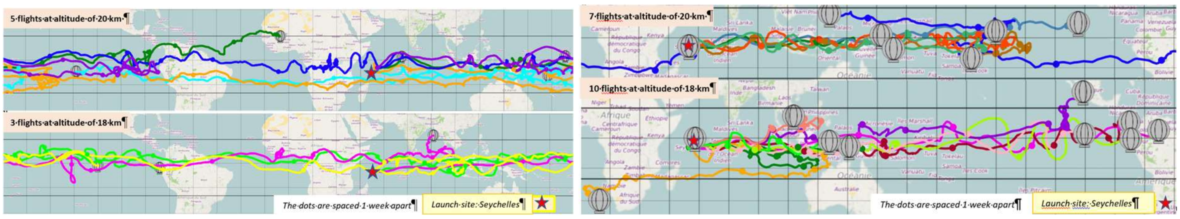


Fig.14: Trajectories of the Strateole 2 validation 2019-20 and scientific campaign #1 2021-22

4.2.2 Operations management

Regarding the operations, two phases have to be staffed during this kind of long duration campaigns:

- The first phase corresponds to the launch campaign operations, that last around two months, on site in Mahé, Seychelles, to prepare and launch up to 20 balloons, and monitor each of them until it reaches its float altitude and working overpressure of the envelope,
- The second phase is the flight monitoring of the balloons flotilla from remote, from the redounded control centres in Toulouse and Aire sur l’Adour, for about 2 to 3 months more. Nominally, the inflight operations are carried out during working hours, and a system with automatic alarms on abnormal values of parameters (overpressure, altitude, battery level, electronic temperatures, etc.) is active 24 hours a day.

The operation team for the monitoring of the flights was composed as follows:
A mission manager and a deputy (2 people) for the general flight management and interfaces with the scientific Principal Investigator. The flight management was performed daily by a flight manager (RDO) and a control center operator (OCO), ten people have held each of these positions. Then some experts came in support of the operation pair, namely the Flight physics expert (EPV, 7 persons held this position), the on-board / ground interface expert (ECC, 4 persons), the onboard segment expert (5 persons), the ground segment expert (4 persons):
A pair RDO & OCO was on duty 6 days a week, during working hours, and another RDO & OCO pair replaced them for the 7th day, and on-call duty to solve potential anomalies (24 hours a day, 7 days a week)

Daily operations consisted on:
- Controlling the EUROS gondola good health, battery state of charge, daytime functioning of solar panels
- Checking the update of the website of balloon trajectories, for consultation by the ATC authorities of overflown countries, control of the balloon positions, automatically updated hourly, analysis of trajectory forecast, updated every 12 hours, eventually giving information to ATCs or French Embassies about an upcoming over flight.
- Paying special attention to balloons whose planned trajectory takes them outside the authorized area
- Telemetry recovery not nominally transmitted and solving of potential anomalies
- Configuration changes command

With a first release on November 11, 2019, the flights of the validation campaign were controlled for about 3 months, 7 days a week and 24 hours a day: A total of 26 CNES people were involved, some of them fulfilling several functions.

5. The SB system and operations

With the help of the miniaturization of electronic systems, instruments weighing less than 3 kg can now accurately measure the atmospheric content of greenhouse gases and aerosols under small balloons, and contribute to the study of climate change. Micro hygrometers, particle counters (LOAC), pico SDLA spectrometers, or AIRCORE air samplers are now qualified to fly in the stratosphere and calibrate satellite data. Also see [2].

The advantage of light payloads, is the possibility to fly them under light balloons systems, according to the ICAO rules: Being non-lethal, the flight train can descend anywhere under a parachute, even among populated areas, and the housekeeping system can be very simple, no radar transponder, nor remote control of the balloon is required.

Thus, SB, latex light balloons, capable of carrying 4 kg at an altitude of 35 km before burst, are a means increasingly used by CNES and the CNRS during regular scientific measurement campaigns with the instruments listed above. The SB flights are carried out in particular from the CNES balloon operations centre in Aire sur l'Adour and from other CNRS sites in France.

The SB are also suitable for technological tests in the stratosphere of small instrumental systems, in particular developed by students who are then trained to space technologies at low cost. CNES has launched more than 200 sounding balloons from Aire sur l'Adour since 2018, and 30 of them were performed by CNES in 2024.

