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Abstract DUSTER (Dust from the Upper Stratosphere Tracking Experiment and Retrieval) is an instrument designed to collect nanometer to micrometer scale solid aerosol particles in the upper stratosphere on board balloons. With three DUSTER flights we have demonstrated that: (1) the instrument's performance was within the design parameters of environmental specifications (-80 °C; 3–10 mbar); (2) inertial impact collection of aerosols ~ 500 nm to 24 microns on holey-carbon thin films mounted on Transmission Electron Microscope mesh grids was achieved; (3) the design of an active collector exposed to the air flux and an identical collector "blank", not exposed to the air flux, to monitor possible contamination permits unambiguous identification of collected particles; (4) save storage of collected samples and subsequent retrieval in the laboratory was achieved with no measurable contamination; (5) reduced sample manipulation allowed the chemical and structural characterization of collected dust particles by Field-emission scanning electron microscopy and energy dispersive X-Ray analyses, and infrared and Raman micro-spectroscopy.

The main and most ambitious goal is the collection and characterization of solid aerosol particles smaller than 3 microns of solar system debris that are currently not sampled on a routine basis by other instruments in the upper stratosphere. DUSTER will provide a record of the amount of solid aerosols, their size, shapes and chemical properties in the upper stratosphere, including particles less than 3 microns in size. The DUSTER program identified 25 particles as collected during the 2008 flight with sizes in the range of 0.4 to 24 microns.

Keywords Balloon Borne collectors · Extraterrestrial dust · Solid aerosols · High stratosphere

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1 Introduction

Solid and condensed sub-micrometer particles present in the stratosphere are a mix of terrestrial and extraterrestrial materials. The region of the upper stratosphere is thought to be favoured by the extraterrestrial component while volcanic ejects are more prevalent in lower stratosphere. Only routine dust collection campaigns would confirm this scenario. To this purpose we developed an instrument that can collect in situ, uncontaminated, submicron particles from the upper stratosphere for laboratory analyses. In a brief summary of extra-terrestrial material entering the Earth's atmosphere it follows that this dust size fraction is the most abundant (Hughes 1994). Solid objects, viz. asteroids and comets and their debris, continuously cross Earth's orbit. Depending on their original size, structure and composition, they can: (1) survive reaching the Earth's surface (meteorites, size 1 to 10^5 m) leaving vaporized/condensed matter behind in the atmosphere; (2) produce very bright meteors during their atmospheric passage, called "fireballs" (meteoroid size 10^{-1} to 10 m) or meteors (meteoroids, size 10^{-3} to 10^{-1} m), that leave fragments of the incoming objects as recoverable micrometeorites and meteorites and (3) form a steady rain of interplanetary dust particles (size 10^{-3} to 10^{-8} m) (Hughes 1994). During atmospheric deceleration, meteoroids are ablated in the upper mesosphere. The incoming particles evaporate due to atmospheric friction in the altitude range of 70–110 km (Ceplecha et al. 1998). Dust with a wide range of sizes will form distinctive dust layers that can be traced settling through the atmosphere by Twilight optical detection (Mateshvili and Rietmeijer 2002; Kumari et al. 2005), or by LIDAR (Klekociuk et al. 2005). This dust is likely to have atmospheric residence times of weeks to months. In the past only very few attempts were made to use balloon-borne collectors to sample the condensed aerosol and solid dust in the upper stratosphere, at altitudes higher then 30 km (Soffen 1965; Testa et al. 1990; Wainwright et al. 2003). However, these collections left open several issues on the characterization of micron-size and smaller grains because of the then available analytical techniques and issues on contamination control (e.g., assembly and disassembly procedures, balloon self-contamination control), small sampled air volumes, and lacking compositional data on the collections performed for research such as exobiology aims. The impact-collection technique allows information on stratospheric particles that is not provided either by optical particle counter (e.g., Rosen 1964; Hofmann and Rosen 1977; Renard et al. 2010) and by high volume filter samples (Wood 1964). Nevertheless experiments that used optical counter technique showed limitations in collecting small particles and sampling sufficient volumes of air to collect large (>2 microns) particles. LIDAR and satellite measurements (e.g. Vaughan and Wareing 2004; Hofmann et al. 2009; Bingen et al. 2006) are generally not calibrated by data coming from dust morphological and compositional characterizations. In general the properties of solid and condensed dust in the upper stratosphere remain poorly known. Complete morphological and chemical characterization of particles collected at altitudes >30 km remains incidental with few exceptions, among others, the collection campaigns in May 1985 by Testa et al. (1990) with transmission electron microscope particle characterization (Rietmeijer 1993). Collections of extraterrestrial particles in the upper lower stratosphere will complement the existing high-flying aircraft collections at lower altitudes for particles $\sim$3 microns and larger (Rietmeijer 1998). A laser ionization mass spectrometer carried aloft into the upper troposphere and lower stratosphere by these NASA aircraft flights was used to characterize particles ranging from 0.2- to 3 micrometres in diameter (Murphy et al. 1998). They found evidence for meteoritic particles based on their 39K/23Na ion ratios. Despite the higher than chondritic Na/Fe, and lower Mg/Fe and Ca/Fe, ratios of these stratospheric particles these chemical signatures still were within the range of surviving meteor particles from a reservoir in the mesosphere (Cziczo et al. 2001). This reservoir also contains sub-micrometer meteoric particles that are oxidized mesospheric metals (Plane 2003) although solid evidence for these particular particles is still lacking. They and micrometre-sized aerosols from extraterrestrial sources still remain to be directly sampled and characterized. While settling from the top of the mesosphere into the upper troposphere they serve as nucleation sites for liquid aerosols and as such they may play a role in sulphate aerosol formation (Brownlee 1985) and ozone depletion through heterogeneous reactions (Plane 2003). The smallest <3 micrometre dust is mostly associated with meteoroids that deposit meteoric constituents in the Earth's upper atmosphere but meteoroids will also enter the atmospheres of Venus and Triton and conceivably those of exoplanets. The smallest dust that DUSTER will collect is relevant to solar system and exoplanet atmosphere research.

Modelling indicates that the ~0.5 to 1 µm diameter could be interstellar grains, which represent direct samples of the contemporary interstellar medium through which the Sun is moving. During a few weeks each year the Earth in its heliocentric orbit is moving away from the direction of motion of these interstellar grains through the solar system (Flynn 1997). During this period of time these contemporary interstellar grains enter the Earth's atmosphere at velocities that will prevent the grains to be heated to their melting point an could be collected when settling in the upper stratosphere. These grains are among the most ambitious targets of our collection effort.

We here describe a newly developed instrument, DUSTER, designed to collect dust in the upper stratosphere for laboratory characterization. In addition, the contamination control remains an issue of concern in every dust collection performed up to now. DUSTER was specifically designed to highly control and identify any possible contamination.

2 Instrument Design

2.1 Performances Requirements

DUSTER design was focused to create an instrument that overcomes the limitations indentified in the previous collections such as contamination control and the use of sticking material to entrap particles. To achieve this goal we developed an instrument capable of collecting refractory aerosols with diameter down to 0.2 microns at altitudes between 30 and 40 km, these altitudes are only accessible through the use of stratospheric balloons.

Particular attention was paid to select a low velocity collection method and a sample substrate that would prevent respectively modification of the collected particles and contamination.

The guidelines followed during the design of the instrument are the following:

- Cleanliness, high quality contamination control and characterization of possible contaminants;
- Limiting manipulation of collected particles and the substrates used for dust collection;
- Dust collection with low impact velocity between particles and substrate;
- The pumping system must meet the requirements of the upper Stratosphere environment.

