LAVOISIER : A LOW ALTITUDE BALLOON NETWORK FOR PROBING THE DEEP ATMOSPHERE AND SURFACE OF VENUS

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ABSTRACT

The in-situ exploration of the low atmosphere and surface of Venus is clearly the next step of Venus exploration. Understanding the geochemistry of the low atmosphere, interacting with rocks, and the way the integrated Venus system evolved, under the combined effects of inner planet cooling and intense atmospheric greenhouse, is a major challenge of modern planetology. Due to the dense atmosphere (95 bars at the surface), balloon platforms offer an interesting means to transport and land in-situ measurement instruments. Due to the large Archimede force, a 2 cubic meter He-pressurized balloon floating at 10 km altitude may carry up to 60 kg of payload. LAVOISIER is a project submitted to ESA in 2000 [1], in the follow up and spirit of the balloon deployed at cloud level by the Russian Vega mission in 1986. It is composed of a descent probe, for detailed noble gas and atmosphere composition analysis, and of a network of 3 balloons for geochemical and geophysical investigations at local, regional and global scales.

1. CONTEXT AND GENERAL DESCRIPTION OF THE MISSION

One of the most promising area in Solar System science is the comparative study of the three terrestrial planets (Venus, Earth, Mars). Why did the three planets evolve in such different ways, from relatively comparable initial states? The small size of Mars, favoring atmospheric escape and allowing a relatively fast cooling of the interior, certainly played a role in making the present Mars so inhospitable. Venus has almost the same size and density as Earth, and was probably initially endowed with similar amounts of volatile material. The absence of water in significant amounts, possibly explained by intense hydrogen escape at early epochs, and of molecular oxygen in the present atmosphere, which requires extremely strong primitive escape and/or massive oxidation of surface material, remains poorly constrained and understood. Because of the massive carbon dioxide atmosphere, there is a large greenhouse effect at the surface of Venus, where the temperature is ≈470°C. The way such a strong greenhouse built up and stabilized is not well understood. How did the atmosphere evolve, under the combined effects of escape and interaction with solid planet? How did the history of tectonism and volcanism influence, or was influenced by, atmospheric greenhouse, mantle convection and core solidification rate? Did the last general resurfacing event, ≈0.5-1 Gyr ago, occur in coincidence with complete freezing of the core, and vanishing of a primitive dynamo? Which processes are presently controlling the thermochemical equilibrium between the surface and the atmosphere, what is the nature of the feedback processes, what are the roles of carbon, sulfur and chlorine cycles? Is there a present volcanic activity?

The Magellan mission, through radar imaging, topography and gravity measurements, provided an enormous amount of information, allowing substantial advances in Venus geodynamics. Our knowledge of Venus geochemistry is less advanced, despite Pioneer Venus and soviet missions, which provided a good preliminary insight into atmospheric composition (and surface composition), but technological advances should allow to go much further. The Venus-Express mission will provide a wide picture of middle atmosphere thermal structure, radiative balance and circulation, and of cloud physics and chemistry. Although Venus Express, as well as the Planet C orbiter of JAXA (launch date : 2008), will also bring information on the radiative balance and composition of the deep atmosphere, this information will not be sufficient for an in-depth characterization of surface-atmosphere interaction and atmospheric geochemical cycles. In-situ measurement of the atmospheric composition, at both global and local scales, and with some vertical and horizontal sampling capability, is a necessary step for that purpose. The advantage of in-situ measurements is that they are more precise, complete, time and space resolved, than remote sensing measurements. There is a strong need for in-situ measurements of the deep atmosphere and surface material of Venus (chemical, isotopic, electromagnetic, acoustic, radioactivity probes, …) on future missions.

The successful Venus balloon experiment of the Vega mission, near twenty years ago, strongly advocates for a deep atmosphere balloon mission, in the follow up of Venus-Express, allowing to complete atmospheric investigation, and to go further in our understanding of surface and interior states and processes. Why using balloons? In the low atmosphere of Venus, the Archimede force is large. The mass of 1 cubic meter of atmosphere at the ground level is more than 60 kg, which makes a balloon of, let say, 2 cubic meters able to carry up to 100 kg (60 kg at 10 km altitude). The low atmosphere of Venus can be compared, in terms of ambient pressure, to a region of the ocean located at 1 km below the surface. Using balloons for exploring the deep atmosphere of Venus is therefore an attractive means, provided technical challenges like thermal insulation, energy generation, tolerance of materials and components to extreme environmental conditions, can be solved. Balloons, carried by zonal winds, may travel over typically one thousand kilometers per day, even at low altitudes, and can be used as landers by deflation of their envelops. Individual balloons may therefore allow to probe the atmosphere and surface at local and regional scales, with a possible extension to a more global scale by the simultaneous use of several balloons, which can be operated in a networking approach.

A typical geochemical mission, similar to the LAVOISIER project proposed in January 2000 in response to the ESA announcement of opportunity for the flexible missions F2/F3, might be studied. It could consist of a Venus descent probe/ balloon flotilla system oriented toward : (i) measuring with a high accuracy the noble gas elemental and isotopic composition ; (ii) characterizing the main chemical cycles (carbon, sulfur, chlorine) in the low atmosphere, and their interaction with surface minerals ; (iii) helping in improving radiative transfer models through the spectral measurement of infrared fluxes, and measuring the surface temperature ; (iv) constraining small-scale and meso-scale dynamics of the deep atmosphere (winds, atmospheric mixing, meteorological events like storms) ; (v) constraining the morphological and mineralogical characteristics of the surface through visible-near infrared spectro-imaging ; (vi) searching for still hypothetical phenomena like : lightning, volcanic activity, crustal outgassing, seismic activity, remnant magnetization.

