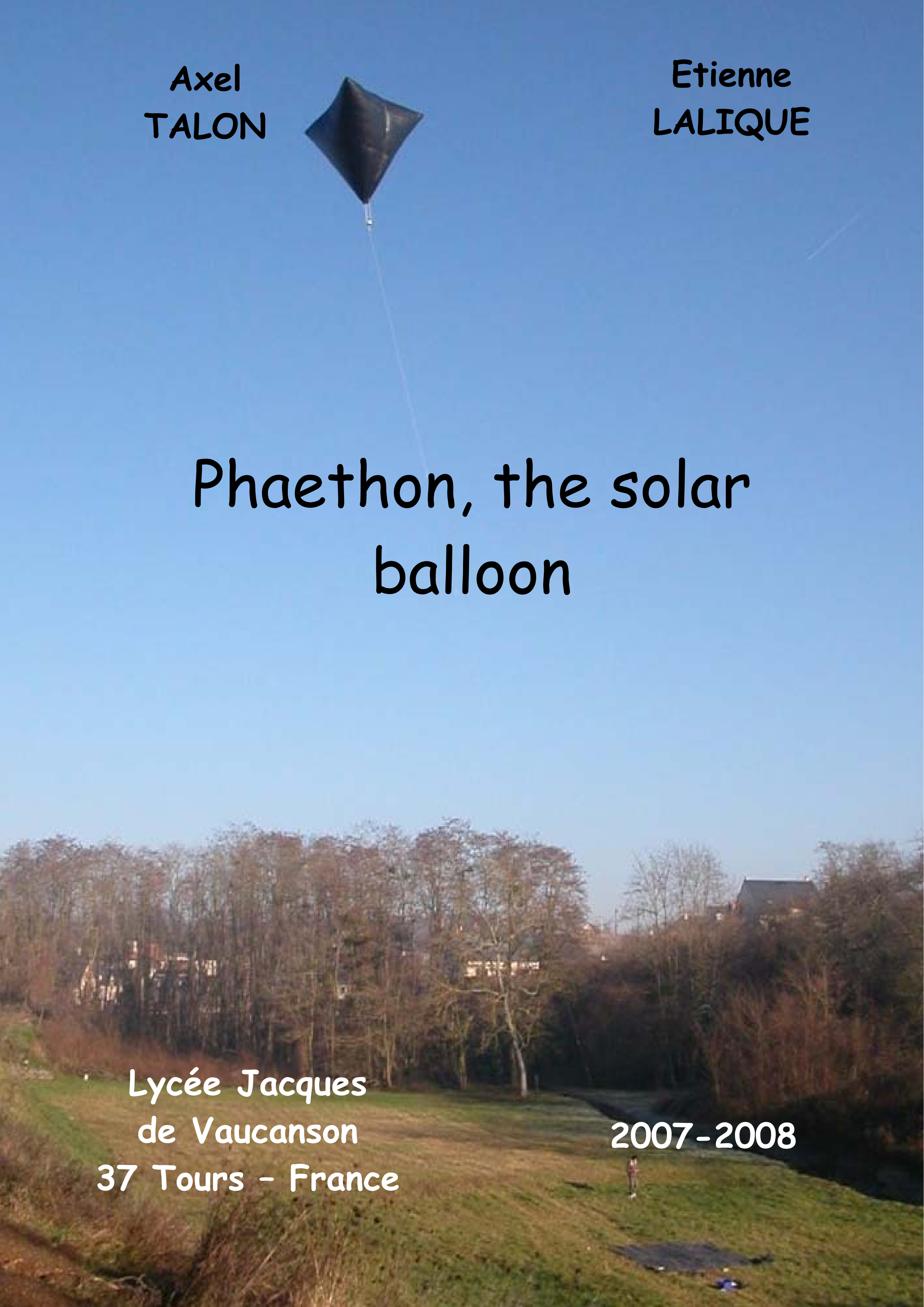
Axel
TALON

Etienne
LALIQUE

Phaethon, the solar balloon



Lycée Jacques
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37 Tours – France

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Synopsis

As we were pupils of eleventh year, we decided to study more in detail the solar balloons. The previous year, we had had the opportunity to study a sounding balloon inflated with helium. Surfing on the Net, we then found a website focusing on solar balloons. Their specificity and their ecological interest having appealed to us! A solar balloon is a hot air balloon which uses the energy of light to go up . Its envelope is made by black plastics which absorbs almost entirely the collected solar radiation, converting them into infrared rays allowing to warm the air inside.

To begin with, we led a static study of the balloon to answer the following question: in theory, what mass a given balloon can lift ?

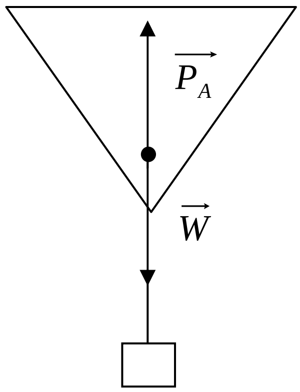
Then, we studied the flight of a solar balloon. We tried to foresee its horizontal track, and to follow its vertical one.

A. What mass can be lifted by a balloon ?

Our study had to take into account each step of the ballon flight (made of polythene, adhesive tape and ropes), the air inside and the payload added to the balloon. We analyzed the mechanical equilibrium within the terrestrial frame of reference. When static equilibrium of this system is reached in this frame, the balloon is subject to forces that balance each other out according to Newton's 1st law. Consequently, we had to study the forces that act on the balloon at mechanical equilibrium, then we had to estimate the parameters on which the forces depend. Finally, we had to apply the inertia principle to calculate the mass that the balloon could lift.

1) Mechanical equilibrium of the balloon

a) Assessment of outside forces acting on the solar balloon



Doc.1 : Assessment of forces

In that experiment, we consider two forces acting on the system:

The weight *W*: The weight of the whole system can be divided into three parts :

Weight of the envelop (twine, adhesive tape, ropes), weight of the inside air, and weight of the payload added to the balloon. So we can write:

$W = W_{payload} + W_{inside\ air} + W_{envelop} = (m_{payload} + m_{inside\ air} + m_{envelop}) \times g$.

- $\overrightarrow{W}$: Weight in Newton (N).
- m_{load} : mass of the payload in kg ; $m_{inside\ air}$: mass of the inside air in kg ; $m_{envelop}$: mass of the envelop in kg.
- g : strength of the gravitational field in $N.kg^{-1}$. ($g = 9.81\ N.kg^{-1}$ at ground level, in Tours).

We need to know the density of inside air μ and the volume V of the balloon to compute the weight of the inside air :

$\mu = m/V$ so $m = \mu V$.

- Buoyancy $\overrightarrow{P_a}$: According to Archimedes' principle, an upward and vertical force is exerted on any object immersed in a fluid (liquid or gas). This force is equal to the weight of the volume of the displaced fluid. In the case which we study, the fluid is the ambient air. So, the standard is: $Pa = m_{ambient\ air}\, g = \mu_{ambient\ air}\, V\, g$.

P_a : buoyancy in Newton (N) ; g : strength of the gravitational field in $N.kg^{-1}$; V : volume of the balloon in m^3.

Consequently, we need to know the volume of the balloon, the density of the inside air and of the ambient air to evaluate the two forces.

b) Parameters influencing the forces acting on the balloon

→ Volume of the balloon

To save time and for practical reasons, we choose to build a tetrahedral ballon (tetroon) that is cut out in one single piece.

Considering the line of the tetroon, we can compute its volume as follow: $V = \frac{\sqrt{2}}{12}a^3$. Taking into account the plastic we use, the line of our tetroon is 5.77m long, so its volume V is $22.7m^3$.

→ Density of air

It is assumed that air is an ideal gas, that is to say that the average distance between air molecules is great enough so that the intermolecular forces are negligible.

According to the ideal gas law: pV = nRT, knowing that : $\mu = \frac{m}{V}$ and $n = \frac{m}{M}$ therefore, $pV = \frac{m}{M}RT$.

So : $\boxed{\mu = \frac{m}{V} = \frac{pM}{RT}}$

p : atmospheric pressure in Pascal (Pa) ; M : molar mass of the ambient air in $kg.mol^{-1}$.