The instrument design is compliant with different operational conditions to meet the need of collection campaigns performed at different times of the year as the different aerosol components depend on time of the year and on different geographical locations (Bigg 1976;

Table 1 DUSTER technical requirements

Mass	≤35 kg
Power	≤25 W
Envelope	$310 \times 410 \times 310\ \mathrm{mm}^3$
Operative altitude	30 to 40 km
Operative temperature	−60 to 110 °C
Particle size collected	0.2 to 40 µm diameter
Atmosphere sampling rate	$\geq 1\ \mathrm{m}^3/\mathrm{h}$

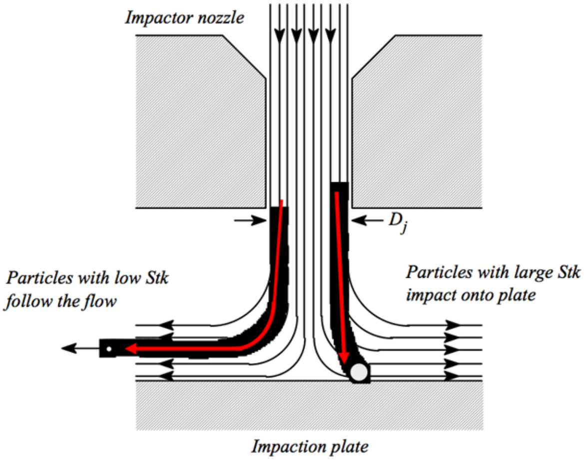


Fig. 1 A schematic view showing the interaction between air flow and mechanical elements which allows the aerodynamic separation and collection of solid phase dispersed in the gas

Plane 2003). A small, lightweight and autonomous instrument is necessary in order to have the possibility to flight as piggyback payload, and as standalone gondola.

Considering both the data obtained from satellite observations (Bingen et al. 2003) and those from previous in situ measurements and collections (Testa et al. 1990) it was possible to assess the condition of average dust loading in the stratosphere. With these data it is possible to impose a constraint on the performances for the atmospheric sampling device in order to collect a few hundred particles per flight. We evaluated, assuming a stratospheric balloon mission duration of 24 h, that a flow rate equal to 1 cubic meter per hour for the sampling system, is the minimum value necessary to obtain few hundreds of particles. The technical requirements for the instrument are summarised in Table 1.

2.2 Collecting Method

The use of balloons as a means to reach the upper stratosphere requires the use of active systems for stratospheric aerosol sampling and decoupling from the air stream. We have selected inertial-separation as our means of collection. This is a well-established technique for solid particle monitoring, which is based on the decoupling between the gas flux and particle when proper acceleration is induced in the flux. Due to inertia, a particle moving in a gas stream can strike slow-moving or stationary obstacles (impacting targets) in its path. As the gas stream deflects around the obstacle, the particle continues toward the object and impacts the collecting surface (Fig. 1).

According to impact theory, the dimensionless Stokes number, Stk, is the governing parameter for impaction and it is defined as follows:

$$\mathrm{Stk} = \frac{\rho_p D_p^2 U C_c}{9W}$$

where μ is the dynamic viscosity of the air, d_p is the diameter of the particle, ρ_p is the particle density, W is the nozzle diameter, U is the jet velocity and C_c is the Cunningham slip correction factor. The slip correction factor is given by:

$$C_c = 1 + \frac{2\lambda}{d_p} \cdot \left(A_1 + A_2 \cdot e^{\frac{-A_3 \cdot d}{\lambda}}\right)$$

where λ is the mean free path, d_p is the particle diameter, $2\lambda/d_p$ is the dimensionless Knudsen number (K_n) and A_i are experimentally determined coefficients. For air (Davies 1945): $A_1 = 1.257$; $A_2 = 0.400$; $A_3 = 0.55$. Stokes' law is a solution for the drag force (F_d) of a rigid sphere obtained by solving the Navier-Stokes equations in the viscous limit of Reynolds number $\ll 1$. The solution imposes no-slip at the particle surface and, therefore, assumes that the relative velocity of the fluid is zero at the surface. This assumption begins to break down for particle diameters several times the gas mean free path when such particles experience "slip" at their surface. In stratospheric conditions (pressure and temperature) the Stokes' law is not satisfied. By including a slip correction factor C_c, Stokes' law can be modified to apply for particle diameters on the order of the gas mean free path and smaller. Starting from the flow-rate value fixed as the minimum necessary for DUSTER and considering the smallest diameter of the particles that would be collected, the required nozzle diameter of the inertial impactor was calculated by using the Stokes number.

The smallest particle diameter that DUSTER must collect and the free mean path for the air molecule at 40 km of altitude determine the value of the Knudsen number:

$$K_n = \frac{2\lambda}{d_p} = 60$$

With an air molecule of 300 pm in diameter at a temperature of 263 K and a dust particle with a diameter of 0.2 μm the Cunningham slip factor is:

$$C_c = 100$$

Assuming a flow rate Q of 1 m^3/h, the velocity (U) of the flow in the nozzle is:

$$U = \frac{Q}{\pi(\frac{W}{2})^2}$$

imposing a Stokes number of 0.5 for the particle with diameter of 0.2 μm, we calculated the radius of the nozzle $R_{nozzle} = W/2$

$$R_{nozzle} = 0.0035 \text{ m}$$

considering a $\mu = 1.68410^{-5}$ Pas, and a conservatively assumed particle density of $\rho_p = 2000\ \mathrm{kg/m^3}$. The collecting stage was designed using a diameter of 0.007 m for the nozzle.

2.3 Collectors

DUSTER is designed to allow the collection of samples directly on substrates suitable for different analytical techniques, e.g. Electron Microscopy, Energy Dispersive X-rays analysis

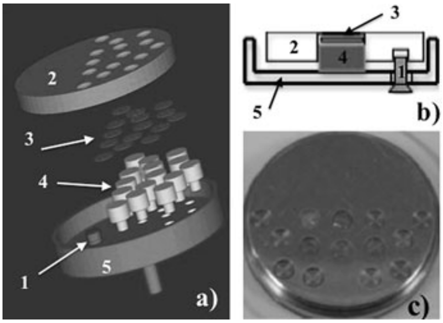


Fig. 2 Duster 2008 collector: (**a**) 3D exploded view; (**b**) scheme and (**c**) image of the assembled view. In panel (**a**) and (**b**): (*1*) screw fixing the gold plated holed mask to the external stainless steel frame; (*2*) gold plated holed mask; (*3*) Transmission Electron Microscope grids; (*4*) stainless steel pins; (*5*) external stainless steel frame of the assembly. The collector dimensions are: diameter of the gold holed mask = 23 mm, total diameter of the collector = 24.5 mm, total height of the sample holder = 16 mm, diameter of the holes in the gold mask = 2.46 mm, diameter of the TEM grids = 3.05 mm

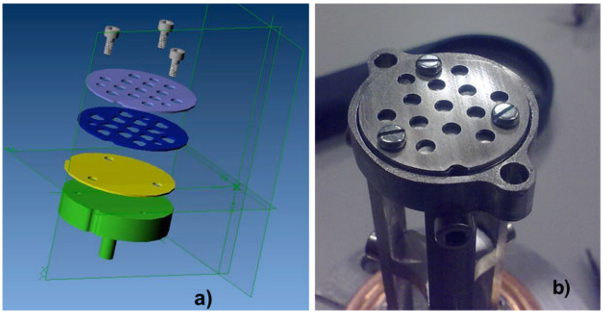


Fig. 3 (**a**) Collector exploded view. The three parts are linked together by 3 screws, once fixed with the base the holes of the first disk constitute the hollow where the TEM GRIDS will be housed, the holes of the second disk are concentric with the holes of the first but with a diameter smaller than the diameter of the TEM grids to lock them inside the sample holder. (**b**) DUSTER collector in final configuration

(EDX) and micro-spectroscopy without the necessity of sample manipulation. Two different collectors were designed and built. The first design was used in the 2008 DUSTER campaign but revealed limitation in performances. Based on this experience we redesigned the collector, then used in the 2009 and 2011 campaigns, to simplify the mounting and dismounting of the collecting substrates.