The descent probe could be equipped with ultra-sensitive and precise in-situ and optical instruments, allowing to catch a local, but precise and as complete as possible, view of the atmospheric vertical structure and surface characteristics. The descent probe could also provide a precise picture of noble gas elemental and isotopic composition. At the same time, a typical number of 3 pressurized balloons could be deployed at low altitude (10 km), and instruments onboard operated during a few days, or a few weeks, whereas balloons move around the planet, carried by winds. At the end of this period, balloons might be deflated in a controlled way and softly landed at the surface of Venus, allowing to vertically probe the lower atmosphere at different locations, and finally to perform measurements at the surface. A relay orbiter is not necessarily required, but wishable. This orbiter could also be equipped with remote sensing instruments (infra-red, microwave sounders) working synergistically with low altitude platforms.

2. SCIENCE OBJECTIVES : FOCUS ON A FEW KEY SCIENTIFIC TOPICS AND RELATED MEASUREMENT METHODS

General scientific objectives are described in [1] and [2]. A few examples of key measurements, which cannot be done from an orbiter, are given below, together with related scientific objectives. The list hereafter is far from being exhaustive. The purpose of these examples is simply to illustrate the tremendous scientific potential of a balloon mission to the deep Venus atmosphere and surface.

2.1. Noble gas elemental and isotopic composition of the global atmosphere

The primary atmospheres of the terrestrial planets may be either derived by outgassing from the solid interior or accreted from the outside (e.g. addition of cometary material). Secondary processes such as escape, outgassing from the solid planet, radiogenic contribution, solar wind addition, sputtering, chemical conversion (carbonate precipitation, photosynthesis, water decomposition, etc...) may have significantly altered their primary composition. Noble gases are ideal tracers to understand the formation and evolution of the atmosphere of terrestrial planets. Their chemical inertness and the presence of numerous isotopes among which radiogenic ones (e.g. ^{4}He, ^{40}Ar), nucleogenic ones (e.g. ^{21}Ne) and fissiogenic ones ($^{134-136}$Xe) permit to identify a number of possible sources to planetary atmospheres as well as the fingerprint of physical processes previously mentioned. Unlike chemical compounds, they can be found in the atmospheres of the terrestrial planets, in meteorites of various types and in the solar wind. Attempts at modelling the terrestrial atmospheric evolution have confirmed the high potentiality of these elements.

The composition of Venus atmosphere according to the previous measurements by Pioneer and Venera missions is : CO_2 (96.5 %), N_2 (3.5%), He (12 ppm), Ar (70 ppm), Ne (7 ppm), Kr (0.7- 0.05 ppm), Xe (?). The only element for which an isotopic composition is available is Ar but it is worth considering a confirmation because of possible interferences in the previous measurements (e.g. with HCl) especially if an accurate measurement of the ^{36}Ar/^{38}Ar is necessary. Therefore estimates of He, Ne, Kr and Xe isotopes would provide invaluable information necessary for comparative planetology and to constrain models of atmospheric formation and evolution (for both Venus and Earth).

- Helium : the abundance and isotopic composition of helium results from the competition between : (i) outgassing from the solid interior ; (ii) escape from the atmosphere ; (iii) input from solar wind. On Earth, outgassing from the solid interior consists of two well identified fluxes : one rich in ^{3}He (primordial) from the mantle and a purely radiogenic one in relation with crustal outgassing. The same components will have to be considered on Venus but with a completely different relative importance: volcanism on Earth in relation with plate tectonics is a major phenomenon. Release from the crust is a rapid process because of erosion. On Venus the much higher temperature should promote escape from deeper crustal layers but how does erosion play a role? Input from the solar wind is limited on Earth because of the magnetic field. The absence of a significant field on Venus will have an influence on the abundance and isotopic composition of He in Venus atmosphere.
- Neon : in the terrestrial atmosphere, Ne isotopes are intermediate between a planetary component (chondritic) and a solar component. The question is whether this results from mixing of these two components (mantle Ne is solar) or more simply, from mass fractionation as a result of massive escape from the atmosphere in its early stages. Mesuring Ne isotopes in the atmosphere of Venus will greatly help constraining such problems.
- Argon : ^{40}Ar is the radiogenic product of ^{40}K. On Earth, it is a major component of the atmosphere (1%), testifying of the importance of outgassing. On Venus, ^{40}Ar is less abundant than on Earth while ^{36}Ar is far more abundant, illustrating a drastic difference between the two planets. Where does ^{36}Ar come from? Its ratio to Ne precludes a significant solar contribution. Its total abundance corresponds to what is recorded in the most gas rich chondrites, a very surprising result.
- Krypton and Xenon : Krypton isotopes may provide some information on the escape processes because of the possibly mass fractionated pattern easy to interpret in the absence of radiogenic/ nucleogenic contributions. Its ratio to Ar and Xe would permit to characterize its source in Venus atmosphere. Xenon carries more information than anyone of the other noble gases because of its numerous isotopes including radiogenic/ fissiogenic isotopes from short and long lived parents. Is the terrestrial missing xenon a unique signature of our planet? Does Venus exhibit isotopic anomalies in ^{129}Xe, $^{134-136}$Xe? Are Venus atmospheric Xe isotopes mass fractionated relative to the Earth/Solar references?

