

PEGASO: AN ULTRA LIGHT LONG DURATION STRATOSPHERIC PAYLOAD FOR POLAR REGIONS FLIGHTS

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ABSTRACT

Stratospheric Balloons represent a powerful and affordable tool for several scientific disciplines. With little expense, compared to satellite projects, balloons are able to lift payloads from few kilograms to 2 tons or more, well above the troposphere performing a month or more of experimentation. The payloads are then carefully brought back to the surface where they can be made ready to fly again in a short turn around time. This low cost, diversified scientific experimentation, and the short turn around time between launches is not possible via satellites.

We introduce the PEGASO (Polar Explorer for Geomagnetism And other Scientific Observations) balloon payload developed by the INGV (Istituto Nazionale di Geofisica e Vulcanologia) and La Sapienza University with the PNRA (Progetto Nazionale di Ricerche in Antartide) sponsorship (Cardillo, A. et al, 2003). This light payload (10 Kg) has been operated 5 times in polar areas by the Italian Space Agency (ASI) and Andøya Rocket Range (ARR).

PEGASO carries a 3-component flux-gate magnetometer, is powered by a solar cells array, uses an IRIDIUM based bi-directional telemetry system for data transfer and remote control, and a GPS localization system.

1 INTRODUCTION

1.1 Balloons from polar areas

Launching from Polar Regions offers several advantages (if launching from there is compatible with the scientific requirements). Launching during the polar day allows the payload to stay in the sunlight for months. This solves the most part of energy and temperature problems, extremely important for long experiments, and offers an easy way to orientate the payload. Moreover, the circumpolar stratospheric winds bring the balloon in a circular predictable trajectory making easy its recovery. This localized trajectory can be of great interest for polar sciences, for cosmology (instruments can integrate for days the same portion of sky), for earth sciences. The trajectory itself is an object of investigation for atmosphere scientists. Launching Stratospheric Balloons from polar area is a usual activity in the southern hemisphere, but quite new for the northern one. Big Long Duration Balloons (LDB up to 3 weeks of operation) with a weight of over two tons, have been successfully operated from McMurdo (USA, Antarctica), getting impressive results (De Bernardis, P., et al., 2000). Pegaso is the first LDB experiment carried out in the northern hemisphere.

1.2 Stratospheric magnetometry

The mathematical description of the Earth's magnetic field and its variations is usually performed by means of stable observatories. To increase the coverage measurements are periodically performed (every 5 years) using mobile instruments. Anyway there are large uncovered surfaces (oceans, polar areas) where partial measurements are conducted by ships, airplanes and satellites. Satellite measurements are too far from the Earth's surface to investigate wavelengths shorter than 1000 Km, and ground measurement are affected by errors induced by short-wavelength crustal anomalies. This results in errors in the field model, which, for wavelength of 100-1000 Km, may suffer of an excessive indetermination. A measurement operated at 35 Km of altitude will permit to investigate large crustal anomalies and medium mantle-core anomalies in the ambiguous wavelength range.

Actually PEGASO uses a 3-axis-fluxgate magnetometer to detect the module of the magnetic field, and to separate the vertical field component. The use of a proton magnetometer is also possible, since the circular flight over a polar area will never bring the instrument to work out the operating angle (which is the negative characteristic of a nuclear magnetometer).

The data treatment consists of a measurement reduction using geomagnetic observatories (diffused in the northern hemisphere) to separate the internal from the external field; existing spherical harmonic models will be used to study anomalies (IGRF2000). Here a truncated Taylor series will solve the non-linear relationship between the total field and the Gauss coefficients. Data process will take into account the increasing of the external field contribution and the decreasing of the internal one (roughly 10%) at the flight height.

1.3 Pegaso objectives

Although born for magnetometry PEGASO reached some ancillary objectives.

The scientific purpose was the study of the Earth magnetic field in an area not well covered by ground or satellite measurements

Another objective, both scientific and logistic, was to investigate about the quality of the stratospheric trajectories in the site chosen by ASI and ARR for stratospheric ballooning in northern polar area, Longyearbyen. This city (Svalbard Islands, 78° 14'N) easily reachable by plane can offer support (airport, meteorological office, hotels) and hosts the University Centre in Svalbard (UNIS). This site mirrors, in the northern hemisphere, the position of the NASA/NSBF balloon launch base in McMurdo (Antarctica, 77° 51'S). Thanks to the Gulf Stream, the temperature in Longyearbyen is much warmer than in McMurdo.

The technical objective was to design and realize a cheap long duration payload for polar areas magnetometry, complying with the flight rules for stratospheric balloons (real time localization, termination control, radar visibility). Due to economical constraints, the payload was realized employing off-the-shelf parts, and adapting them for using in the stratosphere.