The 2008 collector is composed of a gold-plated stainless steel disk pierced with 14 pass-through holes to accommodate standard gold TEM (Transmission Electron Microscope) grids that support holy carbon films for dust deposition. The pass-through holes have different diameters on the two sides of the disk. The hole on the exposed surface has a diameter smaller than the TEM grid diameter. The TEM grids are fixed in the holes by a stainless steel pin, an external frame, fixed with three screws to the gold plated disk, held in place the entire assembly (Fig. 2).

The 2009 and 2011 collectors consist of 13 TEM grids housed in a custom mechanical holder, which is composed of: (1) a round base (5 mm thick and 23 mm in diameter) with a pin allowing accommodation in the FE-SEM chamber; (2) a thin plate (0.5 mm) pierced with 13 holes with a little buttonhole each, to better manipulate the TEM grids and (3) a thin plate (0.5 mm) pierced with 13 holes for the purpose to fix the TEM grids in their positions (Fig. 3).

2.4 Pumping System

The pumping system design has been realized following the performance requirement and taking into account the challenging conditions in the upper stratosphere (low pressure, low temperature). In order to obtain the flow rate required (Table 1), to preserve pumping system redundancy, and to save mass the pumping system was built coupling 6 micro carbon-vane. A configuration with 6 micro-pumps, coupled in parallel, save 50 % of mass obtaining redundancy for the system with respect to a single pump configuration.

Two different pump models have been selected and tested; the characteristics and technical specifications are reported in Table 2.

The two pump models differ in the method by which the motor is connected to the mechanical elements of the pump. The pump Fuergut supports the shaft through a ball bearing while the Thomas pump supports it by means of bushings.

The tests at low temperature demonstrate that the Thomas pump works well at temperatures below −60 °C. The Fuergut pump has a lower power consumption but cannot be used below −30 °C. The relevant results of the environmental tests performed on the selected pumps are reported in Table 3.

In order to reach the DUSTER flow rate required (Table 1) 6 different pumps were connected in parallel. Each pump is connected to an aspiration pipe by means of an electro-valve placed between the in-let of the pump and the pipe (Fig. 4a). The micro electro-valves completely isolate the pumps from the pumping system: if a pump fails the valve will exclude the pump from the system. The flow rate of the sampling system has been measured with tests in a climatic chamber reproducing pressure and temperature stratospheric conditions (Fig. 4b). In order to evaluate the performances of each pump model (Table 2), two pumping systems have been assembled. The flow rate of each pumping system has been measured at three different pressures at 3, 6 and 10 mbar, corresponding to 30, 35 and 40 km altitude (see Table 4). The two pumping systems assembled respectively with the Fuergut and the Thomas pumps are both compliant with the flow rate required. The model of the pumps is thus selected depending on the environment temperature expected during the collection.

Table 2 Main technical characteristics of selected pumps

Pump model	Power supply [V]	Flow rate [l/min]
Thomas Model G 12/04 EB	12	8
Fuergut Model DC06/21FK	5	5

Table 3 Test results on two types of selected pumps showing their power consumption, operative temperatures and flow rate

	Thomas	Fuergut
Power consumption	1.2 [W]	0.55 [W]
Operative temperatures range	−120 °C +80 °C	−40 °C +80 °C
Flow rate in relevant environment	8.53 [l/min]	5.30 [l/min]

Table 4 Flow rates measured for the Pumping System assembled with the two types of pumps

Pump model	3 mbar	6 mbar	10 mbar
Thomas	1.1 [m^3/h]	1.35 [m^3/h]	1.4 [m^3/h]
Fuergut	1.0 [m^3/h]	1.1 [m^3/h]	1.1 [m^3/h]

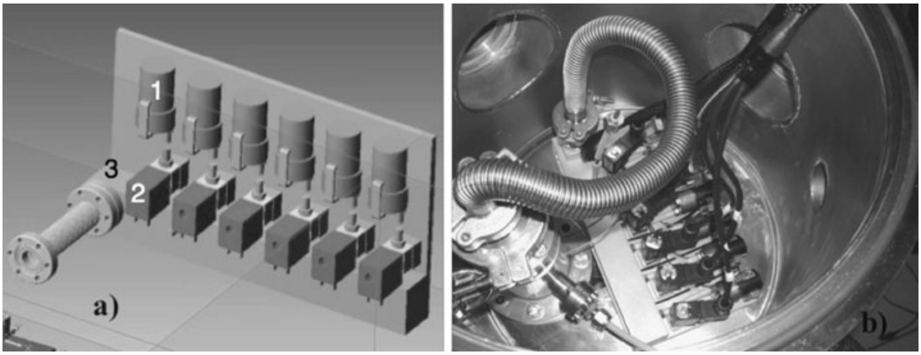
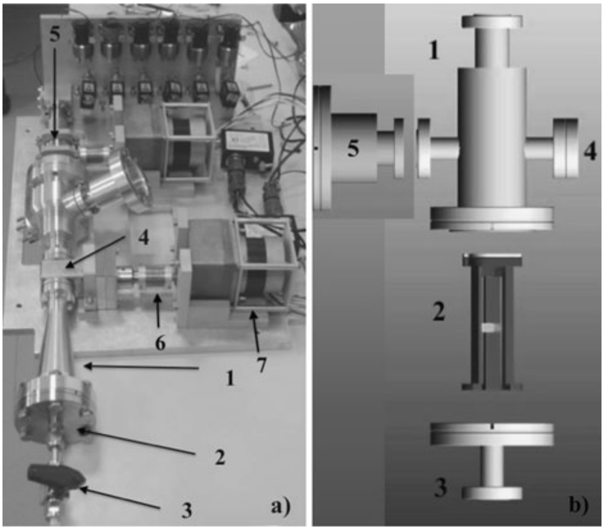


Fig. 4 (**a**) Pumping system mechanical configuration: (*1*) pump, (*2*) micro electro-valve, (*3*) connecting pipe; (**b**) The pumping system in the climatic chamber simulating stratospheric conditions of pressure and temperature to measure the flow rate

Fig. 5 (**a**) (*1*) inlet pipe; (*2*) CF 40 flange; (*3*) valve used to maintain the vacuum in the inlet pipe; (*4*) gate valve; (*5*) butterfly valve; (*6*) flexible mechanical joint; (*7*) stepper motor actuating the gate valve. (**b**) Collection chamber exploded view: (*1*) part of the collecting chamber (*2*) dedicated support for the collection substrate; (*3*) part of the collecting chamber where the dedicated support is fixed; (*4*) blind CONFLAT 16 flange; (*5*) secondary chamber hosting the "blank substrate"



2.5 Collecting Chamber: Design, Cleanliness and Contamination (Control and Characterization)

The collection of stratospheric particles for microscopic examination is a singularly difficult problem. All possible sources of self-contamination from the balloon vehicle or from the sampling instrument must be scrupulously and continuously eliminated during entire flight operations. The major sources of such extraneous materials in the past tended to be the exhaust from pumping systems and dust deposited on the balloon and equipment at launch site, during launch and ascent. Additional contamination would be possible at the landing site. Previous experiments, apart from the Testa et al. (1990) flight, made no provisions to avoid contamination during ascent and recovery. Addressing these problems the DUSTER design implements a collection chamber that can be sealed by ultra high vacuum (UHV) valves when in non sampling mode plus a one shot mechanism that seals the inlet pipe prior to reaching 20 km of altitude (Fig. 5).

To simplify assembling and integration, the substrate for dust collection is fixed on a dedicated support mounted on one part of the collecting chamber which connects to the other part by means of a CONFLAT 40 flange (Fig. 5). The support of the collection substrate is made of stainless steel; the two parts of the chamber are made of ERGAL™. On "part 1" of the chamber two CONFLAT 16 ports were foreseen: one is closed by a blind flange, the second is connected to a secondary chamber where a "blank substrate" is housed (Fig. 5b). The blank, identical to the collection substrate but not exposed directly to the airflow, is used to monitor the contamination of the whole collecting chamber and in particular that of the collector substrate during all the operations. The assembly, formed by the collection chamber plus the blank chamber, is connected to the in-let, exposed to the atmosphere, and on the other side to the pumping system by means of two UHV valves: (1) the in-let is connected to the chamber by a gate valve and (2) the pumping system is connected to the chamber with a flexible pipe and a butterfly valve (Fig. 5a). The two valves are operated by 2 stepper motors and monitored by 2 encoders.