It can be concluded that the behavior of planetary atmospheres, past and present, is complex. The noble gases provide much information that may greatly help constraining models of atmospheric evolution of both Earth and Venus, two planets with quite different atmosphere which otherwise look quite similar. Concerning isotopes of light elements : H, C, N and O, they exhibit highly variable isotopic compositions depending on the diverse chondrite classes and planetary objects. They result from : (i) nucleosynthetic processes ; (ii) heterogeneity in the Solar nebula ; (iii) fractionation processes upon accretion ; (iv) differenciation and evolution of planetary objects. On Venus, where the temperature is significantly higher than on the Earth, fractionation is expected to be less significant. From the isotopic composition one therefore expects mostly information dealing with comparative planetology. Under this aspect, oxygen isotopes (^{16}O, ^{17}O, ^{18}O) will be of particular significance as they permit establishing different fractionation lines for the diverse objects of the Solar system. In the future, analyses of solid samples will require an accurate knowledge of this atmospheric reference.

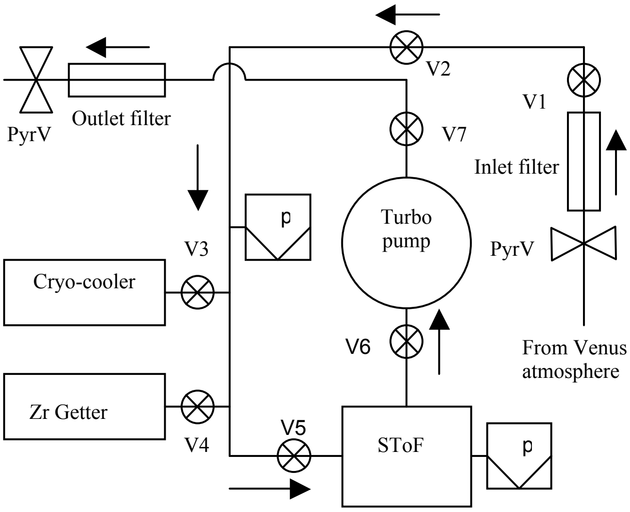

Fig. 1. Schematic view of a system composed of a static time-of-flight (StoF) mass spectrometer and separation/ purification line.

An isotopic analyzer using a time-of-flight mass spectrometer coupled with a gas separation/ purification system might be used (see Fig. 1). Noble gases are first separated from reactive gases through chemical gettering by using a zirconium getter. In a following step, noble gases are separated from each other by cryotrapping on an activated charcoal bed, cooled by a Stirling machine, yielding three separate fractions : [He, Ne], [Ar], [Kr, Xe], which may be analyzed separately in a static mode (without carrier gas). In this way, it is possible to reach high sensitivity, and to remove a few mass interferences (like $^{20}Ne/^{40}Ar$), in such a way to measure isotopic ratios with an accuracy better than 1%. This method has been extensively used in the laboratory since fifty years to analyze noble gases in terrestrial and meteoritic samples, and is presently being developed for Mars in-situ exploration [3]. Such a static ToFMS analyzer, devoted to the measurement of global atmosphere noble gas abundances and isotopic composition, could be operated on board the descent probe, by sampling atmosphere around 60 km altitude, and analyzing noble gases during the 1-2 hrs descent of the probe through the atmosphere.

2.2. Chemical composition of the atmosphere and its spatial/ temporal variability

Sulfur compounds, and their vertical structure, are insufficiently characterized, in particular below 25 km, where the uncertainty on SO_2 is nearly one decade. SO_2 is an important gas of the atmosphere, since it is very reactive. Chemical equilibrium with rocks (calcite : $CaCO_3$) calls for an equilibrium value of 100-130 ppmv of SO_2 [4]. Early measurements of SO_2 with Pioneer Venus Large Probe GC and MS and Venera 12 GC found values of 130-180 ppmv in the range 42-22 km. Later measurements with local UV spectroscopy on Vega 1 and 2 show a similar value at 40 km [5], confirmed by IR spectroscopy from the Earth [6]. However, Vega measurements show a distinct decrease of SO_2 mixing ratio for decreasing altitude, with 20 ppmv at 10 km, the lowest reliable measurement of SO_2.

COS has been measured from Earth around 35 km, S_2O is not detected but could be the "missing" strong UV absorber [7]. H_2S is measured within a factor of 2, but its vertical profile is unknown. H_2O is around 30 ppmv, but still poorly constrained. The CO mixing ratio was found to be in the range from 17±1 ppmv, measured at 12 km altitude (Venera 11/12, [8]), to 23±5 ppmv, measured at 36 km altitude (IR Earth-based observations, [9]). There is a close relationship between CO concentration and oxygen fugacity fO_2 through the thermochemical reaction :

$$CO + O_2 \rightarrow CO_2 + O$$

and oxygen fugacity may therefore be deduced from CO abundance through thermochemical models. This point is discussed in details by Fegley et al (1997).

Dual columns Gas Chromatograph

The dual columns GC is designed to perform individual qualitative and quantitative analyses of the main atmospheric species within a large dynamic range. This instrument requires a direct inlet of gaseous samples into its injection port (sampling step of 10 min., sample size of 1 µl). Each sample is then pushed by a carrier gas (Helium) through two analytical columns operating in parallel and through the detection system. The first column (type MolSieve) allows the separation of the noble gases (Ne, Ar, Kr, Xe), N_2, O_2, CO and CH_4. The second column (type Silica-PLOT or PLOT U polymer) allows the separation of SO_2, CO_2, COS, H_2S, H_2O, NH_3 and C_2 hydrocarbons.