The scientific purpose was the study of the Earth magnetic field in an area not well covered by ground or satellite measurements (1.2).

2 STATISTICAL STRATOSPHERIC WIND ANALYSIS

Statistical stratospheric wind analysis and its impact on the balloon trajectories were evaluated for 2000, 2001 and 2002 summers, as support at the ASI programs in 2003 (Peterzen S. et al,2003). The wind data analysis for each year spans a period from May through August. The analysis data utilized for these procedures came from the European Centre for Medium-Range Weather Forecast (ECMWF). A complete set of data derived from satellite and radio-sounding measurements was available every 6 hours, for each degree of latitude and longitude in the area of interest. For the three years period we have constructed the geopotential altitude graphs at 5 mb (Fig. 1 shows the typical isobaric behavior in the Polar Regions that allows LDB flights) and ground track trajectories. They were simulated through a 20 days cycle by using a linear interpolation in space and time with a step of 0.5 hours and considering the balloon at a constant pressure level of 5 mb (Fig 2). The summary of the favorable LDB period for the considered three years is shown in Table 1.

This summary indicates the number of potential days the circulation pattern would support a circumpolar trajectory of a stratospheric balloon in the 5mb range. Table 1 depicts an average of around 50 days per summer season. Given this averaged period, it was reasonable to expect up to 1200 hours at float altitude per payload. Similarly collecting the radio-soundings of the international stations around Antarctica it is possible to see when the favorable conditions happen. Measurements made during winter 2000 from stations located around the South Pole show the favorable condition starts around mid December and stops at the end of January

3 PEGASO MISSIONS

4

3.1 Trajectory prediction

Already used during the Trasmediterranean and local flights managed by the ASI base in Trapani (Sicily) (Musso, I. et al., 2003, 2004) the predictions of stratospheric balloons trajectories have been applied at the 2005-06 Pegaso missions. We have used the National Centers for Environmental Prediction (NCEP) forecast data. Its grid steps are 1° in latitude and longitude and 3 hours in time. The balloon's float altitude was considered constant around the maximum pressure level of the available data (10 mb). Fig. 3 shows the 5 days predictions made before and during flights, obtained by linear interpolations in space and time.

The prediction error has been evaluated too by comparing the real and predicted trajectories. Fig. 4 shows the root mean square of the error as function of prediction time.

Four simulations have been considered during each balloon flight, starting from the actual position and for 5 days of duration.

3.2 Missions

Five PEGASO have been launched since 2004, four from Longyearbyen and one from MZS (Italian station in Antarctica). All the balloons are 10000 m³ balloons, produced in USA. All of them were equipped with an auxiliary positioning system based on GPS and telemetered via Argos. The auxiliary system is connected to the balloon bottom so it allows tracking the balloon after separation. In the first 3 flights lithium cells powered the Argos system. A small solar panel, buffered with a rechargeable battery, powered the Argos system during the last two flights. The typical flight chain for PEGASO is shown in Fig. 7.

This is the list of Pegaso's missions:

PEGASO A (2004) From Longyearbyen was launched to check the system design, returned only telemetry data and position. No magnetometer was provided for the first flight, which further investigated the circumpolar trajectory. The flight lasted for 40 days before termination and showed a westward path although launched late in the season.

PEGASO B&C were launched in 2005. Pegaso B was equipped with a 3 axis fluxgate magnetometer, and traveled 9966 km before termination, occurred 25 days after launch.

PEGASO D (2006) was launched from MZS Station (Terra Nova, Antarctica). Some logistic and technical problems delayed the launch which occurred too late for a circular trajectory (. Moreover some malfunction inside the telemetry stopped the data transmission: during the most part of the flight the system was just able to execute remote commands.

Pegaso E (2006) was launched from Longyearbyen again, at the right time to obtain a perfect circumpolar trajectory, and was terminated over Greenland, in a place suitable for recovery. Pegaso E hosted also RDR/BXR a joint Norwegian-Italian student experiment to study high energy particle precipitation and associated Bremsstrahlung radiation in the polar atmosphere. Figures 5 and 6 show the Pegaso Trajectories. A list of the launched Pegaso appears in table 2.

4 INSIDE PEGASO

The basic idea that brought to the PEGASO design was to build an expansible payload (recovering costs much more than the payload itself) capable to conduct scientific measurement at the affordable cost of a stratospheric pathfinder. PEGASO (Polar Explore for Geomagnetism And other Scientific Observations) was originally thought just as a flying magnetometer. Like in a pathfinder ARGO was the first communication system evaluated for data downloading. ARGOS PPT is light, affordable and reliable. Unfortunately ARGO suffers of some lack of communication at the required data rate for magnetometry, and the project moved toward the Iridium System. Iridium offers the power of a bi-directional communication, which is highly desirable for two reasons:

- A local data buffer may be easily managed with bi-directional communication; this allows to reduce the communication time establishing a connection only when required (near to buffer full)
- It is possible to remotely control the payload.