In order to control the contamination on the collector substrate all mechanical parts with surfaces exposed to the collector are assembled in a class 100 clean-room. All these mechanical parts are cleaned with ultrasonic cleaner before they are assembled. The chamber is then sealed in clean room by the two UHV valves in closed position. Similarly the inlet pipe was cleaned and integrated in the clean room, and connected on the other side of the gate valve and sealed by a ConFlat 40 flange. This flange is maintained fixed to the inlet during all pre-flight operations, and is released by a one-shot mechanism when the balloon reaches about 20 km of altitude. A complete characterization with high resolution FESEM (Field Emission Scanning Electron Microscope) imaging of the entire collection surfaces of the actual and blank collectors is performed before their integration in the instrument. The complete scan of the single substrate produces about 150000 images; the images are stitched to create mosaic images of the TEM grids. The high resolution imaging of the collecting surfaces permits a complete characterization of potentially pre-existing particles. With this characterization method particles with diameter down to 0.1 μm can be identified and marked. After the collection campaign the same high resolution imaging process is performed on the two substrates. A comparison between the pre and post flight images identifies new particles; these last sitting on "blank substrate" can be used to identify possible contaminants: morphological and compositional analyses on new particles collected by the "blank substrate" help in the identification of possible contaminant on the "collection substrate".

2.6 Instrument Frame

The instrument structure consists of a box (410 × 310 × 310 mm) made of aluminium bars and two aluminium plates inserted into the box. The plates act as support for the collecting chamber and control elements of the instrument. The first plate fixed under the box holds the electronics and the batteries; the second plate is mounted above the electronics and holds the collection chamber and the pumping system (Fig. 6). The aluminium box is covered by insulating panels to insure a benign environment for the sensors, electronics and mechanism of the instrument. All the components of the instrument are inside the box except for the inlet pipe which allows the atmospheric sampling, protrudes from the insulating panels and the GPS and IRIDIUM antennas.

The structure of the instrument has been analyzed with FEA (Finite Element Analysis) software to verify the compliance of the instrument to the typical loads. Two different instrument configurations were investigated (Fig. 7):

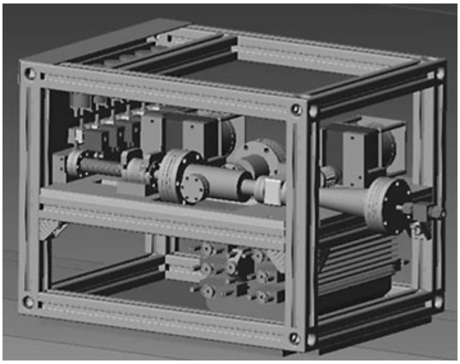


Fig. 6 3D mechanical design showing the DUSTER instrument in the aluminum frame

Table 5 Load cases studied with Finite Element Analyses

LOAD	Direction
10 g	−Z
5 g	45° in XZ plane
10 g	X
10 g	Y

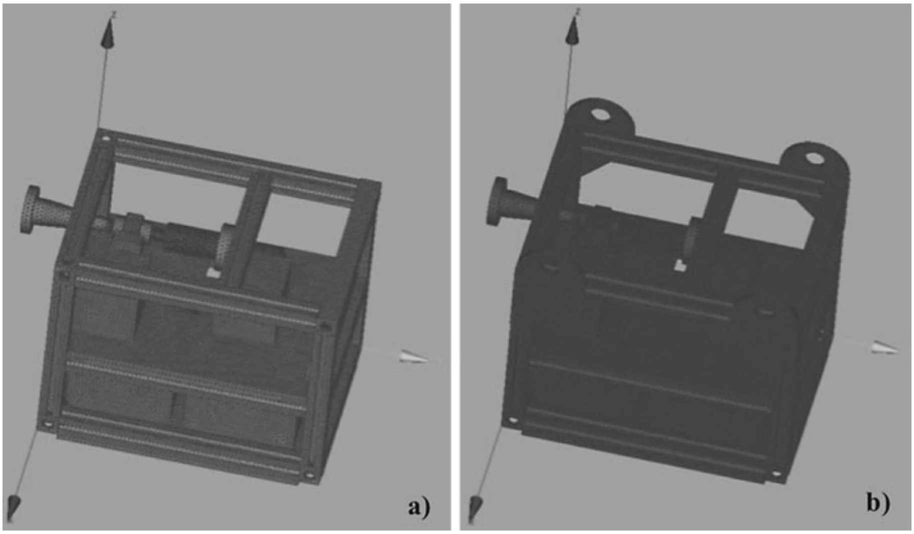


Fig. 7 (**a**) DUSTER Finite Element Analyses model in piggyback configuration and (**b**) DUSTER Finite Element Analyses model in the stand-alone configuration with the reference frame

- DUSTER fixed on an external structure as piggy-back of a larger gondola;
- DUSTER as standalone gondola with mechanical interface to the flight train.

In Table 5 are reported the load cases studied.

The FEA analyses results are reported in Table 6.

In all load cases, investigated for DUSTER in the piggyback configuration, the stresses calculated by the FEA analyses are smaller than the limits for the material of the structural

Table 6 Summary of the analyses result for DUSTER in the piggyback and standalone configurations

Load case	Max deployment [mm]	Max stress [MPa]
DUSTER in piggyback configuration		
10 g −Z	0.03	5.85
5 g 45°	0.012	4
10 g X	0.029	8.3
10 g Y	0.017	10.5
DUSTER in standalone configuration		
10 g −Z	0.063	21.4
5 g 45°	0.12	49.5
10 g X	0.3	133
10 g Y	0.24	127

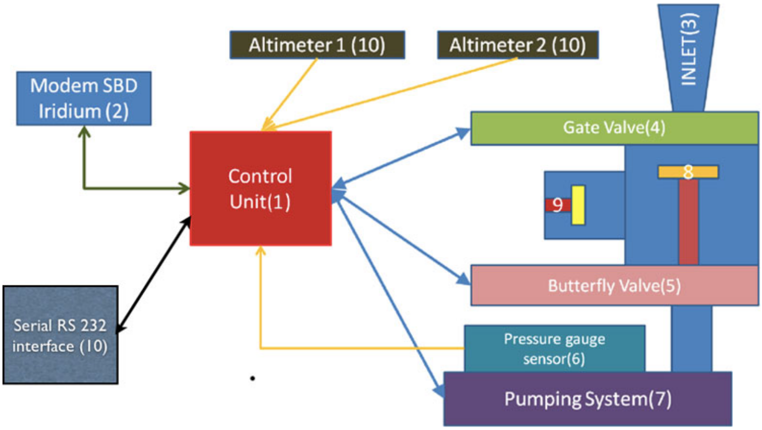


Fig. 8 DUSTER block diagram: (*1*) Control Unit; (*2*) IRIDIUM Transceiver; (*3*) INLET pipe exposed to atmosphere; (*4*) Gate valve connecting INLET to collecting chamber; (*5*) Butterfly valve between collecting chamber and pumping system; (*6*) Pressure gauge monitoring flow through the instrument; (*7*) Pumping System with 6 micro-pump car- bon vane; (*8*) Collecting substrate; (*9*) Contamination control substrate; (*10*) Serial RS 232 interface; (*11*) GPS antenna

frames. The deflections are extremely small; in all cases the maximum deployment is below 0.03 mm for the overall structure. Displacements and stresses calculated by FEA analysis of DUSTER in the standalone configuration are larger than the case of DUSTER in the piggyback configuration, but still below the strength limits for the materials used in structural elements.