The instrument is composed mainly by 4 sub-systems : (i) gas supply sub-system : it includes all the parts used for the injection and elution of a sample. These parts are mainly the injector, the on/off micro-valves, the carrier gas tank, the pressure regulator, the filters and the pipes ; (ii) The chromatographic columns : the two columns are metallic tubes of 10-20 m length, 0.18-0.25 mm inner diameter coated, on their inner wall, by a thin layer of stationary phase (few microns of respectively MolSieve and Silica or U phases) ; (iii) The detection sub-system : universal micro-detectors are used at each column end. A first stage of nano-TCD (Thermal Conductivity Detector) allows a non-destructive detection of all the eluted species in a range from few percent to few ppm. A second stage of miniaturised HID (Helium Ionisation Detector) could be added in order to detect species abundances in the range 100 ppm - 1 ppb ; (iv) The electronic acquisition and command sub-system.

Most of the hardware components listed above (helium tank, valves, columns, nano-TCD, electronic, ..) have already been qualified for past and present similar experiments (ACP and GCMS experiments on Cassini-Huygens mission, COSAC experiment on Rosetta cometary mission). Concerning the miniaturised HID, a R&T study is under progress to adapt commercial components to usual mission constraints.

Tunable diode laser spectroscopy

On Venus, the best altitude range for TDLAS method is the upper atmosphere, including the cloud region (from ≈80 km to ≈40 km). The accuracy of the measurements at these altitudes will be approximately constant with altitude: while descending in the atmosphere, the number of molecules in the cell in increasing, but because of line broadening the absorption remains the same. The best discrimination (isotopic measurements) occurs above 60 km. Below, where the lines broaden, the sensitivity and discrimination degrade progressively. At pressures exceeding 10 bar, the collisional broadening is no more described by Voigt profile, and is poorly parametrized, so the quantities cannot be accurately retrieved from measured absorptions. The TDLAS method is hardly applicable already at 30 km at exterior pressure. It is possible, however, to study this altitude range very important for surface-atmosphere interaction by means of active spectroscopy in a cell, if the gas will be analysed at reduced pressure. It might be possible to take advantage of the gas sampling system of a mass-spectrometer, or to employ a dedicated sampling system. The best sensitivity and discrimination is achieved at pressures of 0.1-1 bar.

Possible atmospheric targets of TDLAS in Venus atmosphere are numerous, and may be divided in two categories: (i) CO_2 and/or H_2O isotopic ratios ; (ii) molecular species (HCl, OCS, HF, H_2S, CH_4, NH_3, HBr, HI). Concerning molecular species, the typical accuracy of the measurements varies from a few ppbv (HF, CH_4) to one ppmv (HCl) and a few tens of ppmv (OCS, H_2S). Concerning isotopes of CO_2 and H_2O, which are of particular interest, the main characteristics may be summarized as follows.

Table 1 : Characteristics of molecular absorption by species of interest.

Molecule	Spectral range (cm^{-1})	Altitude (km)	Abs. Opt. Path : 10 m	Value range	Accu-racy
H_2O	7295-7315	40-70	0.02-0.1	≈30 ppmv	$<10^{-3}$
		70-90	0.01-0.001		$\approx 10^{-2}$
		30-40 (1)	≈0.15		$\approx 10^{-2}$
HDO (2)		≈60	TBD	D/H≈ 150 (3)	TBD
$^{12}C^{16}O_2$	5337-5339	30-TBD	0.001		$<10^{-3}$
$^{13}C^{16}O_2$	5010-5020	TBD	0.05		$<10^{-3}$
$^{12}C^{16}O^{18}O$	5040-5050	≈60 km	0.05		$<10^{-3}$
$^{12}C^{16}O^{17}O$	5040-5050	≈60 km	0.02		≈0.01

(1) The lower atmosphere (0-30 km) is as well accessible if a gas sampling system reducing the pressure is possible.

(2) Spectroscopic data by [10].

(3) In units of SMOW value.

2.3. Oxygen fugacity

Any sound information on the oxygen mixing ratio of the troposphere of Venus would provide a definite clue for choosing between competing cosmogonic models, namely: different conditions of formation and/or different evolutionary paths. Calculations of the oxygen mixing ratio - from the CO/CO_2 ratio and the temperature- thanks to spectrometric observations of the upper Venus atmosphere from the Earth, or on the basis of mass spectrometric/gas chromatographic analysis down to the surface of the planet (*Pioneer-Venus* and *Venera 11/12*), are somewhat unsatisfactory because: chemical equilibrium may not be realized throughout the atmospheric column ; and/or uncertainties exist in atmospheric mixing rate and composition.

Given the 17±1 ppm carbon monoxide mixing ratio measured on board *Venera 11/12* in the lower Venusian atmosphere (12 km), a 50% confidence interval on such a value, extrapolated downwards, would result in an order of magnitude uncertainty on the calculated oxygen mixing ratio at the surface (735 K), a variation of 10 K yielding an error by a factor of 3 on the inferred value. The most comprehensive study of the redox state of the lower atmosphere of Venus leads to a two orders of magnitude uncertainty of the surface oxygen fugacity, centered at $10^{-20.85}$ bars [4].