Unfortunately the use of Iridium increased the weight and, for payloads exceeding 4 Kg it is required a termination system (parachute) that needs to be remotely operated. The possibility to control the payload may be useful to operate a ballasting system (Romeo, G.,2004). This may prolong the flight (more data, see Fig. 12) or correct an imperfect launch. When the design started Iridium modems (for use in stratospheric condition) were not easy to get, and much more expensive than ready of the shelf Iridium phones. This brought to house the project in a pressurized vessel to allow all the electronic stuff to enjoy the lab room conditions (20°C, 1 bar) even in the stratosphere (Fig. 14). An inexpensive GPS (Trimble Lassen), already checked in the stratosphere, supplies position data, and inexpensive and frameless flexible solar panels set (Uni-Solar) supplies the energy, keeping the battery charged during the flight. Fig. 7 shows the complete flight chain (balloon + parachute + Argos + payload).

Data logged by PEGASO (every 30 seconds) are stored in a circular buffer, waiting for a call from the ground station. This happens hourly. The system acquires the 3 magnetic field components and GPS position as well as house keeping data (power, temperature, pyrotechnic devices status). Fig. 8 shows the vessel layout. Fig. 9 shows the ground station block diagram, at the INGV Data Centre. An emergency subset of the ground station can be easily implemented on a laptop (connected to an Iridium phone). The communication to the balloon occurs in plain ASCII. Although more expensive in terms of data transfer this choice allows a ground operator to contact the balloon and (knowing the vessel password) to operate remote controls without a specialized ground station.

Data recorded by Pegaso are the 3 components of the magnetic field, position from GPS, 3 solar panels temperatures, magnetometer head temperature, vessel temperature, 3 solar panels currents, 3 solar panels voltages, battery voltage and current. Figure 13 shows a fragment of recorded data from the solar array.

Fig 15 shows the rough data of the vertical magnetic field recorded by Pegaso-B. One-day period oscillations are caused by height of the balloon and by the sun elevation. The medium level varies with the distance from the magnetic pole.

6 FUTURE SCIENTIFIC MISSIONS

Interest in polar flight opportunities has been expressed by atmospheric physics, planetary science, biology, and high-energy astrophysics groups. In Italy several teams are developing science payloads for LDB flights. In various states of development are:

- 1) The OLIMPO microwave/sub-mm telescope, an experiment devoted to the measurement of the Cosmic Microwave Background in the direction of Clusters of Galaxies and the anisotropy of the far IR background radiation. The instrument features arrays of 19, 37, 37, 37 bolometric detectors respectively at frequencies of 150, 240, 350, 540 GHz. The resolution is few arcminutes (Masi, S., et al., 2005).
- 2) The BAR-SPORT experiment, a proposed balloon-borne microwave polarimeter aimed at the measurement of the polarization of the Cosmic Microwave Background at 90 GHz, with extremely low instrumental polarization (Cortiglioni, S. et al., 2003).
- 3) The BOOMERanG experiment, after the successful flights from Antarctica (De Bernardis, P., et al., 2000), will map foregrounds polarization at 350GHz: this measurement is propaedeutic to a B-modes polarization of CMB satellite.
- 4) We consider the described version of PEGASO obsolete, any more. The new version, equipped with an attitude control system and a magnetic gradient meter is under development.

7 CONCLUSIONS

Polar Stratospheric Balloons provide access to space at a reasonable cost. This is extremely interesting for earth sciences, atmosphere science and cosmology. The success of Pegaso missions demonstrated the possibility to build a small cost-effective long duration payloads and operate them getting scientific and technical results. The LDB (Long Duration Balloon) program is an established activity in the southern hemisphere, carried out by NASA/NSBF. The interest in this technology is rapidly growing and ASI, in a cooperative effort with ARR (Peterzen S. et al., 2005), is developing a program of balloon launches from the Svalbard site of Longyearbyen. This complementary one in the Northern Polar regions will add significant opportunities to scientific groups worldwide.

Pegaso missions are the first step in this direction. They have just achieved nice technical and scientific results, testing instrumentation and performing geophysical measurements.