R : ideal gas constant in $Pa.m^3.mol^{-1}.K^{-1}$ (R= 8.314 USI). ; T : air temperature in Kelvin (K).

μ : density of air in $kg.m^{-3}$.

Using this formula, we are able to compute the air density, knowing its temperature, its pressure and its molar mass.

Example: $p = 1{,}013.10^5$ Pa ; R = 8,314 $Pa.m^3.mol^{-1}.K^{-1}$; T (in K) = θ (in°C) + 273,15 ;

M_{air} = (80/100) x M_{N2} + (20/100) x M_{O2} (it is assumed that air is simply composed of 80% of nitrogen gas N_2 and 20% of dioxygen O_2) : M_{air} = 0,80 x 28,8 + 020 x 32 = 28,8 $g.mol^{-1}$ = $28{,}8.10^{-3}$ $kg.mol^{-1}$.

At a temperature of 30°C : μ = $1{,}013.10^5$ x $28{,}8.10^{-3}$ /(8,314 x 303) = <u>1,16kg.m^{-3}</u>; at 0°C : <u>μ = 1,29kg.m^{-3}</u>.

c) Theoretical mass that a given balloon can lift

According to the inertia principle, buoyancy has to exactly offset the weight so that the balloon is in equilibrium. Concerning our balloon, we act on the mass of the load so that net weight is balanced by buoyancy, so that the balloon will stay in the air.

In short, weight has to be the same as buoyancy.

$P_a = W \leftrightarrow \mu_{ambient\ air}\, g\, V = W_{load} + W_{inside\ air} + W_{balloon} \leftrightarrow \mu_{ambient\ air}\, g\, V = (m_{load} + m_{inside\ air} + m_{balloon})\, g \leftrightarrow$

$\mu_{inside\ air}\, V = m_{load} + m_{inside\ air} + m_{balloon}$.

So, the payload is: $\boxed{m_{load} + m_{balloon} = (\mu_{ambient\ air} - \mu_{inside\ air}) \times V}$

d) The mass that our balloon has actually lifted

→ First try

We put a thermometer at the centre of the 22.7 m^3 balloon for our first experiment. As the ambient air was 0°C, the temperature of the air inside reached 30°C at the centre of the balloon. The ballon lifted 2 kg more than its own mass. We can see wether the outcome of the experiment are consistant with theoretical expectation:

A 0°: $\mu_{ambient\ air} = pM/RT = 1.013.10^5 x28.8.10^{-3}/ (8.314x273) = \underline{1.285\ kg.m^{-3}}$

A 30°C: $\mu_{inside\ air} = pM/RT = 1.013.10^5 {*}28.9.10^{-3}/(8.314x303) = \underline{1.158\ kg.m^{-3}}$

From which $m_{load} + m_{balloon} = 1.285x22.7- 1.16x22.7 = \underline{2.88\ kg}$.

Computation of the theoretical payload of our solar balloon

width **PET** (in m)	T_ambient (°C)	T_inside (°C)	Pressure (in h/Pa)	mass of the balloon (in kg)	g (in N/kg)	M_{air} (g/mol)
5	0	30	1012	1.23	9.81	28.8

Line (in m)	V (in m^3)	μ ambient (kg/m^3)	μ inside (Kg/m^3)
5.77	22.7	1.28	1.16

Pa (in N)	W_{air} (in N)	$W_{balloon}$ (in N)	W_{load} (in N)
285.6	257.3	12.1	16.1

$\mathbf{m_{load}}$ **(in kg)**
1.65

Doc.2 : The theoretical mass that can be lifted by our balloon

In such conditions, the balloon was able to go up with a total mass of 2.88 kg. As its mass was 1.23 kg (including thermometer and basket) the balloon could lift a 350 g payload. So, there was a difference of 1.65 kg between the theoretical value and the experimental one. We developed two hypotheses to explain this difference:

- When the envelope of the balloon warms up, the plastics may expand and the shape of the ballon may become more round, as it is shown on the picture on the right. Thereupon, the volume may increase, allowing the balloon to go up with a higher mass. However, to lift an extra charge of 350g, the volume of the balloon should have reached 25.8 m^3 which means that it should have increased by a little bit more than 3 m^3. This seems unlikely.

Doc.3: 24/12/07 try

- Heterogeneity of the temperature inside the balloon seems to be a more realistic hypothesis. In the first experiment, the temperature sensor was placed in the middle of the balloon. The envelope absorbs the solar rays which are converted into infra-red rays which heats the inside air. As the air inside the balloon is heated from the surface to the center, the temperature of the air in the center of the ballon may be lower than the temperature of the air which is closer of the surface, because of the time required to homogeneize the temperature by conduction and convection. Il this hypothesis, the average temperature inside the balloon is probably higher than what is indicated on the sensor

→ **Second try**

We decided to make a second attempt, and this time we placed two thermometers : one at the centre of the balloon, the other at 30cm from the upward surface of the balloon.

Measurements : atmospheric pressure : 1003 hPa ; ambient temperature : 5°C ; temperature at the centre of the balloon: 29°C; temperature near the upward surface inside the balloon: 37°C , payload: 1.80 kg.

With this experiment, we came to the conclusion that the temperature inside the balloon is far from being homogeneous. It is much higher near the surface. However, even with several thermometers, it seems difficult to precisely compute the average value of the temperature. Nevertheless, we can deduce the average temperature inside the ballon according to the mass of the payload:

A 5°: $\mu_{ambient\ airt}$ = pM/RT = $1{,}003.10^{5}$x$28{,}8.10^{-3}$/ (8.314x278) =1.27 $kg.m^{-3}$

A 29°C: $\mu_{inside\ airt}$ = pM/RT = $1{,}003.10^{5}$*$28{,}9.10^{-3}$/(8.314x302) =1.15 $kg.m^{-3}$

A 37°C : μ_{inside} air = pM/RT = $1{,}003.10^{5}$*$28{,}9.10^{-3}$/(8.314x310) =1.12 $kg.m^{-3}$

So m_{load} = 1,270x22.7- 1,15x22.7 – $m_{balloon}$ = 1,49 kg

m_{load} = 1,270x22.7- 1,12x22.7 – $m_{balloon}$ = 2,17 kg

1.80 kg, which is the payload actually lifted, is an intermediate value. Thanks to the value of this mass, we can compute the average density of the air inside :$\mu_{inside\ air}$ = 1,14 $kg.m^{3}$, which amounts to an average temperature of 32.6 °C inside the ballon.

To maximize the payload, one has to maximize the difference of temperature between the inside air and the ambient air. So, what are the better conditions to obtain the heaviest payload ?

2. How to increase the payload ? Origin and quality of the radiation

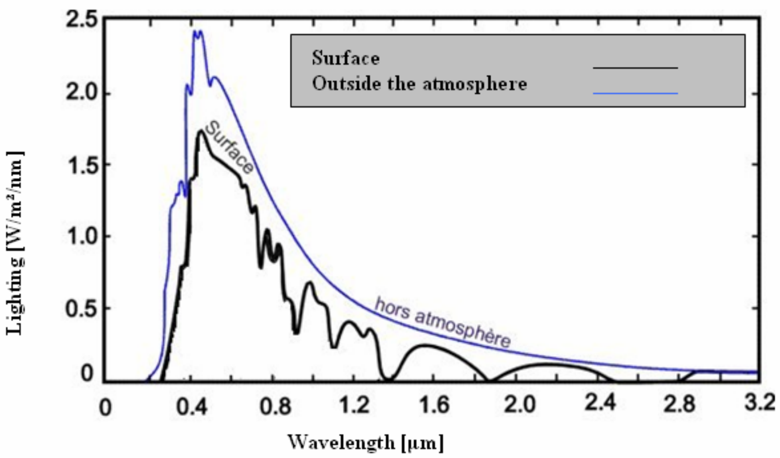
We decided to use black polyethylene as material composing the envelope as it is highly resistant, thin (18 to 20 µm according to the dealer) and highly absorbent. The albedo of the polyethylene is virtually equal to zero (the albedo being the % of energy the balloon reflects compared with the energy it absorbs). It absorbs almost the whole of the light, i.e. 95% (albedo= 0.05), according to the measurements taken by a radiometer. But, what does the light energy absorbed by the balloon depends on ?

a) Solar energy (direct radiance)

The sun gives out energy in the form of electromagnetic rays, called the solar radiance. Human eye perceives only a part of this radiance. This part corresponds to the wavelengths going from 400 nm to 700 nm.