Up to now, the SB mission profile consists in a 1,5 to 2 hours' ascent at 4 to 5m/s, up to 25 to 35 km, then the envelope bursts and the payload descends in less than one hour under a parachute. The payload can perform measurements during ascent or descent.

See below a picture of an SB launch, and a flight profile, in fig.15.

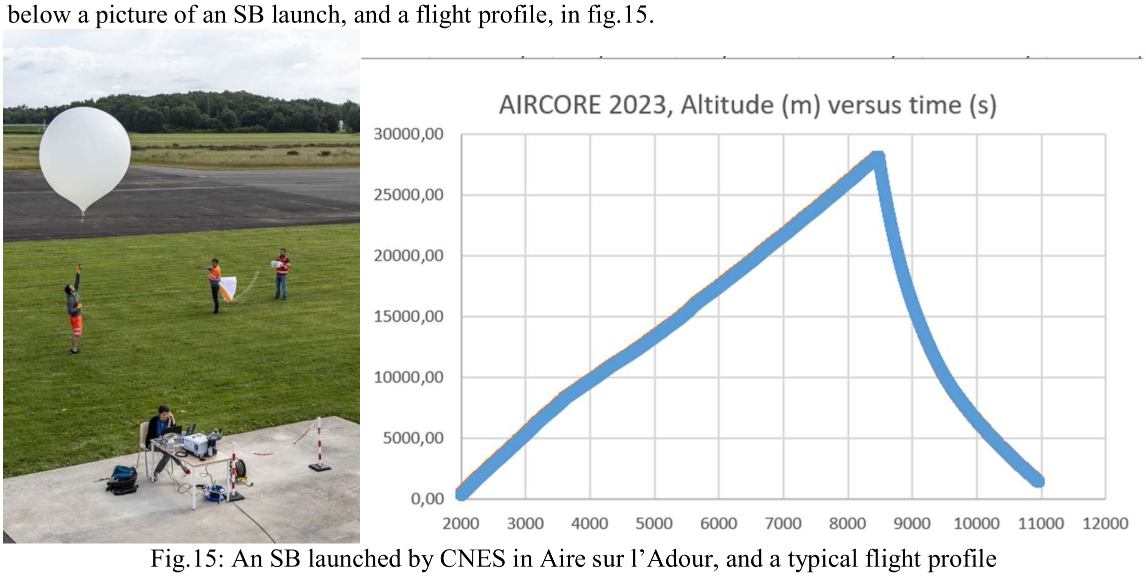


Fig.15: An SB launched by CNES in Aire sur l'Adour, and a typical flight profile

6. The BALMAN steerable balloon:

CNES and HEMERIA have been working for three years on a major innovation, aiming at giving the capability to a simple balloon to be steerable and to follow a controlled trajectory to go from one point to another, or to remain overflying a dedicated area. The first steps of the project have been funded by the France Relance government initiative and by CNES Defense credits.

This bi-balloon is consisting of a pressurized pumpkin balloon filled with air, of about 25m in diameter, containing a helium ballonet. The vehicle is capable of controlled vertical excursions between 16 and 22 km, to use the stratified winds of the stratosphere, variable in directions and velocity, to move towards a target area and to stay there sustainably.
It is the increase of the mass of air sucked through an on-board compressor that allows the balloon to go down (it is heavier), and the venting of this air that allows it to ascend (it is lighter), see the principle below, in fig.16, 17, 18.

Fig.16: BALMAN ground test

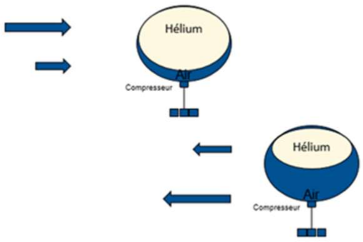


Fig.17: The operating principle

Fig.18: The BALMAN maiden launch

This "persistent" balloon, whose concept has been proven by the Google's Loon project, paves the way to new scientific and technology applications, as well as Earth observation high resolution imagery, civilian and defense security and surveillance. Today, the manufacturing process has been validated, the subsystems have been qualified at ground, and the launch procedures have been defined.
The housekeeping system is up to now the EUROS system, also used on the CNES SPB flights.
The first technological flight, operated by CNES, was successfully performed in October 2024 from the Kourou spaceport, in French Guyana. It allowed validating the ascent phase of the bi-balloon, the end of flight activation, and the drift descent of the balloon system. Both the envelope and the flight train were recovered in the ocean, close to the Salvation Islands.

7. Ballooning and sustainability

The balloon activities have several advantages regarding reduced environmental impact, and can for sure contribute to sustainable space projects.