3 DUSTER Subsystems

The need for an instrument that can operate either as standalone gondola or as a piggyback payload has imposed the requirement for the control system to be as flexible as possible, and with the opportunity to work in different operative modes. In Fig. 8 we show the DUSTER block diagram.

The control system's main functions are:

- Reading external sensors
- Managing Communication Interfaces (Communication BUS with Gondola or Telemetry System)
- Operate mechanism, pumping system and thermal control.

3.1 Instrument Sensors and Thermal Control

The external sensors mounted on the instrument can be divided in two groups: (1) operation sensors and (2) housekeeping sensors. The first group has two altimeters for redundancy and two encoders connected to the two stepper motors that operate the two automated UHV valves. The second group consists of: (a) eleven thermometers placed on the instrument components (control system, power supply, pumping systems, UHV valves and motors); (b) an amperometer connected to the main power supply that monitors the total power consumption; (c) six amperometers that monitor the power consumption of the pumps; (d) a pressure gauge sensor connected to the pumping systems to monitor the flow rate through the instrument; (e) a GPS receiver. The atmospheric pressure sensor (altimeter) is a critical part of the control system: it measures the barometric altitude and triggers the sampling process. The sensors HPA by Honeywell provide an absolute pressure range from 0 to 121 kPa with ± 0.03 % full-scale accuracy, in the operating temperature range (-40 °C to 85 °C). These sensors are connected to the control system by two RS 232 serial ports. Heaters are mounted on the valves of the collecting chamber, on the motors, and on the support of the pumps (most thermal critical devices). When the temperature drops below a set value the control unit activates the heaters to maintain the components within the operational temperature.

3.2 Control Unit

The heart of the electronics control system is an HELIOS DiamondSystems PC104 SBC (Single Board Computer). In Fig. 9 we show its functional diagram. Helios is a low power PC/104 form factor SBC combining a highly integrated CPU with high-accuracy data acquisition circuitry on a single board, reducing size while increasing ruggedness. Helios utilizes a Vortex integrated single chip CPU operating at 800 MHz and 256 MB of DRAM soldered on-board and incorporates an IDE hard drive interface, mounting capability for a solid-state flash-disk up to 4 GB. Helios also provides a 10/100Base-T Ethernet interface, two RS-232 serial ports and two RS-232/422/485 serial ports. This SBC extremely rugged, thanks to the design of the electronic board, allowes fan-less operation from -40 °C to $+85$ °C.

In order to control the stepper motors connected to the gate valves two PC-104 AIM-Motion-104 boards have been connected to the SBC by means of the PC104 bus. The AIM104-MOTION-1 is an 8-bit PC/104 module providing single axis motor control. These boards read the measurements of the encoders connected to the motors. To control the pumping system switch on/off a PC-104 module with solid state relays has been connected to the SBC PC 104 bus, the pumps are individually connected to the relays of the board, each pump can be turned on or off independently. We designed and produced two custom PC104 boards in order to: (1) manage the 6 electro-valves of the pumping system, and operate other six devices with current consumption up to 1 A (can be used in case of instrument as stand-alone gondola to manage balloon control, e.g. gas valves, ballast release); (2) conditioning the thermal and power consumption sensors.

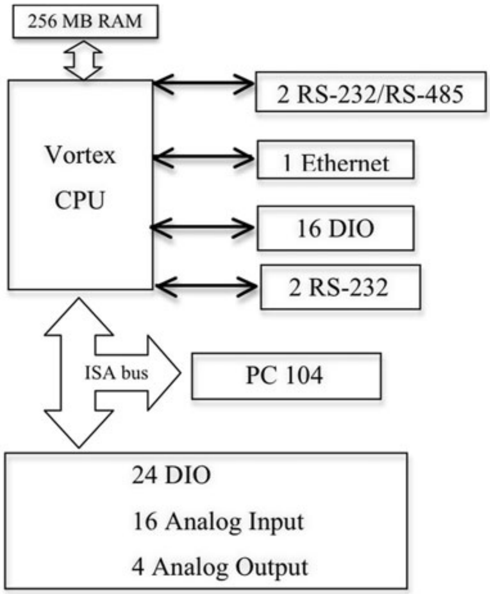


Fig. 9 Helios Single Board Computer functional diagram: communication and DAQ modules are fully integrated in the SBC increasing the ruggedness of the board

3.3 Telemetry Hardware

An IRIDIUM SBD (Short Burst Data) transceiver has been used to implement a telecommand/telemetry (TC/TM) system allowing operations control from ground through commanding and housekeeping data transmission. The SBD transceiver is a low cost, Iridium Satellite LLC manufactured product, designed as an OEM module to be integrated into applications that only use the Iridium SBD service. The transceiver is connected by a serial port (RS232 interface) to the control unit.

The Iridium SBD service provides: (1) Mobile Originated (instrument) messages up to 340 bytes; (2) Low, uniform global latency (less than 1 minute); (3) Mobile Terminated (experimenter) messages up to 270 bytes; (4) Global Coverage.

The on-board software sends Mobile Originated SBD (MO-SBD) data messages via the Iridium transceiver: it loads the data message into the transceiver and instructs it to send the data message. The data message is then transmitted across the Iridium satellite network to the Iridium Gateway. The data message is then transferred via e-mail to the experimenter host computer system where it is processed and stored. Mobile Terminated SBD (MT-SBD) messages are sent to the Iridium Gateway via e-mail from the experimenter host computer system. The Iridium Gateway sends a ‘Ring Alert’ to the Transceiver when a MT-SBD message has been queued; this Ring Alert is transferred to the unit control by the serial port, and the message is downloaded and interpreted by the on-board software.

3.4 Instrument Mechanism

The cleanliness requirement imposes the implementation of two mechanisms to operate the valves that shield the collection chamber for contamination. These two mechanisms were built connecting two stepper motors with encoders to the shaft moving the closing plate of the two manual UHV valves. The motor shaft is connected to the valve with a flexible joint in order to avoid mechanism blockage due to misalignments between the motor and the valves (see Fig. 5a). In order to monitor the position of the valves, the control unit reads the encoder and the valve position is sent to ground by telemetry.

A single shot passive mechanism has been implemented to seal the inlet of the instrument. A blind flange closes the inlet pipe. A valve that allows isolating the inlet pipe after evacuation is mounted on this flange (Fig. 6a). Before the launch operations, with a vacuum pump connected to the valve, the pressure in the inlet pipe is lowered to 6 mbar, the last operation on the instrument before the take off foresees the removal of the bolts fixing the flange. When the balloon reaches an altitude of about 20 km the flange detaches from the pipe autonomously without using any active device: at this altitude the differential pressure between the inlet pipe and the atmosphere allows the flange detachment.

3.5 Power Supply

The electrical power required (about 20 W) to operate the instrument during the sampling phase is guaranteed by the combination of a rechargeable battery with capacity of 20 Ah and four solar panels producing 27 W each. The four panels, connected in parallel to the rechargeable battery are mounted in such a configuration that at least one of them is pointed towards the sun. The instrument can operate with or without the solar panels. A summer circumpolar flight can be performed relying only on the power provided by the solar panels. If solar panels cannot be used the rechargeable battery can be substituted by a package of one shot lithium battery with capacity up to 64 Ah allowing 30 hours of operations.

4 Instrument Software

The on-board software allows the complete management of the instrument operations (open/close valve, switch on/off pumping system, sensors data storing, TC/TM managing and serial communications). The instrument can operate in two different modes: (1) Autonomous Mode and (2) Slave Mode.