Blue curve: solar radiance above the atmosphere

Doc.4 : Spectral density of the energetic of the solar radiance



Black curve: solar radiance at direct ground level, height of the sun: 65°, standard and clear atmosphere

The main part of the solar energy is radiated in the visible and infrared but also in the ultraviolets. The amount of solar energy received by time unit and by square meter perpendicular to solar rays at the upper limit of the atmosphere, in the case of average Earth-Sun distance is named solar constant. This solar energy has been estimated at 1367 W/m².

b) Propagation of solar radiation in the atmosphere

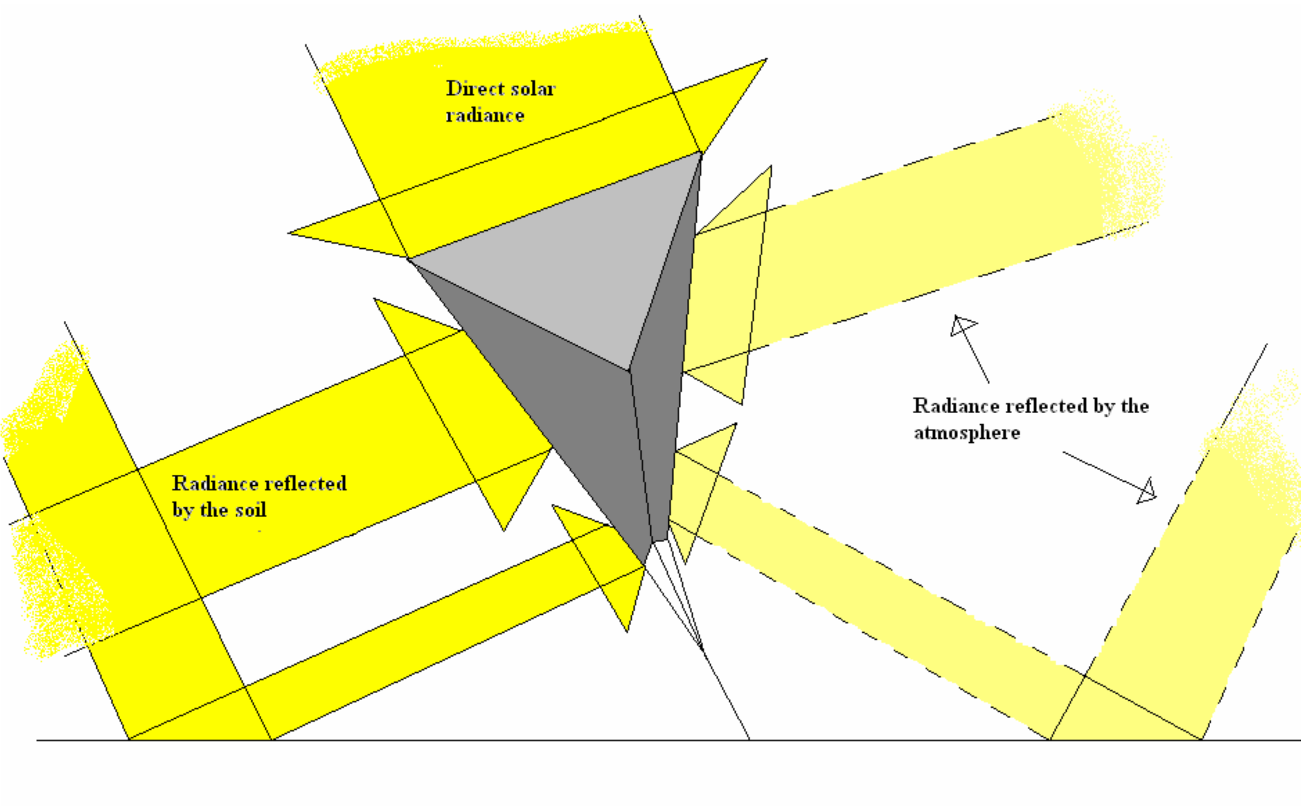
When the solar radiance is propagated in the atmosphere, there are interactions between this solar radiance and the components of the air, and with all the particles in suspension (aerosol, water droplets and ice crystals)

Solar radiance can be reflected, diffused or absorbed:

→ **Reflected**, by the ground, that is to say sent back in a privileged direction (specular or mirror reflection)

→ **Diffused** : the light is dispersed in all directions. There can be a diffuse reflection due to thin particles or molecules in higher atmosphere. It highly depends on the size of the considered particles. For example, the influence of the molecules in the air is more important upon the short wavelengths (blue) than on the long one (red) because of Rayleigh scattering law.

→ **Absorbed** by the gases composing the atmosphere. This absorption is selective as it only absorbs some wavelengths of light. Selective absorption is due to steam water, ozone, carbon dioxide and dioxygen.



Doc.5 : Direct, diffused and absorbed solar radiance

The Direct solar radiance is the radiation that reaches the Earth's surface without having been diffused. The black curve represents the direct solar radiation spectrum on the Earth's surface. It is considerably different from the radiance that reaches the upper limit of the atmosphere especially as it is absorbed by the gases that comprise the atmosphere. The radiance is attenuated and even totally absorbed for certain wavelength.

c) Influence of clouds

Clouds perceptibly modify the importance of diffuse and direct radiance, as clouds are referred to as diffusers. Remember that the albedo corresponds to the ratio of diffusely reflected energy to incident one. The albedo of clouds varies from 0.4 to 0.9 depending on the type of clouds, their thickness, and the height of the Sun etc. Besides, clouds absorb a part of solar radiance even if it is a small part. Thicker clouds absorb less than 10% of the incident energy. The following chart shows measurements of the remaining global radiance after having crossed various types of clouds. When the sky is cloudy, the global radiance reaching the surface is always lower to the global radiance reaching the surface when the sky is cloudless under equivalent conditions. Other remark, low clouds are the more absorbent clouds, whereas high altitude clouds let through the major part of the incident radiance.

High altitude clouds		Mid altitude clouds		Low altitude clouds			
Cirrus	Cirrostratus	Altocumulus	Altostratus	Stratocumulus	Stratus	Nimbostratus	Fog
0,83	0,80	0,50	0,41	0,34	0,25	0,18	0,17

Doc.6a : Albedo of various types of clouds (ref : La météorologie 8ème série n°31, septembre 2000)

d) Influence of the Earth's surface

The albedo of the Earth surface is the ratio of the radiance reflected by the earth surface to the radiance reaching the earth surface (surface's and body's diffuse reflectivity). This albedo is very different depending on the type of the surface and its condition (as well as with the incident wavelength and the height of the Sun). Here are some average albedo values for different types of soil or conditions of the surface.

Doc. 6b : Different Earth's surface albedos (ref : La météorologie 8ème série n°31, septembre 2000)

Type of surface	**Albédo**
Black object	0
Dark rock (ex: basalt)	0,05
Dark waters(ex: oceans)	0,07
Black soils (ex: ashes)	0,05 à 0,16
Concrete	0,15 à 0,30
Sand	0,25 à 0,30
Ice	0,30 à 0,50
Huddled up snow	0,50 à 0,80
Fresh snow	0,80 à 0,90
Perfect mirror	1,0

B- What is the typical flight path of a solar balloon?

After these mechanical studies, we decided to go further by studying the typical flight path of a solar balloon. First: we planned to estimate the track of our balloon. Second: we tried to analyzed the real track of our balloon.

We had to build a more voluminous tetrahedron (76 m^3) and a basket big enough to carry measurement tools in order to carry out experiments aboard: measurements of physical values (pressure, ambient air temperature, inside air temperatures and lighting), GPS follow-up, horizontal and vertical shots (camera and video camera).