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YEAR	START	FINISH	DURATION (days)
2000	30 May	20 July	50
2001	10 June	20 July	40
2002	20 May	30 July	70

Table 1: Artic Anticyclone period

PEGASO	POLE	LAUNCH DATE	FALLING DATE	N° of flights days	KM covered	Magnetometer
A	NORTH	24 July 2004	31 August 2004	39	12 624	No
B	NORTH	29 June 2005	23 July 2005	25	9 966	Yes
C	NORTH	5 July 2005	18 July 2005	13	6 317	No
D	SOUTH	1 february 2006	7 March 2006	35	13 978	Yes
E	NORTH	14 June 2006	2 July 2006	18	10 193	Yes

Table 2: PEGASO missions table.

Fig. 1: Anticyclonic circulation, 16 July 2002, 5mb

Fig. 2: Artic Ground Track Trajectory, 15 July 2002, 5mb constant level

Fig. 3: Trajectories and prediction. Gray traces represent Pegaso B (light gray) and C (dark gray). Segmented traces represent the trajectories prediction.

Fig 4: Root mean square of the prediction's error of the three missions Pegaso from Svalbard. The picture is calculated for four simulations each flight, made every 24 hours and with a duration of 5 days each.

Fig.5: trajectories of PEGASO's from Longyearbyen the track colors are relative to different payloads. Red: PegasoA; yellow: PegasoB; cyan: PegasoC; green: PegasoE. PegasoE, launched early in the season, traveled a perfect circular trajectory and was terminated in point in Greenland, accessible for recovery.

Fig. 6: Trajectory of PEGASO D from Mario Zucchelli Station (Antarctica) 2006

Fig. 7: PEGASO flight chain. This photograph of PEGASO E shows the complete flight chain. The termination, controlled by the PEGASO electronics by a long electrical wire inside the parachute canopy

Fig 8: Vessel layout a pressurized cylinder contains all the electronic parts of Pegaso allowing them to work in comfortable conditions

Fig 9: Ground station block diagram. Since an Iridium phone can be accessed from anywhere the ground station does not need a special place to work. It has been set in the INGV building to use the available resources. The flight control software automatically downloaded data, upgraded the web site and periodically notified the balloon(s) position to the interested personnel, and issued alarms in case of loss of height or malfunctions.

Fig. 10: Pegaso A ready to fly.

Fig. 11 The effect of the ballast releasing during the 2006 flight.

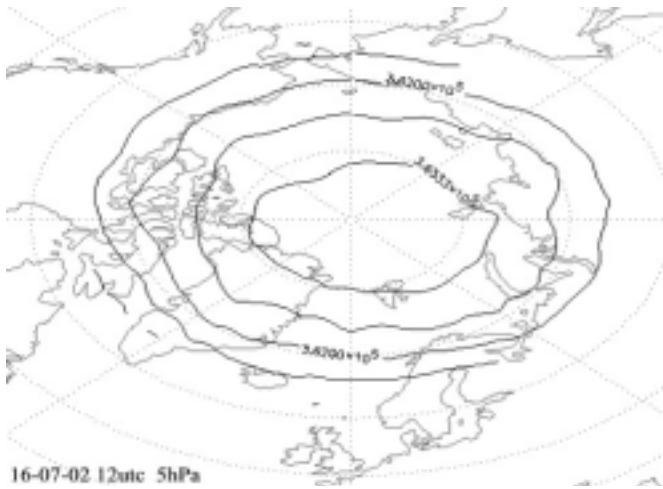
Fig. 12 The quick 5-kilometers descent shown in figure 11 was compensated by operating the four of ballast tubes. This raised the balloon of 9 kilometres, probably saved the flight and increased the estimated duration of over 10 days.

Fig. 13 Fig. A house keeping data fragment from PegasoE. Pegaso uses 3 flexible panels folded in a cylindrical shape. Current and temperature are individually monitored. The oscillation is caused by the gondola rotations. Note the temperature diagram follows the current diagram, with a delay caused by the panel's thermal inertia.

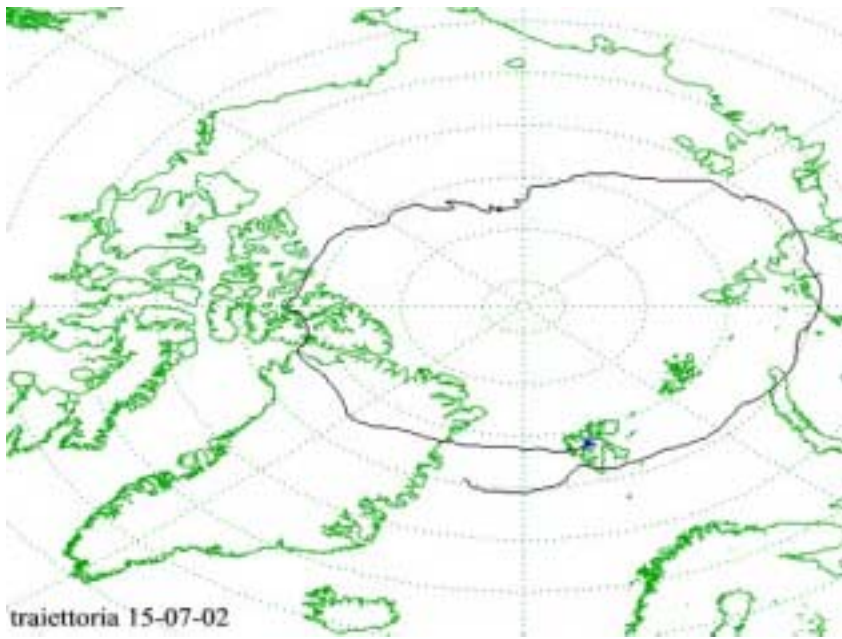
Fig.14 Pegaso E temperature panorama. The aluminum vessel keeps the temperature in a reasonable range. Half of the cylinder surface is exposed to the sunlight, the other half is exposed to the empty space. This balances the temperature inside the vessel. The oscillation in the diagram are tied to the sun elevation.