In the Autonomous Mode all operations to collect stratospheric aerosol are handled by the software following data from instrument sensors (atmospheric pressure, temperature, power supply status). At the switch-on DUSTER is in the Safe Status (valves of the collecting chambers closed and pumping system switched off). The software continuously monitors and stores the sensor readings (pressure, temperature and other housekeeping parameters); when the pressure reaches the operative value, corresponding to the working altitude, the software sets DUSTER into the Sampling Status opening the valves and switching on the pumping system. The software sends at regular time intervals, sensors readings and instrument status by Iridium Transceiver and stores the data on the onboard memory mass. The sampling activity is triggered by the pressure readings. If during the mission a thermal or a power supply contingency, registered by sensors, occurs on critical components (e.g. main electronics), the software sets DUSTER to the Safe Status configuration protecting the collected samples.

In Slave Mode the experimenter handles the instrument operations by using telecommands. DUSTER receives TC by the Iridium Transceiver and the software either changes the instrument status or executes operations. The software sends, by Iridium Transceiver, sensors readings and instruments status. Also in this mode when a thermal or power supply contingency occurs the instrument is forced autonomously into the Safe Status, in order to preserve the collected samples.

The software allows the instrument to have these functions both via the serial interface or through the Iridium transceiver.

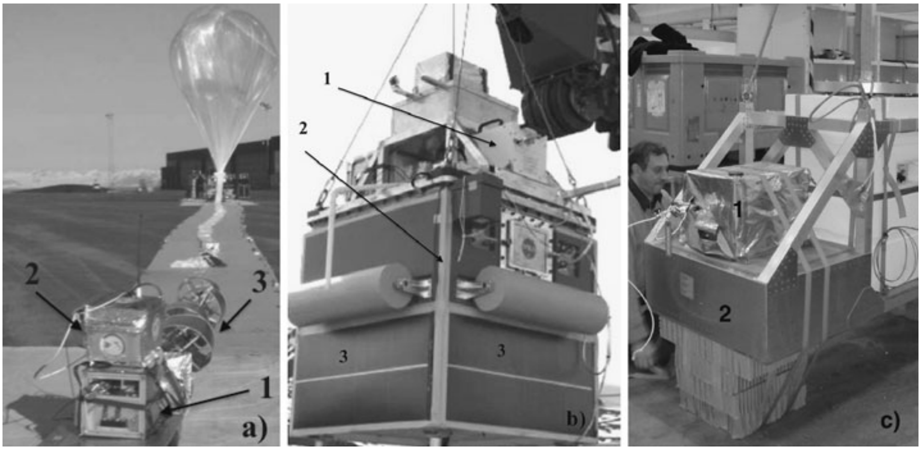


Fig. 10 (**a**) DUSTER 2008 in the stand-alone flight configuration: (*1*) DUSTER; (*2*) ASI Telemetry System; (*3*) Solar panels fixed along the chain. (**b**) DUSTER 2009 in the piggy-back flight configuration on the SORA main payload, pending from the crane: (*1*) DUSTER; (*2*) SORA gondola; (*3*) DUSTER Solar panels. (**c**) DUSTER 2011 in a shared gondola flight configuration: (*1*) DUSTER; (*2*) CNES multi-instrument host gondola

5 Flight Performance and Collection Results

DUSTER after a first technological flight in 2006 from Kiruna managed CNES (Centre Nationale d'Étdudes Spatiales) has performed three scientific flights in three different configurations:

– 2008, the first scientific flight from Longyearbyen (Svalbard, Norway) with an ASI (Agenzia Spaziale Italiana) supported campaign. DUSTER was a stand-alone payload that was directly connected to the flight chain and connected by serial port to an external telemetry system (see Fig. 10a);
– the second scientific flight from Longyearbyen (Svalbard, Norway) in 2009 with the ASI-SORA campaign; DUSTER was housed as a piggyback payload of the SORA gondola, and used its own IRIDIUM telemetry system (Fig. 10b);
– the third scientific flight from Kiruna (Sweden) in 2011 managed by CNES; in this campaign DUSTER was housed on a gondola shared with another payload, and was connected to the ETNA CNES telemetry system (Fig. 10c).

5.1 Instrument Collection Campaigns

As we have already indicated, the first DUSTER scientific flight was made during June 2008. The instrument was launched with a 30,000 m^3 balloon from Longyearbyen (Svalbard, Norway) on 21st of June and was recovered after a flight of about 62 hours on the west coast of Greenland (Fig. 11). During the flight DUSTER sampled 6.6 m^3 of air for 55 hours in the Autonomous Mode.

The instrument was able to properly handle a thermal contingency of the main electronics, the control system of the instrument reached the higher thermal limit; the on-board software autonomously switched off the pumping system and sealed the collection chamber. The thermal and pressure data collected and stored on board are displayed in Fig. 12. After

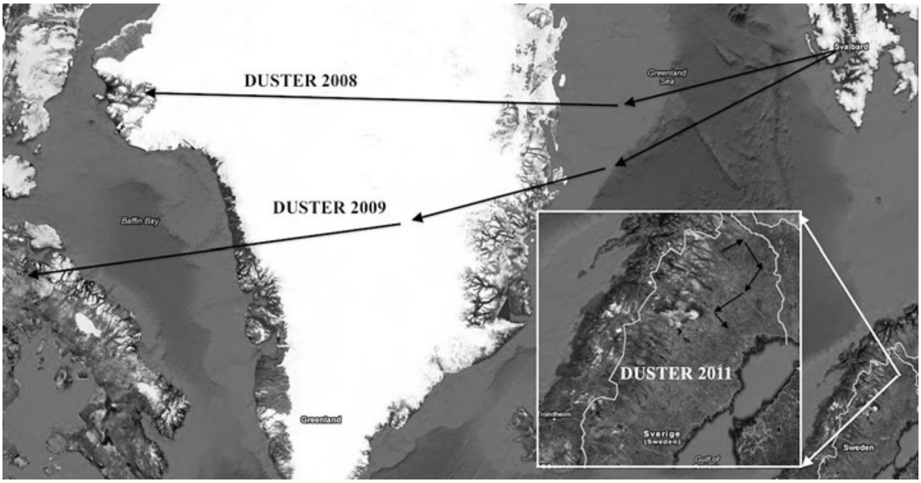


Fig. 11 DUSTER 2008 flight path: launched from Longyearbyen, Svalbard, Norway on the 21st June 2008 and recovered in Greenland after a 62 hours flight. DUSTER 2009 flight path: launched from Longyearbyen, Svalbard, Norway on the 1st July 2009; DUSTER 2011 flight path over the north of Sweden launched on the 4th of April 2011

Table 7 DUSTER flights summary

Flight	Altitude [km]	Flight time [h]	Sampling time [h]	Atmosphere sampled [m^3]	Take off site	Landing site	Particle collected
Duster 2008	37 to 38.5	62	55	6.6	Longyearbyen (Svalbard)	Greenland	25
Duster 2009	33.7 to 39	86	32	35.2	Longyearbyen (Svalbard)	Baffin Island (Canada)	Analyses on going
Duster 2011	31.6 to 33	5.7	2 .8	3.9	Kiruna (Sweden)	Kiruna (Sweden)	Analyses on going

recovery DUSTER was opened in a clean room and the collector was analysed at the FE-SEM. Comparing pre- and post-flight FESEM images of the collector surface 25 particles were identified as collected in the stratosphere at ∼38 km altitude (see Table 7).

The second flight of the instrument was performed from the same launch base and during the same season (1 July 2009) of the 2008 campaign. After a nominal launch and flight of a 8.5×10^5 m^3 balloon, it made a landing after about 86 hours in Baffin Island, Canada (Fig. 11), except for some damages to the external structure because of parachute dragging. More than 35 m^3 of air have been sampled.

The altitude profile and temperature data stored on board are displayed in Fig. 13. During the floating time of the balloon a failure on solar panels limited the power supply of the instrument. As a result the active sampling period was limited to 32 hours (see Table 7). The on-board software managed the contingency well by switching off the sampling system and sealing the chamber with the collected dust. During this flight the instrument was controlled by means of its own IRIDIUM telemetry system, several operations were commanded via telecommand and the TM/TC system worked as expected.