1. Estimations and follow-up of the balloon flight path

a) Follow-up with the GPS/APRS

→ **The G.P.S. (Global Positioning System):** We used a GPS navigator fixed in the basket. The GPS uses Medium Earth Orbit Satellites that are exactly located. To solve for a position on Earth, the GPS uses the triateration principle: the location of the object is on the flight path of three satellites that orbit in outer space around the object. Using four satellites allows the receiver to determine time, altitude, latitude/ longitude and speed. The ham radio operators in Tours defined these five parameters of our system which were sent us during the flight. Each satellite broadcasts its identification number, its precise orbit and the exact time the message was sent. Thanks to this information and the integrated clock synchronized with the one of the satellites, the receiver computes the signal traveling at the speed of light through outer space and measures the distance to each satellite from which it determines the position of the receiver.

→ **Operation of the APRS (Automatic Position Reporting System) :**

In order to follow-up our balloon live, we connected the GPS receiver to the APRS composed of:

- The AX 25 which network transfers data encapsulated in packets and proceeds to fast packet forwarding. Tinitrack is a modem which encrypts these data coming from the GPS receiver.

- A VHF radio transmitter that broadcasts encrypted data on the 144,800 MHz frequency dedicated to the APRS network. The ham radio relay stations receive these data in real-time. They are transmitted through radio waves and the Internet (VPN system, Virtual Private Network), especially through the web site http://aprs.fi/. Our system was identified under the following: F6KCI-11. It is possible to have a look at the data concerning our tries on this web site as they remain available for 6 months. Direct transmission of data or relay station-to-relay station transmission allows a real time follow up of the balloon. In fact a receiver is connected to a lap-top which contains, for example, the UI-View program created by ham Roger Barker G4IDE.

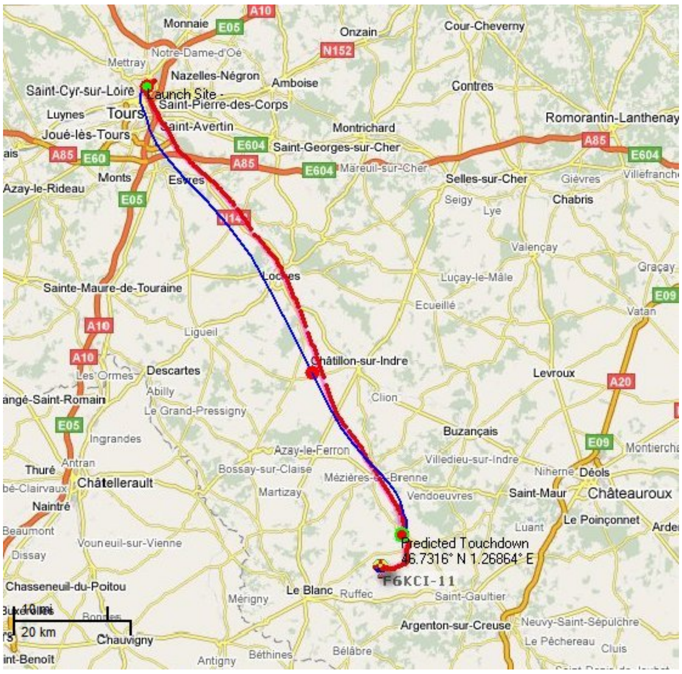
b) Estimations

The software **Balloon Track** created by another ham gives an estimation of where the balloon could land. It uses the following data:

→ Average climbing and descending speeds,

→ Time of descent,

→ Estimations of direction, strength and direction of winds in altitude, collected by the NOAA (National Oceanic and Atmospheric Administration).



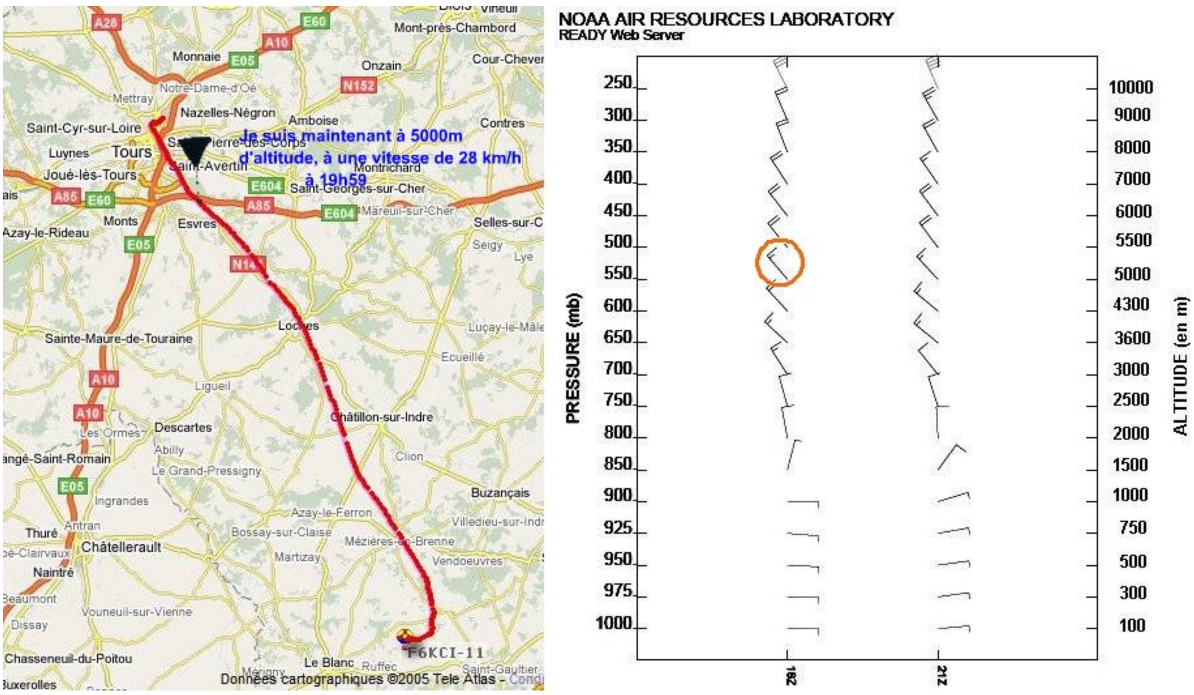
Doc.7 : Real horizontal track of the balloon in red and estimation in blue for the third release (25/04/2008).

The first release of our balloon happened on 4th April 2008 6.30 PM loc. Consequently, we were able to:

→ **Estimate** the climbing and descending speeds of the balloon at the end of the day with a cloudless sky, i.e. 1.5 $m.s^{-1}$ when climbing and 1.9 $m.s^{-1}$ when descending. These values may slightly vary depending on the lighting (position of the Sun in the sky and presence/absence of clouds).

→ **State** that the balloon descent coincides more or less with sunset. Consequently, we are able to estimate the maximal altitude of the balloon. The speed of the whole system decreases before sunset as the gradient of the temperature between inside and outside the balloon becomes insufficient.

So, we were able to plan where the balloon would land for the other releases. For example, for the 3rd release, we notice on the map attached that our estimation was very similar to the effective track of the balloon: the balloon landed 5 km only away from the estimated landing area. So we were able to be quickly on the landing area. We found the balloon only 10 minutes after its landing thanks to the GPS/APRS that had sent a last piece of information while on the ground. But this would have been impossible if we had not been next to it because of its low transmission power (110mW). The following map and chart, extracted from our web site, help us to compare the real track of the balloon (direction and speed) with forecast horizontal winds. For example, we noted that the balloon, 5000m high, flew at around 28 $km.h^{-1}$, at 140° from the North-South axis after 45 minutes of flight. It totally corresponds to the estimations about direction and strength of winds (15 knots, i.e. 27 $km.h^{-1}$). Note that the speed indicated by the GPS is not the horizontal speed. But the vertical one is only 1.5 $m.s^{-1}$, i.e. 5.4 $km.h^{-1}$, it has no importance compared with the horizontal speed ($v^2 = v_x^2 + v_y^2$, i.e. $v_x^2 = v^2 - v_y^2$). We get 27.5 $km.h^{-1}$.