On the other hand, a direct and continuous measurement of the oxygen mixing ratio from, say, 20 km down to the surface, would provide the lacking key parameter. It would allow to study the way the Venusian atmosphere chemically equilibrates, to compute the oxygen budget of the crust-atmosphere system (and, hence, deducing the surface mineralogy) and to model the origin and evolution of the planetary atmosphere. Up to now, this parameter remains an unknown, constrained by instrument sensitivities (upper limits) and by reasonable thermodynamical and geochemical considerations (lower limits), and leads to conflicting models, describing the atmosphere and lithosphere of Venus as comparatively oxidized or reduced. Moreover, if complementing the already known temperature profile, an oxygen profile would give insight into the chemical homogeneity and possible geochemical layering of the Venusian atmosphere.

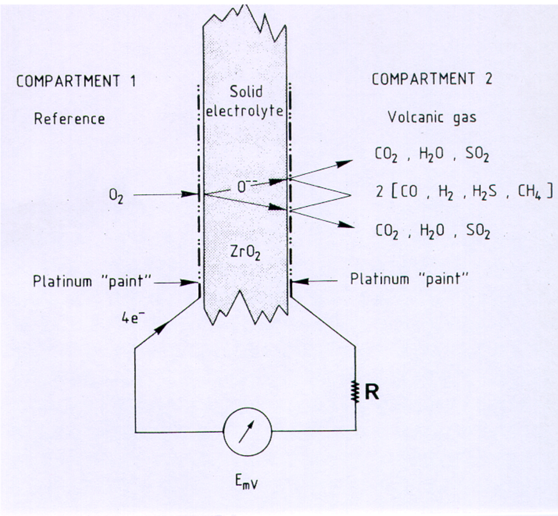

Fig. 2. Principle of a solid electrolyte oxygen sensor. Basically, it is a fuel cell "burning" the combustible atmospheric gases CO, CH_4, COS, H_2S, S_2 and H_2, into CO_2, SO_2 and H_2O, by means of oxygen ions instead of oxygen molecules. In this case, the quiet combustion is an equilibrium process. The counterpart of the flow of oxygen ions in the electrolyte is an electrical current through the external conductor. The resistance of the external circuit being very high, this current is actually negligible and electric charges equilibrate on both electrodes.

The zirconium solid-electrolyte technology offers the possibility of achieving elegantly this goal. With their high accuracy (*i.e.*, ± 0.01 in log P_{O_2} units) in the suitable range of P_{O_2} (down to 10^{-30} atm, given the high total pressures involved) and their short response-time, the ZrO_2 oxygen probes with a solid internal reference are very well adapted for continuous oxygen measurement during the descent - even very fast - of a Venus lander, or during the flight of an atmospheric vehicle. These probes are very lightweight (*ca.* 2g, including wires), do not need a power supply and deliver an electrical potential (< 1V), the radio-transmission of which to the Earth, with a ± 1 mV accuracy, is as straightforward as that of the tension of a thermocouple.

With the presently available technology, a ZrO_2 oxygen sensor (called OES, for Oxygen Electrochemical Sensor, in the following) would start delivering measurements at 12 km altitude (643 K) down to the surface of the planet (735 K) and will continue to do so until the radio equipment of the vehicle is destroyed. With some R&D efforts for increasing the ionic conductivity of the "doped" zirconium at low temperatures, the upper limit of measurement could be slightly shifted upwards, presumably up to 14 km. Heating the sensor would require a low electrical power (2 W, or so), that will add a few grams to the sensor mass (not including the power source), but would extend the range of measurements up to, at least, 30 km altitude.

2.4. Natural radioactivity

Radon (isotopes 222 and 220) is continuously exhaled by the telluric planetary surfaces. Without any scavenging process, its steady mean concentration in the lower troposphere (below the cloud deck) is directly proportional to the exhalation rate, from which the concentration of surface rocks in parent radionuclides (namely U-238 and Th-232) can be inferred (given the emanating power of the surface rocks). Moreover, the structure of the troposphere and the mixing processes driven by atmospheric dynamics will be deduced from the vertical and horizontal (if any) gradients of radon, independently from any consideration on the atmospheric chemistry : this will shed new light onto stagnation and convection processes in the Venusian lower atmosphere. Additionally, volcanic plumes, if they exist, might be detected at large distance of the location where they are formed.

The measurement of the airborne naturally occurring radionuclides of the uranium and thorium series concerns two gaseous isotopes : ^{222}Rn, ^{220}Rn, and four solid or liquid (in the condition of Venusian lower atmosphere) alpha emitting isotopes : ^{218}Po, ^{214}Po, ^{212}Po, ^{210}Po and ^{212}Bi, which are decay products of the radon isotopes.

Two different methods of measurement can be implemented for such an experiment :

- Pulse type ionization chamber, associated with spectroscopic analysis of pulse amplitudes, the ionization chamber being filled with the gas existing locally in the atmosphere.
- Gaseous scintillation techniques, based on the de-excitation of atmospheric molecular species like CO_2 and N_2 by photons emission, after excitation due to the energy transfer of alpha particles. The concerned spectral bands are located in the near UV region of the spectrum (230 to 420 nm). The measurement is then done by photon counting, using a special large aperture and wide field UV optics, coupled to an UV photo-multiplier. A spectroscopic analysis of the output pulses allows discrimination of the various alpha energies, and therefore of the different radionuclides.

The two proposed methods of measurement allow isotopic ratios between the different isotopes to be calculated, allowing study of the diffusion of these isotopes, either under gaseous form, or as aerosols, to be made. The first method described allows local information (few meters around the probe) to be retrieved, whereas the second one allows more wide spatially integrated data to be considered.