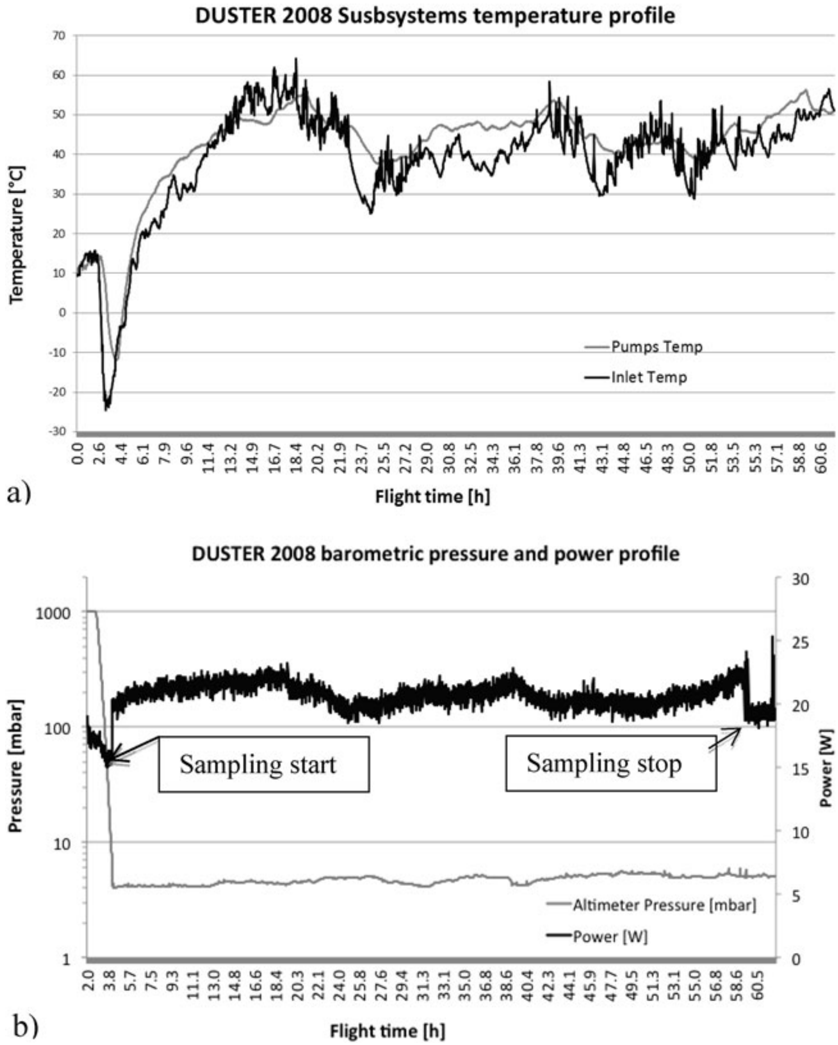


Fig. 12 (**a**) DUSTER temperature measured at the in-let and at the pumping system during the 2008 flight; (**b**) Altimeter readings and power consumption profile for the 2008 DUSTER flight

The third scientific flight was launched from ESRANGE, Kiruna, SWEDEN (Fig. 11). The altitude profile and temperatures data stored on board are displayed in Fig. 14. The sampling was activated during the floating phase when the balloon remained at an altitude between 31.6 and 33.7 km for 2.8 hours with an atmosphere sampled volume of 3.9 m^3 (see Table 7). In this campaign the instrument was housed on a multi-instrument gondola and connected to the ETNA CNES telemetry system by a serial RS-232 port.

5.2 Collected Particles and Instrument Performances

The DUSTER 2008 flight successfully collected 25 natural stratospheric particles with dimensions in the range of the designed DUSTER capabilities. More than half of the grains are

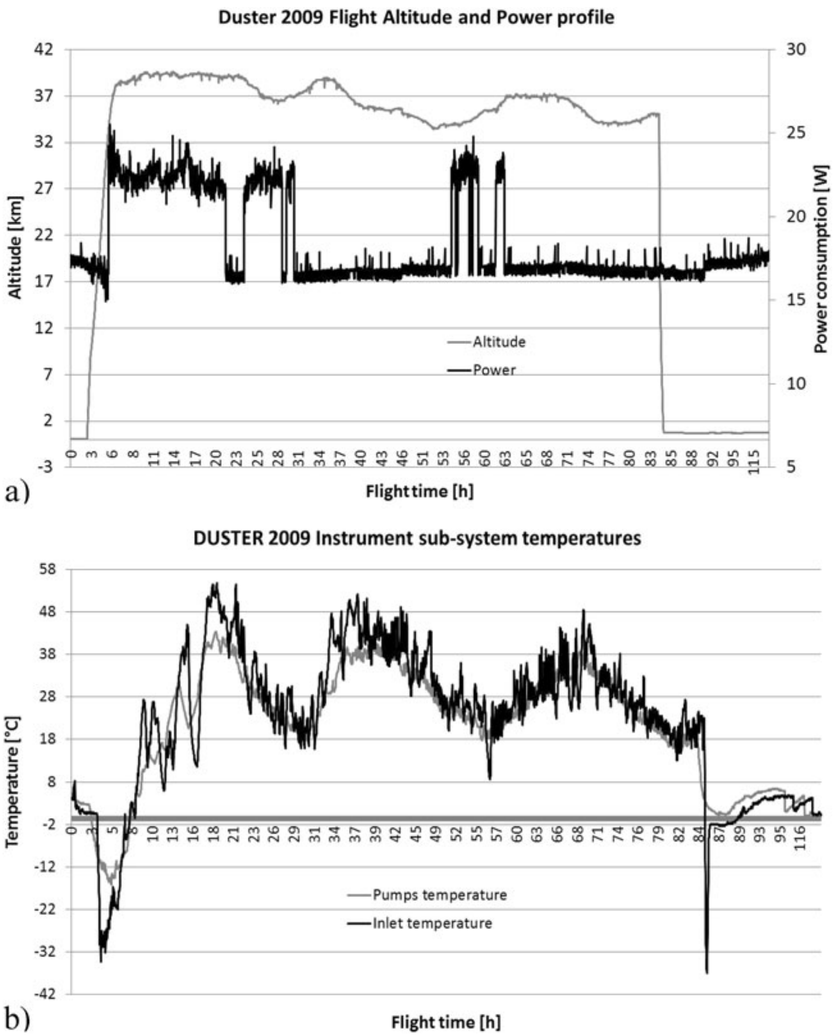


Fig. 13 (**a**) Altitude and power (sampling) profile for 2009 flight. (**b**) DUSTER temperature profile measured at the in-let and at the pumping system during 2009 flight

found in the size range from 0.4 micron to 2 micron. The DUSTER collector instrument was designed to collect, in an autonomous mode on long-duration stratospheric balloon flights, ~200 nm to 40 micron size particles. During the June 2008 DUSTER flight, the instrument collected particles ranging from 425 nm to ~24 microns in size for a population that was dominated by sub-micron dust that were mostly aggregate particles (Fig. 15).

As an example of particles that after FESEM analyses are labelled as "collected" stratospheric particles we show a 1.8 μm conglomerate of small spherical sub-grains sitting on a holy-carbon thin film (Fig. 15).