Doc.8: Comparison of the horizontal track of the balloon with the forecasted horizontal winds. 3rd attempt28/04/08

2) Study of mechanics of flight

a) Assessment of outside forces acting on the solar balloon

→ Specifications of the components of the system:

The balloon : We chose to build a 76 m^3 tetrahedron. Its line is 8.4 m long and we used 3 polyethylene bands, each being 2.5 m large, that we joined side by side. The balloon weighed 2.0 kg, adhesive tape and ropes included. Actually, the volume chosen seemed to be a minimum for the balloon to be able to lift a 2 kg load added to its own mass, with a temperature gradient of 15°C.

The chute: 50g ; Radar reflector: 150g ; The basket: a cube with a 30 cm line and a mass of 1.80 kg made of extruded polystyrene.

Doc.9 : The system

We will study the whole system made of the above-mentioned components; its **total mass is 4.0 kg** including the mass of the inside air. The whole system movement will be studied in the terrestrial frame of reference (cf. Gallileo).

→ Assessment of forces acting on the system S

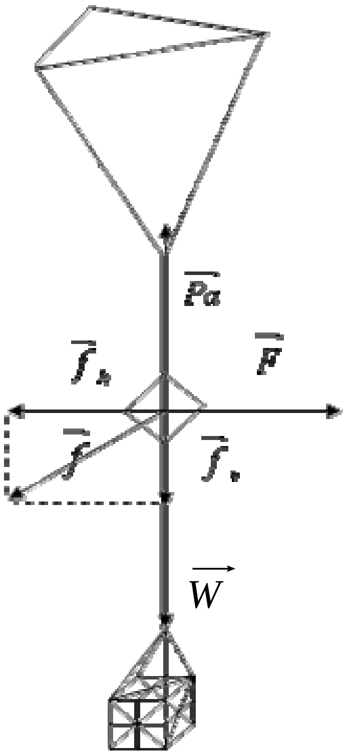
- Weight of the whole system: $\vec{W}$; - Buoyancy: $\vec{P_a}$

- The drag or friction force $\vec{f}$ which is co-linear to the movement can be decomposed into a vertical component $\vec{f_v}$ and a horizontal one $\vec{f_h}$

The force $\vec{F}$ due to the wind is supposed to be horizontal only beyond 3000m high. We came to this conclusion after the discussion we had with Meteo France Tours engineers.

→ Take-off conditions:

Buoyancy $\vec{P_a}$ - directed upward - has to be greater than the weight $\vec{W}$ - directed downward. As there is no movement before take-off, there is no friction when the balloon takes off so as we do not need to take into account the ascendant movements.



Doc.10 : Forces acting on S

So, our tetrahedron can lift a load if Pa > W. To know the minimum difference of cubic mass necessary for our balloon to lift, use the following calculation:

$P_a > W \leftrightarrow \mu_{ambient\ air}\ g\ V > W_{load} + W_{inside\ air} + W_{balloon} \leftrightarrow \mu_{ambient\ air}\ g\ V > (m_{load} + m_{inside\ air} + m_{balloon})\ x\ g \leftrightarrow$

$\mu_{ambient\ air}\ V > m_{load} + m_{inside\ air} + m_{balloon} \leftrightarrow \mu_{ambient\ air}\ V > m_{load} + \mu_{inside\ air}\ V + m_{balloon} \leftrightarrow$

$\mu_{ambient\ air} - \mu_{inside\ air} > (m_{load} + m_{balloon})/V$

So, in our case, the result is: $\mu_{ambientair} - \mu_{inside\ air} > 4{,}0/76 = 0{,}053\ kg.m^{-3} =$ **$53\ g.m^{-3}$.**

Our system is supposed to take off, providing that minimum difference of cubic mass exceeds 53 $g.m^{-3}$.

→ **Climbing of the system:** Once our system is rising, it is then subjected to friction forces ($f = kv^2$). Thus these forces are proportional to the square of its speed and also depend on its shape and $\mu_{ambient\ air}$, through the constant k. We did not get any further yet in this study due to lack of time and knowledge. Maybe, this will be a new goal for next year…

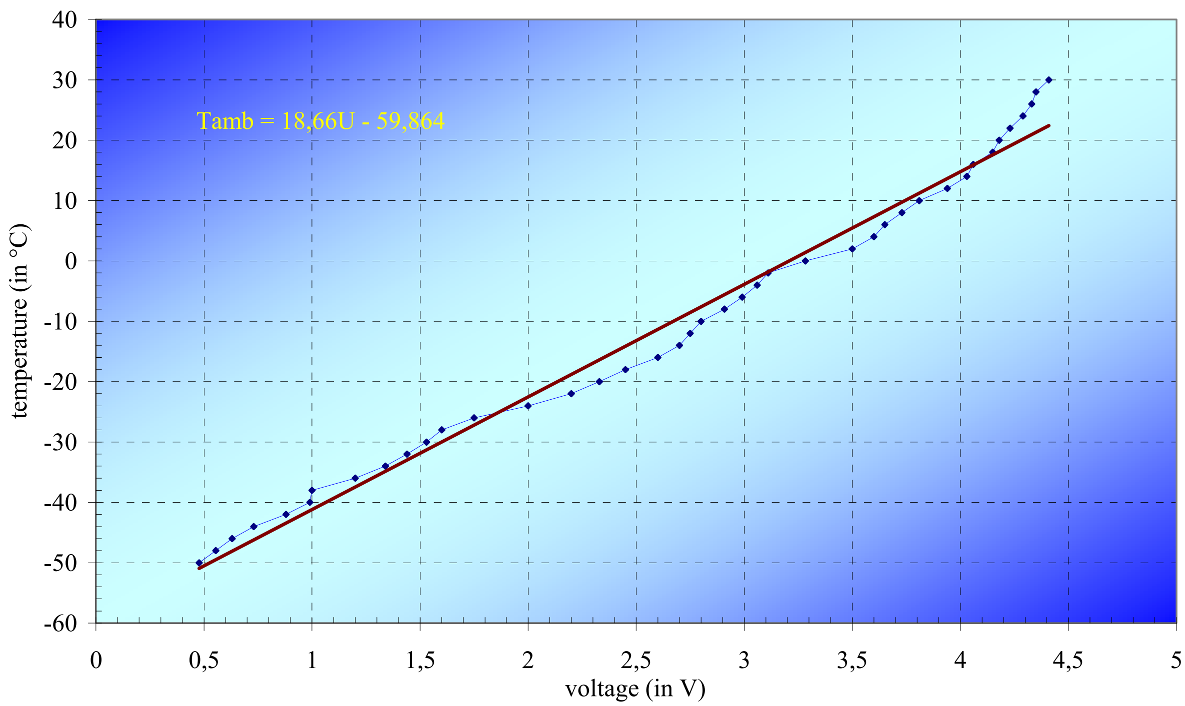
→ **Horizontal movement:** As we studied it previously, this system moves at the same speed as the surrounding air.

b) Measures to study the flight

Several sensors have been installed in the basket to measure the pressure, the inside and ambient temperature, the lighting. These results are sent to the ground by radio. CNES (French Government Space Agency) lend us a transmitter thanks to the Planète-Sciences Sarthe Association. As this transmitter can only send voltage data, we had to calibrate our sensors so as to link one measure to a specific voltage (Refer to the following calibration curve). For further details, visit our website: http://www.vaucanson.org/actions/solaire/experiences/.