2.5. Acoustic detection onboard balloons

The acoustic signals may have three origins. The first type is related to any explosive volcanic eruption. Little is known however on the regime of volcanoes on Venus, especially the gas release during the eruption: even with the lack of water, a significant release of CO_2 and SO_2 might be expected. The second type will be related to acoustic signals generated by quakes. The lack of water in the crust will favour the brittle regime of the crust, but the seismic activity of Venus is unknown. The third type of events will be related to storms, lightning, and other atmospheric events.

Due to the short duration of the mission, the acoustic monitoring is focused for the endogenic sources on the acoustic signals which might be trapped in the atmosphere and therefore recorded at large distances from the sources. Signals from the same source might then be detected on several balloons, and the position of the source might be determined by a classical triangulation.

For atmospheric signals, short period infrasounds can be detected too, but very likely, signals detected on each balloon will be uncorrelated: we therefore propose to have the possibility to determine the propagation direction of the signal with an antenna of receivers.

In contrary to the Earth, the atmosphere of Venus shows no acoustic low velocity zone. However, the very strong decrease of the density at altitude higher than 100 km traps strongly the acoustic energy, with the maximum amplitudes of acoustic modes at altitudes of 50 km. As a consequence the quality coefficient of the fundamental and two first overtones of acoustic modes are higher than 4000 and are therefore strongly trapped in an acoustic channel between the surface and about 100 km of altitude (Figure 3a). A detailed analysis shows however that the trapping is efficient only at frequencies less than 5 mHz. In comparison, the Earth fundamental acoustic mode has a quality coefficient of about 100, and overtones, with frequencies higher than 4 mHz, are not trapped, with coefficient of about 10 (see Figure 3b for the amplitude of the fundamental mode). We can therefore expect good propagation of acoustic signals in this channel. Zonal wind will however produce a distortion of the wave front, which will decrease the precision of localisation. In addition to the acoustic signals generated by volcanoes, three normal modes associated to Rayleigh surface waves have large amplitudes in the atmosphere, as shown by Figure 4. (near 3, 4.4 and 4.9 mHz). As a consequence, the surface waves generated by any quake may produce significant pressure signals and could be detected for strong magnitudes. These signals might have strong amplitudes at periods of about 20 sec, i.e. wavelength in the atmosphere of about 7-9 km.

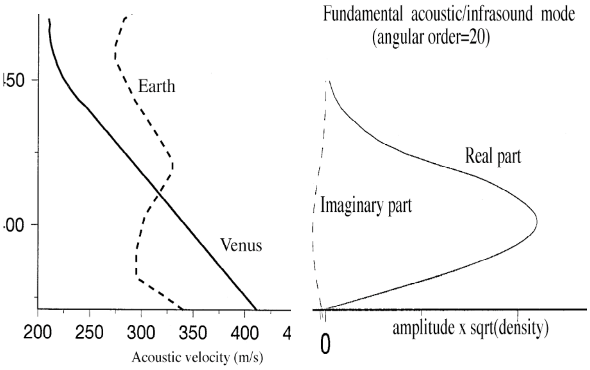

Fig. 3. 3a (left side) : Acoustic velocities of Venus as compared to the Earth. 3b (right side) : Distribution of the kinetic energy of the acoustic mode with angular order 20, with frequency of about 3 mHz.

The instrument is designed for the separation of the pressure changes related to the altitude variations of the balloon and the pressure changes related to an incident acoustic signal for signals in the frequency range 0.1-10 Hz, and for the determination of the direction of signal propagation in the band. We therefore propose to use a long cable of a few 100 meters, in Kapton. The mass of the cable and deployment system is expected to be close to one kg. Along this cable, 3 sensors will be mounted. The complete mass of the experiment might be 1.5 kg.

Infrasonic sensors might be similar to the infrasonic sensors developed in the frame of the Netlander European Mars network mission, and have a resolution of about 10^{-3} Pa in the infrasonic (1 mHz-0.1 Hz) frequency band.

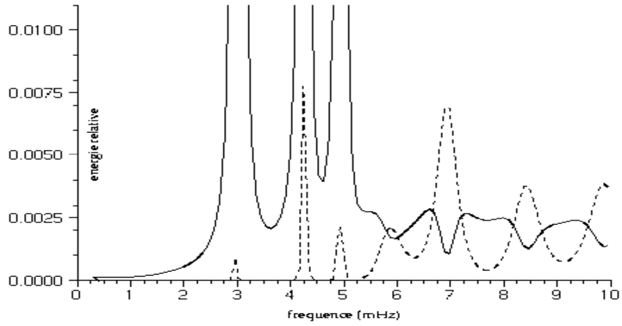

Fig. 4. Portion of the fundamental Rayleigh waves in the Venus atmosphere.

The cable can also be used for the deployment of a potential magnetometer far from the gondola of the balloon. A common instrument with both the magnetometer and the acoustic sensor may therefore be proposed and will result in a significant mass optimisation.

3. PAYLOAD QUICK LOOK

3.1. Balloon Probes

The payload (see Table 2) may be summarized as following :

- Gas chromatograph (GC), electrochemical oxygen sensor (OES), radioactive tracer detector (APID).
- Infrared radiometer (radiative transfer, composition). The VERBE experiment (Venus Energy and Radiation Budget Experiment) consists of a small radiometer operating in four spectral ranges : 1.7 µm, 2.4 µm, 3.7 µm, and an integral channel : 0.8-4 µm, looking upward and downward.
- Radio science (RS) : localization of balloons by VLBI (atmospheric dynamics).
- Radio-electric receiver (RWAEI) and optical photometer (LOD) (for lightning detection).
- Acoustic and magnetic sensor AMS (volcanoes, lightnings, meteorological events ; quakes ; remnant/ intrinsic magnetic field).
- Near infrared camera NIRI for surface characterization (morphology/mineralogy on dayside, temperature on nightside).
- Electromagnetic sounding of inner planet by magnetometry (AMS).
- Relaxation probe for conductivity measurements (RP).