First, the majority of CNES balloon campaigns are dedicated to improve our knowledge on atmospheric chemistry, physics and dynamics, to better model, survey and understand climate change.

Balloons are a unique tool to make in situ measurements in the stratosphere and to calibrate and validate environmental satellites like IASI, OCO, ESA Sentinels, and soon MICROCARB and Earthcare.

Moreover, the majority of the balloon systems are recovered after flight, and the flight trains, instruments and gondolas are repaired and reused from one campaign to another.

Also, the balloon gondolas and payloads do not need to be integrated and tested in expensive clean rooms, and balloon flights provide zero CO2 emission.

CNES has a strong will to work for a sustainable space, and balloon missions, being with low environmental impact, will be more and more considered as alternatives to space mission, when the mission can be achieved from a balloon. As every project has to make efforts in favour of sustainability, the CNES balloon department tries to reduce the launch campaigns impacts, through the following measures:

- Limiting the ground, air and sea transportation of hardware to the launch sites, by procuring the services needed on site (Gas trailers, secured power supply, Launch means…) instead of bringing them from France.
- Making all efforts to recover all the flight items, even at sea. The availability of more steerable vehicles, like the BALMAN, should ease the recovery of long duration balloons.
- Considering the reuse of hydrogen as lifting gas, instead of helium. Working groups, CNES internal and with international partners are studying the matter, and a field test is already foreseen in 2025.

8. Conclusions

Since 2018, CNES and its partners (SSC, CSA, the scientific labs) have successfully implemented 6 ZPB scientific campaigns in Timmins and Kiruna for the French, European and Canadian scientific communities. CNES has succeeded in expanding its ZPB balloon offer by achieving a first transatlantic flight between Kiruna and northern

Canada in late June 2024. Meanwhile, CNES, AEB (the Brazilian Space Agency) and the University of Tocantins have identified an equatorial site in Palmas do Tocantins (10°South) to settle down a new launch base.

The next ZPB campaigns will take place in Timmins (2025) and possibly from Brazil in 2026-2027.
The STRATEOLE 2 validation and 1st scientific campaign have been conducted using SPBs, first scientific results have been published. The 2nd scientific campaign is foreseen in late 2026, again from the Seychelles Islands.
To prepare the future, a deep renovation of the ground and on-board means are in progress for the next 4 years, based on COTS equipment qualified to be usable by all the CNES balloon systems.

Several studies are also underway to increase the performances of the SPB in terms of payload mass, higher flight altitude, longer duration, and trajectory piloting. In particular, the BALMAN, the French steerable balloon, developed with HEMERIA, has passed its maiden flight, and should open new applications and new markets to the stratospheric balloons family.

References

[1] L. Kalnajs, Albert Hertzog, Philippe Cocquerez, M. J. Alexander, Sean M. Davis , T. Deshler , Georges Durry , J. S. Haase , Alain Hauchecorne, Riwal Plougonven, François Ravetta, Jean-Baptiste Renard, Stephanie Venel: Stratéole 2: An Ultra Long Duration Super Pressure Balloon Campaign to Study the Equatorial Upper Troposphere and Lower Stratosphere (insu-02062318)

[2] M. Ghysels, G. Durry, N. Amarouche, J. Cousin, L. Joly, E. D. Rivière, L. Beaumont, A lightweight balloon borne laser diode sensor for the in situ measurement of CO2 at 2.68 µm in the upper troposphere and the lower stratosphere, Applied Physics B, Volume 107, Issue 1, pp 213-220, DOI: 10.1007/s00340-012-4887-y (2012)

[3] A. Hertzog, How can we improve the driving of the Quasi-Biennial Oscillation in climate models? J. Geopshys. Res.-Atmos. 2020

[4] A. Podglajen, et al., Stratospheric Balloon Observations of Infrasound Waves From the 15 January 2022 Hunga Eruption, Tonga, Geophys. Res. Lett., 2022

[5] V. Dubourg, S. Louvel, S. Venel, F. Vacher, A. Deschamps and al., French Balloon Activities 2022-2024: National Report, 45th COSPAR Assembly 2024, Busan, Korea.

[6] S. Venel, Philippe Cocquerez, Albert Hertzog, Riwal Plougonven, Eric d'Almeida, CNES super pressure balloons upgrade for STRATEOLE-2 campaign, ESA Symposium on rockets and Balloons, Visby, 06/2017.