Doc.11 : In the basket on 15/04/08

Doc.12 : Calibration of the outside temperature probe : Ambient temperature =f(U)



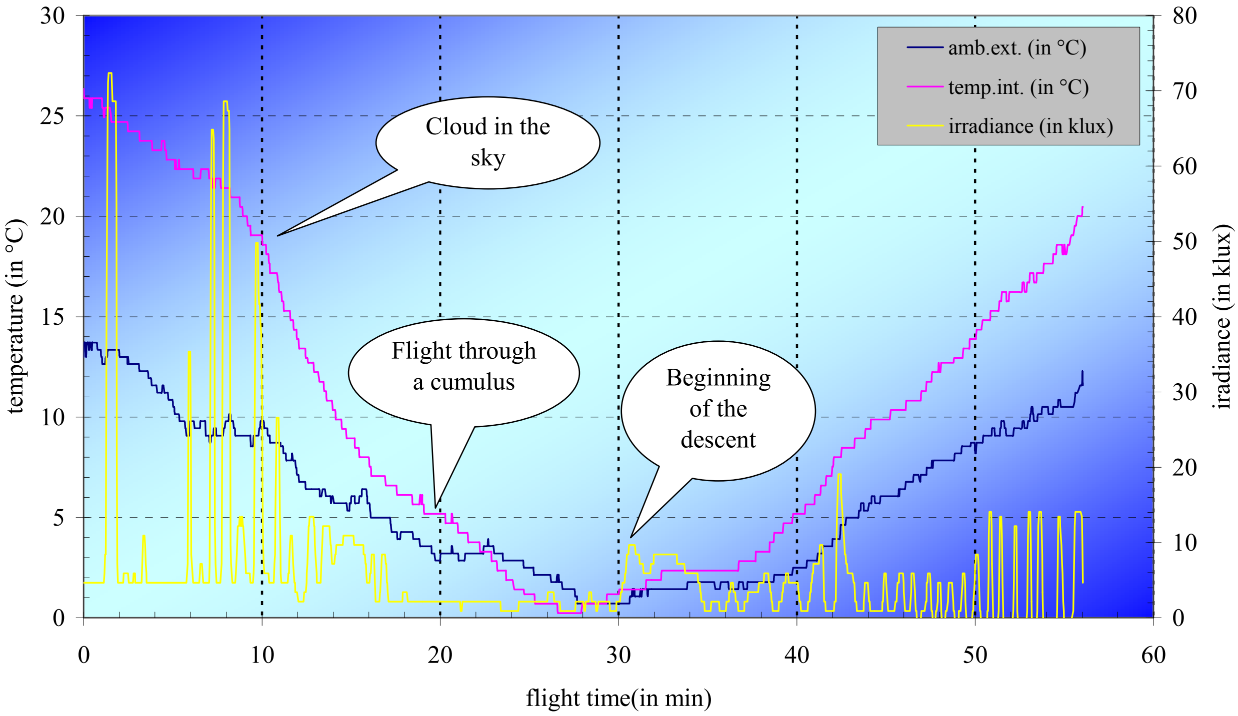
3) Study of the 2nd try


Doc.13 : Picture of the horizon taken at 1, 200m

The second try occurred on April 15th 2008 at 7 PM. The balloon was supposed to land 200 km from Tours, but the flight ended 1 hour later at a 5 km distance only. A cloud disturbed the flight path only 10 minutes after take-off by hiding the sun from the balloon.

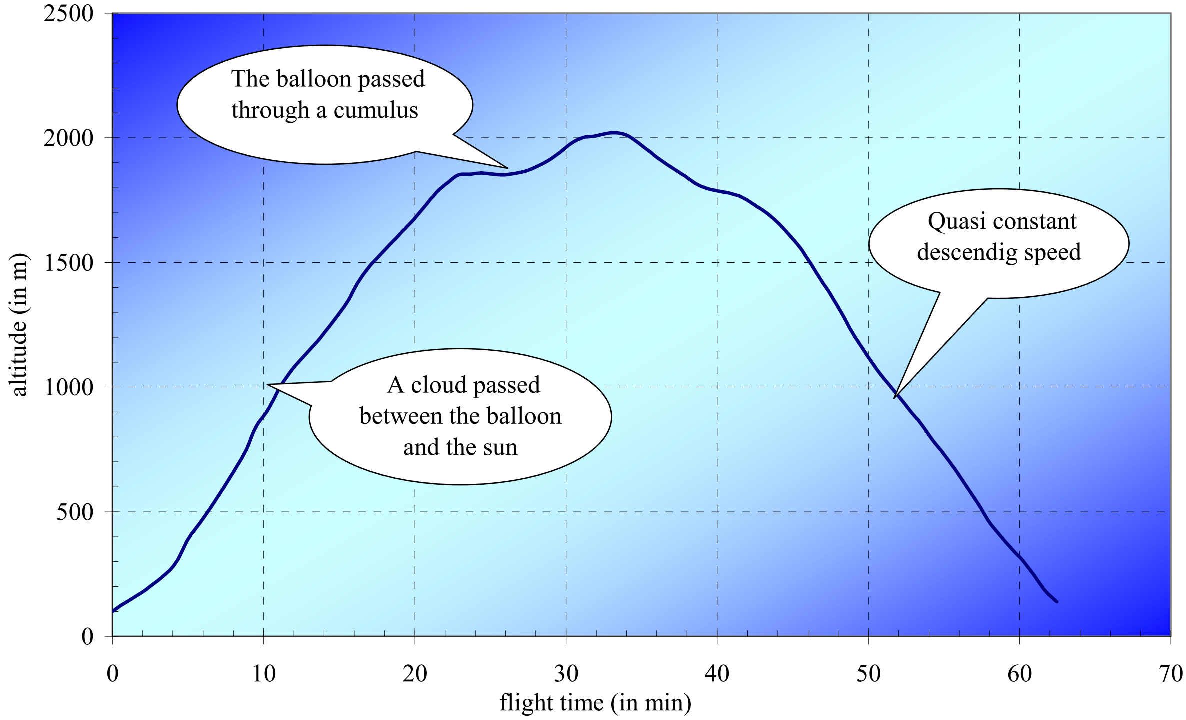
This was noticed on the following curves (doc.14 and 15): during the first ten minutes of flight, the inside temperature decreased slowly compared to the ambient temperature, thanks to an important solar radiation. But after that period, the inside temperature was decreasing faster.

Doc.14 : Measures taken according to flight time



The difference between the inside and ambient temperatures rapidly became insufficient to allow the balloon to fly. The climbing of the balloon slowed down as you can see on the next curve (doc.15). But the balloon resumed a 200 m climb after 28 minutes of flight. We cannot explain this thanks to the previous assessment of the forces. But we noticed the balloon was below another cloud which was attracting it. As we were explained by Météo France Tours engineers, clouds can trigger upward movement due to convection phenomenon. We learnt a lot about clouds and their development from this failed flight: http://www.vaucanson.org/actions/solaire/animations/nuages/meteofrancenuage.htm.

Doc.15 : Altitude in fight



4) Study of the 3rd try

The number of sensors on board was maximum:

- 2 ambient temperature probes
- 2 inside temperature probes
  - 1 at the bottom
  - 1 at the upper surface of the balloon
- 2 horizontal-directed lighting probes
- 2 pressure gages

Doc.16 : picture taken at 4,000 m

Unfortunately, as we noticed when we got the balloon back, the inside temperature sensor which was installed 30 cm from the upper surface fell few seconds after take-off and the measured inside temperature was very close to the ambient one.

a) Take-off

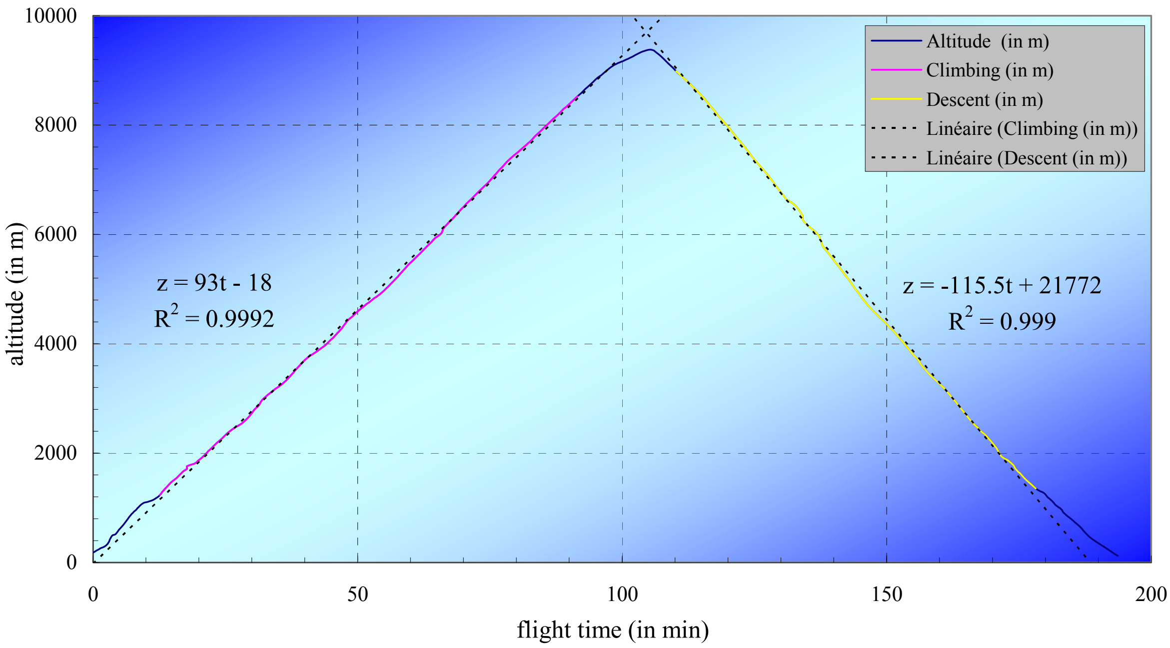
Parameters at take-off: ambient temperature: 18°C; inside temperature (center of the balloon): 34°C; atmospheric pressure: 1018 hPa.