Table 2 : Main budgets of balloon probe payload.

Instrument	Power (average)	Mass (kg)	Volume (Liter)	Data Rate (kbits/s)
GC(1)	2.7	1.5	1.6	0.03
OES	0	0.02	0.01	0.001
AMS(2)	0.5	1.5	<0.3	0.1
NIRI(3)	<0.1	0.12	0.15	0.4*
LOD(4)	2	0.07	0.25	<0.01
APID	0.1-1	2.3	3	0.1
VERBE	1.2	<0.5	0.1	0.2*
RWAEI(5)	1.7	0.3	<0.3	0.4*
RP	0.5	0.6-1.1	0.4-1.2	0.03
APTIV	0.5	0.7	0.5	0.36
TOTAL	10.2	8.1	7.4	1.7

(1) Assumed sampling rate of 30 mn.

(2) Cable of a few 100 meters in Kapton deployed under the gondola

(3) Assumed sampling rate of 1 image per 5 mn interval

(4) Bit rate depends on the number of spikes

(5) 3 short dipole electric antennas 1 m long each, 1 magnetic antenna 10 cm long

*Assumed data compression rate : 5

3.2. Descent Probe

The payload (see Table 3) consists of the following elements :

- Noble gas analyzer : static ToF MS with a separation/ purification line, consisting of a gettyer and a cryocooler (see above).
- Gas chromatograph (GC), electrochemical oxygen sensor (OES) and optical gas analyser (OLGA) (molecular/isotopic composition).
- Infrared spectrometer (atmospheric composition, radiative transfer), Visible/Near Infrared spectro-imager (atmospheric composition, surface mineralogy/morphology on dayside, surface temperature on night side). The VISS (Venus Imaging Solid-state Spectrometer) uses the AOTF technology (Acousto-Optic Tunable System). It may be used for reflectance spectroscopy (0.5-1.2 µm range), in order to determine the mineralogy of surface material, as well to probe atmospheric gases in the thermal infrared (1.7-4 µm and beyond). Several windows exist, where the transparency length (τ=1) is small (a few hundred meters to a few kilometers, see Table 4). It is divided into a VIS-NIR and a IR instrument. An option could be to use a grating spectrometer (Visible Near-Infrared Spectro-imager VNIR).
- Radioactive tracer detector (APID instrument, for Alpha Particle Ionization Detector).

- Atmospheric sensor package APTIV (p, T sensors, accelerometer).

Table 3 : Main budgets of descent probe payload.

Instrument	Power (average	Mass (kg)	Volume (Liter)	Data Rate (kbits/s)
MS(1)	5.6	5	1	0.1
GC(2)	8	1.5	1.6	0.15*
OES(3)	2	0.02	0.01	0.001
OLGA/TDLAS(4)	1.3	0.4	0.2	1.6*
OLGA/UV(5)	5	1	1	0.1
VISS/VIS-NIR(6)	2.5	1	1	5.3*
VISS/IR(7)	6	1.1	1	0.4*
APID(8)	0.1-1	2.3	3	0.1
APTIV	0.5	0.7	0.5	0.36*
TOTAL	31.9	13.0	9.31	8.1
Alternative to VISS/VIS-NIR(9) :				
VNIS	7	3	4.5	3

(1) Assumed time analysis of 1 hr.
(2) data rate : 80 kb per 10 mn analysis.
(3) Power : 2 W if heating required (z>15 km), 0 W if not.
(4) 1 measurement per 5 mn interval assumed..
(5) 1 measurement per 10 s interval assumed.
(6) 1 spectro-image per 5 mn interval assumed.
(7) 1 linear image per minute assumed.
(8) Option 1 : pulse-type ionization chamber.
(9) 1 spectro-image per minute assumed.
*Assumed data compression rate : 5

Table 4 : Characteristics of visible-near infrared transparency windows.

Spectral interval (μm)	Transparency length (1) (τ=1)	Nature of the signal
0.6 - 0.9	1.5-10 km	Solar flux
0.96 - 1.035	15 km	Solar flux
1.09 - 1.11	20 km	Solar flux
1.16 - 1.195	10 km	Solar flux
1.27-1.28	1 km	Solar flux
1.72-1.75	1 km	Thermal emission
2.21-2.46	100 m	Thermal emission
3-3.7	100 m	Thermal emission

(1) Without Rayleigh diffusion

4. INDICATIVE SYSTEM MASS BUDGET

The spacecraft at launch is composed of : (i) The bus, equipped with the telecommunication system, which may be similar to the platform developed for the Mars-Express mission (mass : 440 kg) ; (ii) The descent probe, which is an heritage of the Huygens probe (mass : 190 kg) ; (iii) 3 Balloon Probes (mass : 135 kg each), which can benefit of the heritage of the Mars balloon ; (iv) Hydrazine for maneuvers (mass : ≈50 kg). The total mass of the spacecraft at launch is ≈1100 kg (see table 5 below).

Table 5 : Tentative mass budget of a descent probe-3 balloons system (unit : kg).