DUSTER fills a gap in the information on the amounts and physical and chemical properties of the stratospheric dust at high altitude for a wide range of grain sizes (Fig. 16). These

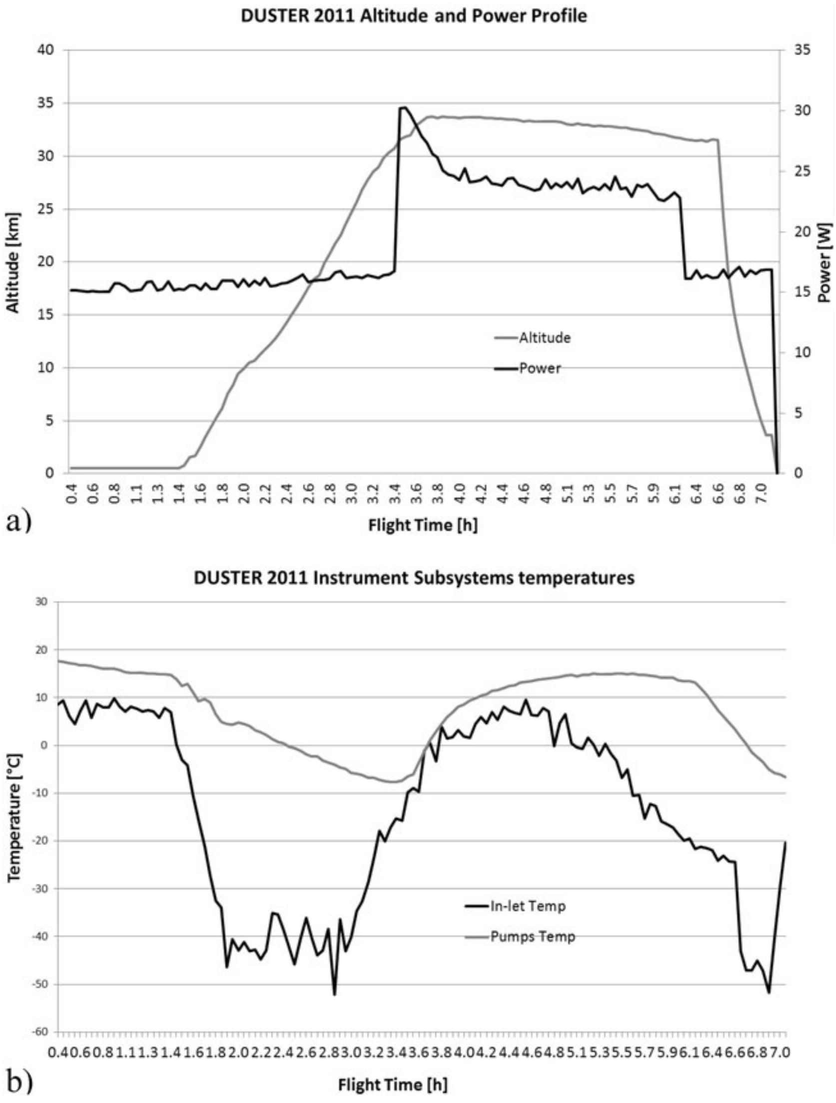


Fig. 14 (**a**) Altitude and power (sampling) profile for DUSTER 2011 flight. (**b**) DUSTER temperature profile measured at the in-let and at the pumping system during 2011 flight

first scientific flight results (DUSTER 2008) confirmed that the instrument meets both the designed technical performances and collection capabilities.

6 Summary

The first DUSTER collector, a prototype used in the technical flight in 2006 from the north of Sweden, purposely designed for dust collection in the upper stratosphere, failed miserably but turned into an engineer's delight of redesign for success (Palumbo et al. 2008). The

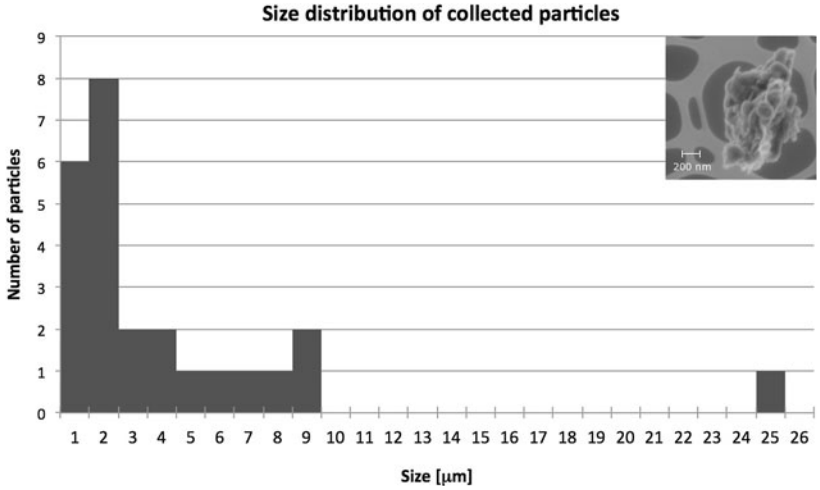


Fig. 15 Size distribution of the 25 identified particles from the Duster 2008 collection. In the insert is shown as an example a SEM image of one of the 25 particles collected in the flight

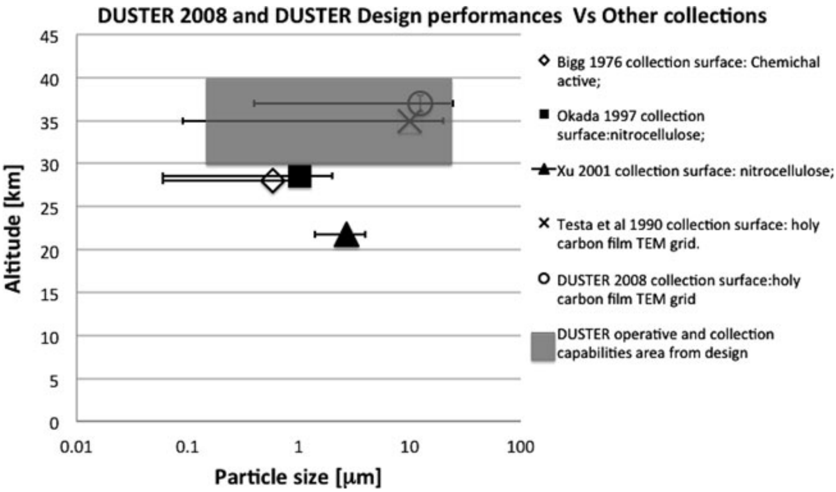


Fig. 16 DUSTER nominal working conditionsfor extraterrestrial dust collections (*gray area*). Altitude upper limit is constrained by balloon capabilities, the lower limit is selected to maximize the extraterrestrial vs terrestrial dust ratio. DUSTER 2008 collection and other balloon borne collection flights and their altitudes: the symbols represent the median size values of the collected particle; the horizontal lines represent the whole size ranges for each collection

new design of the instrument has placed particular emphasis not only on the functional aspects, but also in the procedures for the preservation of collected samples and in the control and characterization of possible contamination. The mechanical parts and of the collectors strictly followed the cleanliness requirements. The final design of the collector, specifically for DUSTER2009 and DUSTER2011, avoids the manipulation of collected samples for the analyses. The choice of the blank collector and the improved mechanical configuration of the collecting chamber enabled the detection of possible contaminants allowing the discrimination between collected particles and contaminants. The development of protocols for collector preparation/characterization and instrument assembly eliminates any ambiguity in the identification of actual collected particles. Another major advantage of the instrument design improvement is an extreme operative flexibility; the instrument with minimal modification can be used as stand-alone gondola, piggyback payload or as a component of a multi instrument platform.

Despite the success of the 2008 instrument, that collected 25 natural stratospheric grains, we still needed to improve the collector design and the efficiency of the sampling system in order to obtain a better flow rate and an increased amount of sampled atmosphere. The laboratory tests we performed on the furtherly improved design, DUSTER 2009 and DUSTER2011, verified the increased amount of flow rate on the whole range of altitudes and temperatures provided in the instrument requirements. Unfortunately DUSTER 2009 experienced a fire after landing independent from the instrument which was hosted on a piggy-back flight. The crash caused a small leak in the valve of the collecting chamber which determined ambient air and smoke from the main payload burning to enter the DUSTER collecting chamber.

At present we are performing the post flight analyses to identify by FESEM collectors characterization the 2009 and 2011 collected particles. On the base of the results of all the flights so far performed, and especially from the 2008 collection we can conclude that the DUSTER facility is able to collect uncontaminated dust particles in an under-explored portion of the stratosphere.

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