So, the inside air cubic mass is 1.15kg.m^{-3}, and the ambient air cubic mass 1.22 kg.m^{-3}.

At take-off, the minimum difference between the inside and ambient airs is about 70 g.m^{-3}. As our balloon needed at least a difference of 53 g.m^{-3} to take-off, we concluded we had a minimum thrust of 17 g.m^{-3}, about 13N with a volume of 76 m^3 (those who do not feel confident with Newton data, 13N is a force equal to the force of a 1.3 kg mass...).

b) Climbing

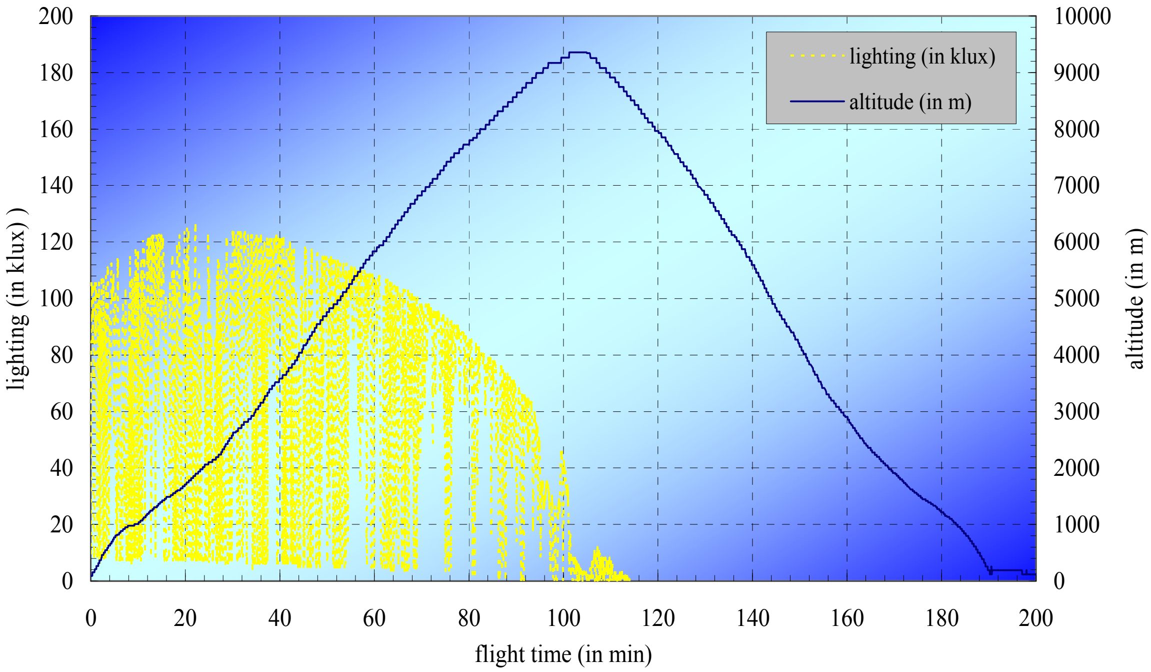
Doc 17: Flight and in-flight modeling



On the above chart (doc.17), the curve represents the balloon altitude according to the data sent by the pressure gage during the flight. We noticed that the climbing occurred at a constant speed, about 93 m.min^{-1}, i.e. roughly 1.5 m.s^{-1}. In the same manner, the descending speed is 116 m.min^{-1}, about 1.9 m.s^{-1}.

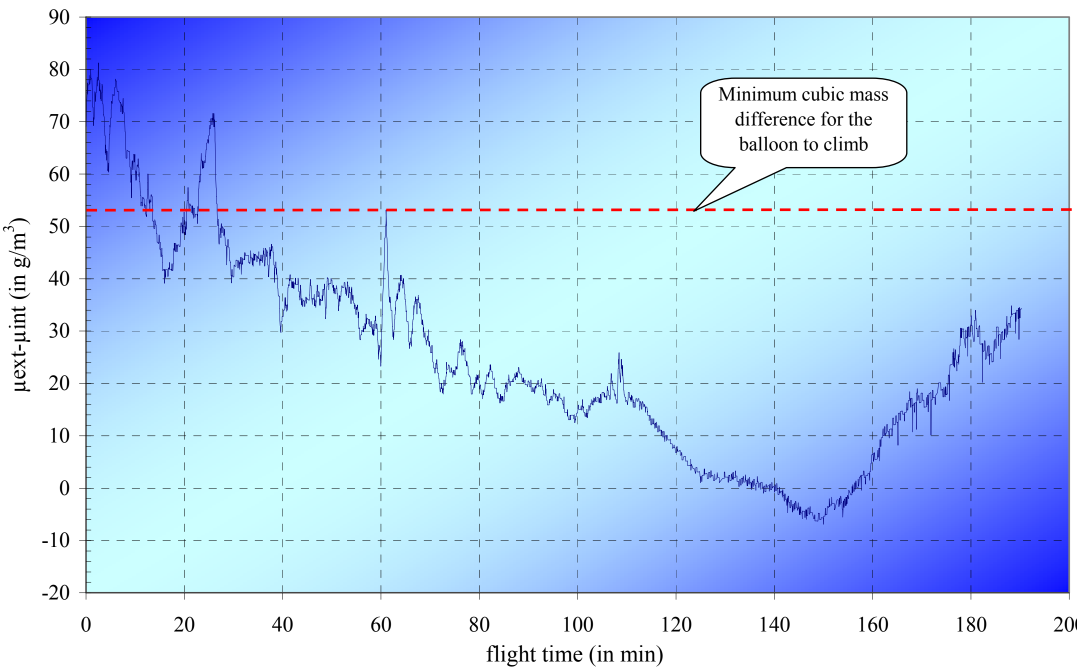
On the document below (doc.18), altitude and lighting are recorded. We notice that the balloon started to slow down after 80 minutes of flight, as the lighting began to decrease quickly as the sun set as well, while the balloon kept climbing.