Fig 15: Rough data of the vertical magnetic field recorded by Pegaso B

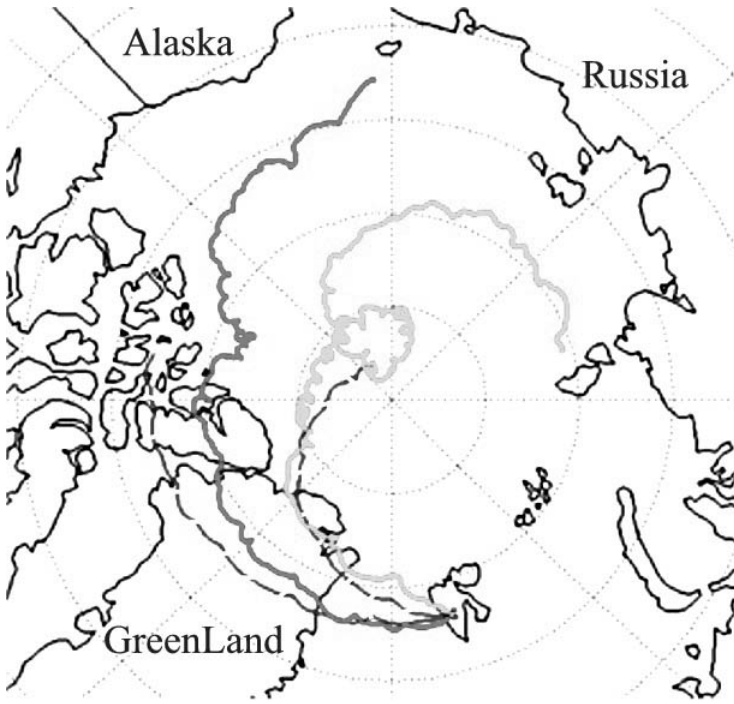
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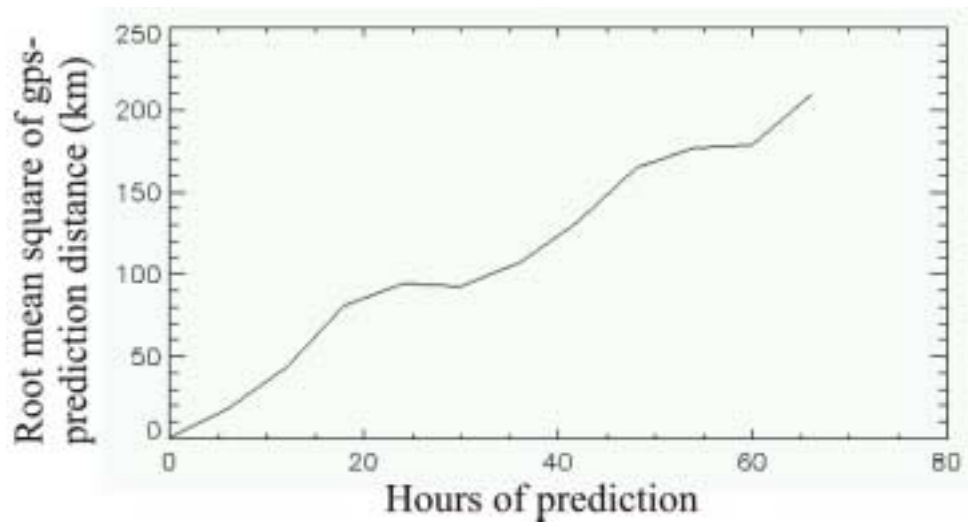
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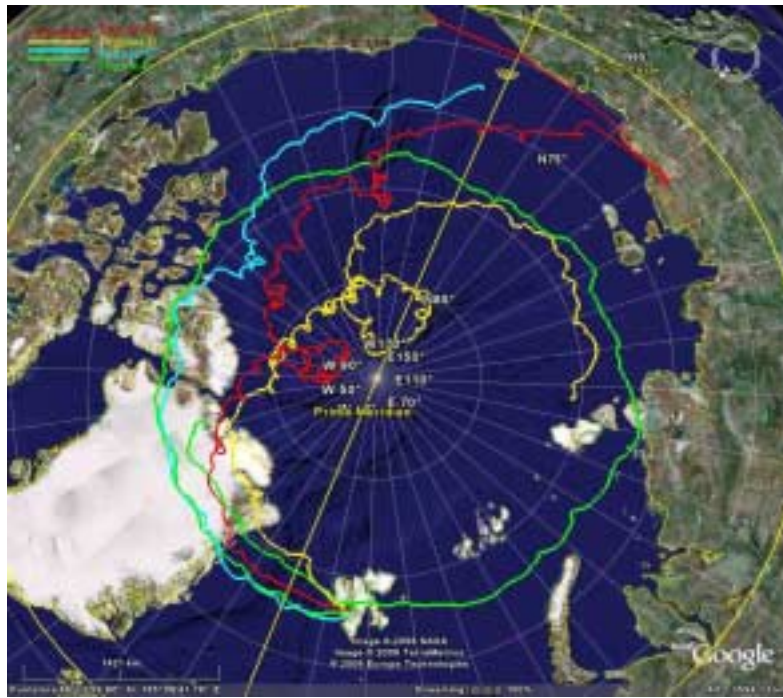