Doc 18: Altitude and lighting during the flight



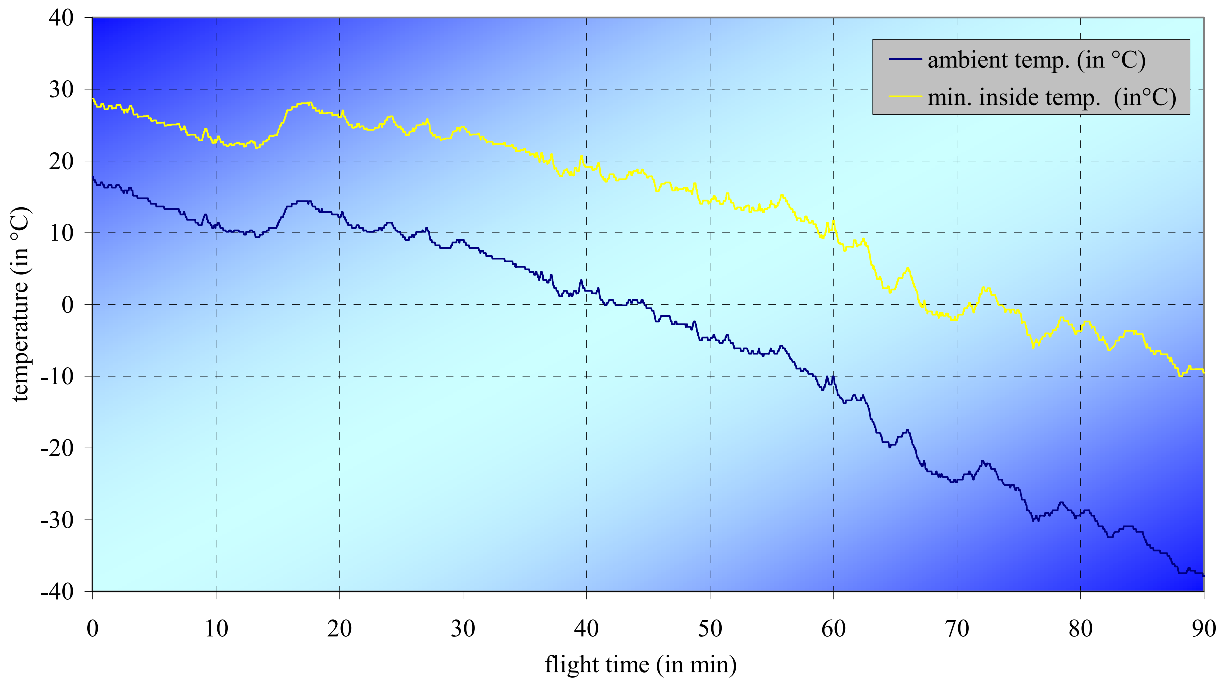
Thanks to these data (ambient temperature, center balloon temperature and pressure), we processed the difference of cubic mass between the inside and ambient airs in the center of the balloon, during the climbing and descending phases. But we noticed, as shown on the following curve (doc.19), that the difference is not sufficient to allow the balloon to climb during the whole flight. The explanation is similar to our studies on the ground: the inside temperature of the balloon is not homogenous and so its average value is far more important than the one at the center of the balloon.

Doc.19 : Cubic mass difference during the flight



Nevertheless, we are able to estimate the minimum average temperature inside the balloon, while it is climbing evenly and vertically. In these conditions, it means that buoyancy is more important than or equal to friction forces and weight altogether. In the following chart (doc.20), we estimate the average temperature inside the balloon so as to buoyancy compensates for the weight of the system. This temperature is always a minimum because friction forces shall be considered. We noticed that the higher the system climbs, the more important the difference of temperature must be. As the pressure decreases – at a more significant rate than the ambient temperature, the cubic mass of the air decreases too, according to the formulae given in the 1st part. After 80 minutes of flight, the temperature gradient must be above 25°C while the balloon is flying at 8,000 m.

Doc.20 : Minimum inside temperature during the climbing



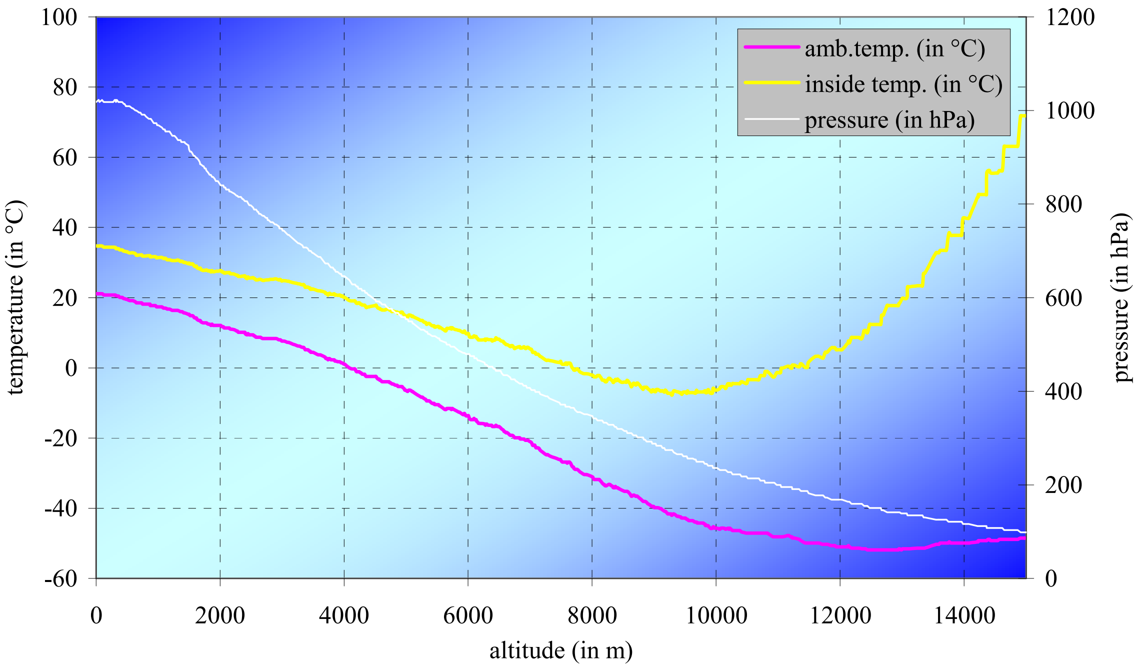
5) New horizons

Several questions remain unanswered, especially the two followings:

→ What is the temperature reached by the balloon envelope facing the sun? The temperature shall be very high as the average temperature allows the balloon to climb. More than two inside temperature sensors should be installed. Let's keep the one close to the center and the other one close to the upper surface. We should stick one on each of the 3 surfaces of the tetrahedron as only one faces the sun at a time.

→ What is the altitude the balloon can reach? Up to now, the balloon has been tested at the end of daylight, maximum two hours before sunset, so as to be able to follow the flight by car and to avoid a long trip. Of course, this altitude depends on the load on board and the lighting received. The maximum altitude should be reached by lightening the load and taking-off four hours before sunset. Last year, we managed to get the data (pressure, ambient temperature) of a sounding balloon flight. So we processed and established the average inside temperature that should exist for the balloon to reach 15, 000m high, as shown on the curves below (doc.21).

<u>Doc 21:</u> Inside and ambient balloon temperatures versus altitude



The balloon reached 11,670 m at the first try. According to these results, the difference of temperature would have reached more than 50°C, with an ambient temperature close to -50°C and an inside temperature of 0°C. For the balloon to reach 15, 000 m, the difference of temperature must be 120°C. This seems difficult. Considering the load on board for the 1st flight, the balloon probably reached its maximum altitude. The load will have to be lightened to decrease the necessary difference of temperature if we want to improve the climbing of the balloon.

We would like to perform a new try so as to answer these questions. It may probably occur on August 24, 2008 at Amboise, during a hot-air-balloon show we were invited to.

Conclusion

To conclude, solar balloons are most cost-effective than balloons using helium due to the envelope and the gas used. However, they request specific weather conditions, such as virtually no ground wind and a cloudless sky. We paid the price during some flight tests when riggings failed due to excessive wind or when, as a cumulus occurred, the balloon landed 5km from the its starting point instead of the 200km scheduled. The solar balloon purpose could be more effective on ice field, where the glare of the sun on the snow is important and the ambient temperature is very low. It could carry loads at cheap cost - 50 € for a balloon lifting a 100 kg load.

Nowadays, ARCA, a Romanian aerospace and aeronautic association established in 1999, develops new technologies to implement private-manned space flights. Balloons using this technology are being tested by ARCA in order to launch lightweight satellites or manned capsules. Actually, a voluminous solar balloon – expected to reach 350 000m^3 – will carry in June a capsule which could accommodate above 22,000 m. At this altitude, air friction is less important and it is no longer a problem (the weight of Ariane rocket is 400 tons compared to its first stage – 350 tons – whose purpose is to pass through the atmosphere of the Earth).

Solar balloons could start a new career, as they are cheap and they protect environment.

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