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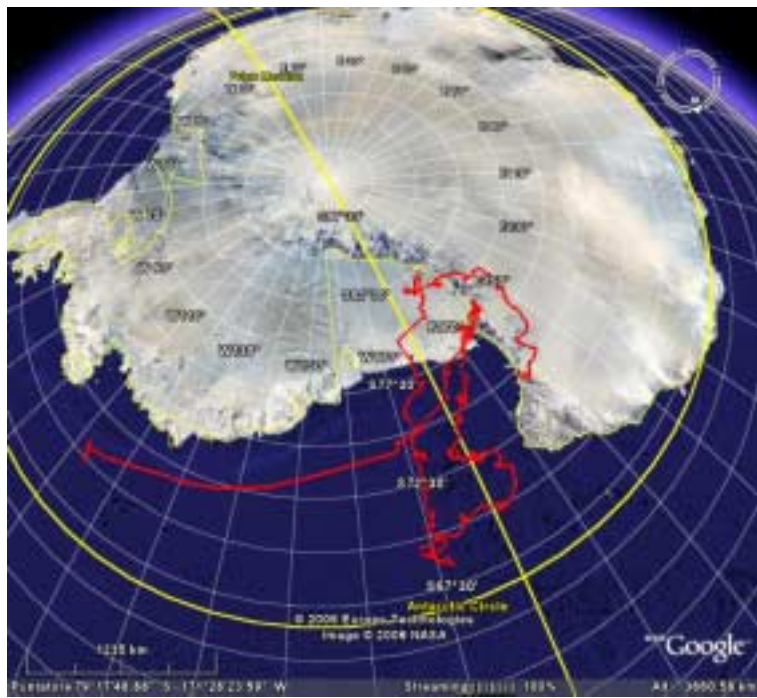
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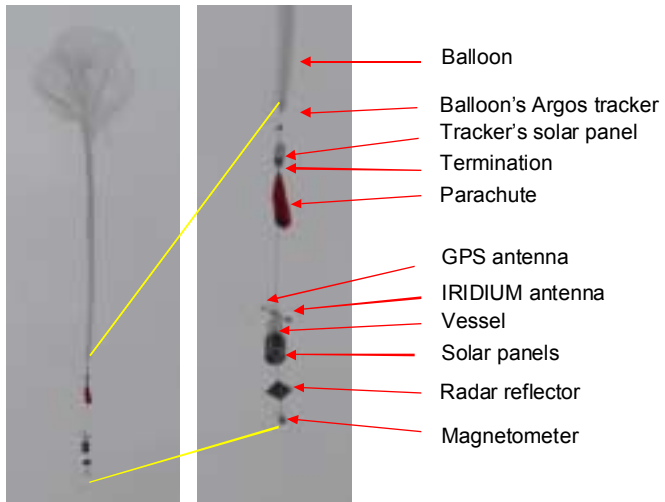
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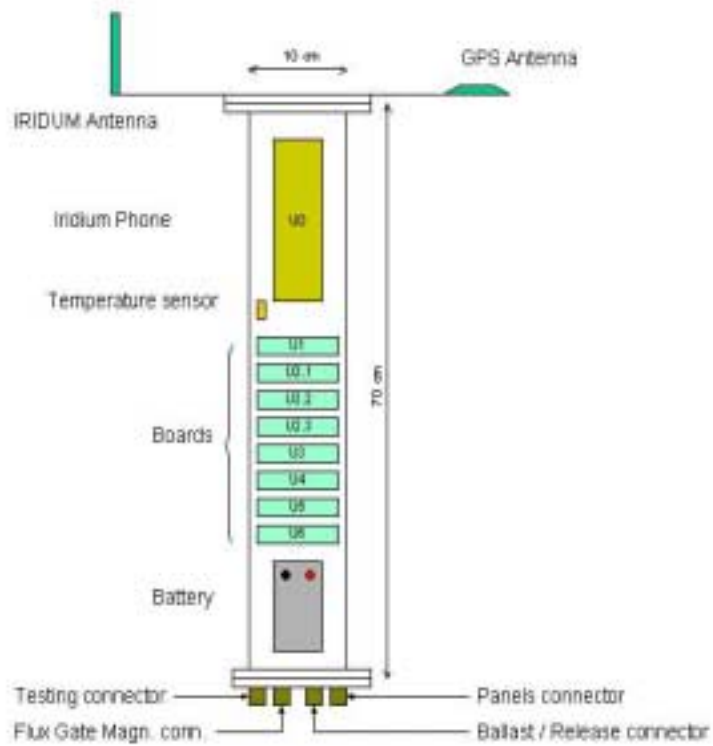
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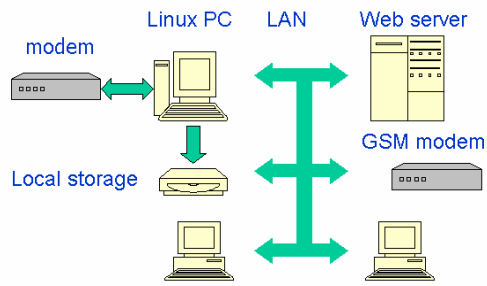


Figure



Ground station at INGV

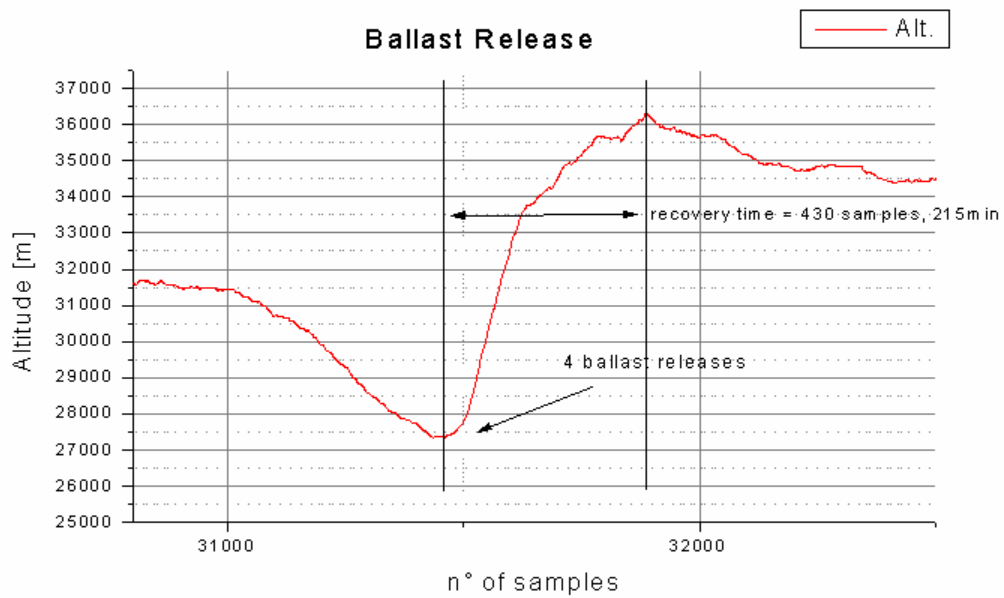
- Communication with 4 balloons
- Data available via web server
- Status via SMS
- Workstations via VPN



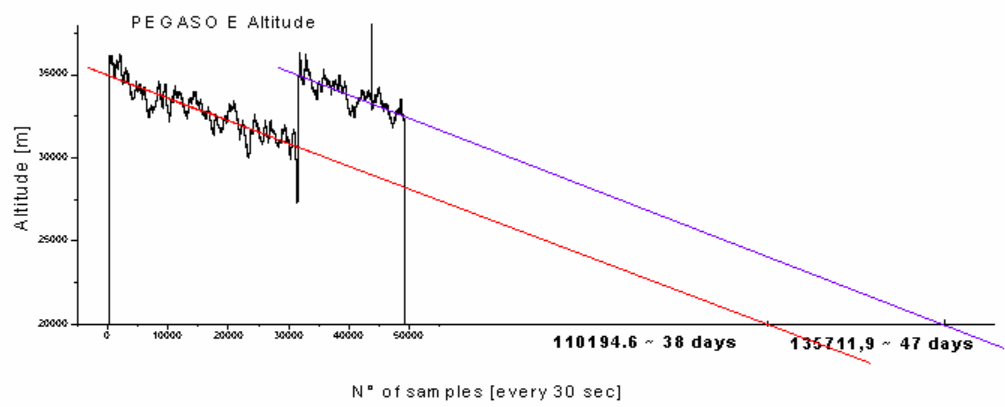
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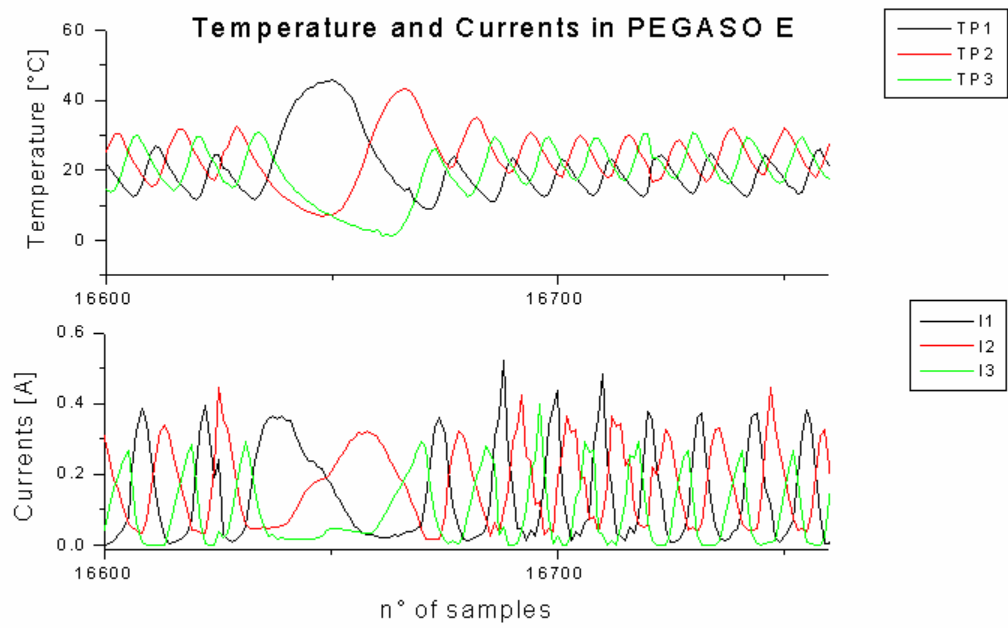
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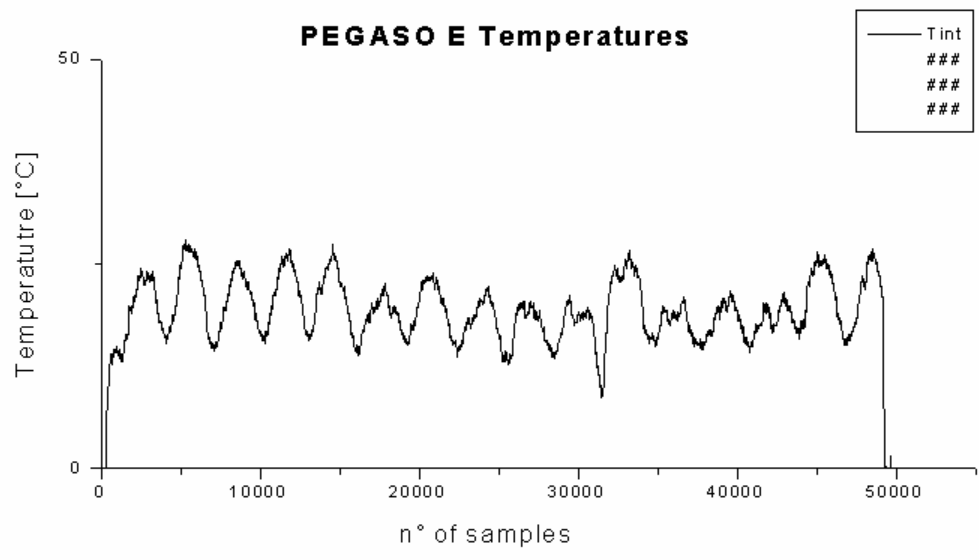
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