Bus	Mars-Express platform	439
	Propellant	50
	Total	489
Descent probe	Structure	70
	Thermal shield	40
	Thermal insulation	40
	Instruments	15
	Batteries	10
	Electronics	10
	Telecom	2
	Total	187
Balloon probe	Cocoon gondola (structure and thermal insulation)	42
	Thermal shield	10
	Instruments	10
	Batteries	10
	Electronics	5
	Telecom	2
	Pressurized vessels	25 x 2
	Helium	6
	Total	135 x 3
TOTAL		1081

5. LAUNCH AND OPERATIONAL SEQUENCE

The spacecraft is put on an Earth-Venus transfer orbit by a Soyuz-Starsem launcher. The arrival velocity at Venus, 3 months later, is about 4 km/s. At the pericenter, the velocity of the fly-by bus increases up to nearly 11.5 km/s. The date of arrival at Venus of the bus is denoted by t_0. The sequence of operations is as following :

- t_1 = t_0 - 20 days : release of the the 3 Balloon Probes (BPs). By adequatly spinning the bus, the release velocities of the BPs, that is their velocities relative to the bus, are adjusted in such a way to distribute them on a great circle of typically 1500-2000 km radius at Venus level (initial required relative velocity of 1 m/s), centered on a point, to be defined, near Venus disk center. BPs are expected to sample latitudes and local times (e. g. (i) one in dayside southern hemisphere, (ii) one in dayside northern hemisphere, (iii) one in nightside). The mass of the Bus + Descent Probe (DP) system is now 680 kg.

- t_1 + 1 hr : chemical deceleration of the Bus+DP system by 200 m/s. By assuming a specific impulsion Isp of 310 s, the required mass of hydrazine for deceleration is about 45 kg. The mass of the Bus+DP system drops down to 635 kg.

- t_2 = t_0 - 19 days : release of the DP, placed on an adequate trajectory toward the target point on Venus. The mass of the bus system is now 445 kg.

- t_2 + 1 hr : chemical deceleration of the Bus system by 30 m/s and reorientation of the bus on a fly-by trajectory. Required mass of hydrazine : 5 kg. The mass of the Bus system is now about 440 kg, that is the weight of the Mars Express platform.

- **Arrival at Venus** in the following order: BPs at t_0 - 24 hr, DP at t_0 - 2 hr, Bus at t_0. Assuming a launch in January 2009 (as in the proposal to ESA), the parameters at arrival are: (i) Venus-Earth distance: 0.52 AU ; (ii) Sun-Earth/Earth-Venus angle : 43° ; (iii) Bus-Venus/Earth-Venus angle : ≈30°. The fly-by Bus and the Earth are facing nearly the same sector of the Venus surface, allowing using both Bus/Probes and Earth/Probes radio links (for localization purpose in the last case, by using VLBI technique) ; (iv) The asymptotic trajectory of the Bus, not strictly parallel to the ecliptic plane, points towards north ecliptic, with an angle of ≈30° with respect to the ecliptic plane. The sub-Bus point on Venus is therefore located near 30° south latitude. The night-side sector represents about 2/3 of the full disk, and is located to the east. The day side-sector is therefore in the morning (due to the retrograde rotation of Venus).
- **t_0 - 24 hr** : deployment of balloons at 10 km altitude and beginning of balloon observation phase. The Bus/BP distance is about 350,000 km. During the 24 hours of their operational phase, the balloons, carried by the wind (a few meters per second, up to 20 m/s), cover a distance smaller than 1500 km. Because the rotation of Venus is very slow (period : 117 days), the bus may be considered as facing the same sector of the Venus disk during the final one-day approach. If BPs are deployed at a distance of 1500-2000 km from the center of the disk, they are in constant radio visibility from the bus. BP-Earth and BP-Bus data transmission, localization of balloons by VLBI.
- **t_0 - 2 hr** : (i) Progressive deflation of balloons and descent down to the surface, reached at t_0, 24 hours after deployment (duration of the descent phase : 2 hours). (ii) Injection of the DP in the Venus atmosphere for a 1 hr to 2 hrs (2 hrs assumed in the present scenario) descent phase. The descent phases of the DP (from 100 km to 0 km) and the 3 BPs (from 10 km to 0 km) are therefore synchronized, the 4 probes reach the surface at the same time. At $t_0 - 2$ hr, the Bus/probes distance is about 40,000 km, and the velocity of the bus is about 7 km/s. High data transmission rate between the probes and the Bus.
- **t_0** : (Hard) landing of probes and end of operations. The Bus/probes distance is of the order of 5000 km. The velocity of the bus is about 10 km/s.
- **$t > t_0$** : The bus is occulted by the planet. Data are transmitted to Earth in a subsequent phase, after de-occultation of the bus.

6. SYSTEM CONCEPT AND THERMAL CONTROL

The bus is designed to take the Descent and Balloon Probes to Venus and also to carry a data relay system for communicating with Earth. An off-the-shelf technology is planned to be used wherever possible. In particular, the bus concept and structure should be based on the Mars Express spacecraft. In this hypothesis, the total mass of the bus, including propellant requires for maneuver and braking phases, is about 485 kg. Up to 3 Balloon Probes can be accommodated on the bus and then released to Venus. Each probe is made of a gondola protected by a thermal shield during the entry phase. The gondola has a hot and a cold compartment. The hot compartment is the outer balcony of the gondola and is dedicated to the sub-systems which can withstand the atmospheric environment (in particular the thermal conditions). These sub-systems are mainly the power s/s and the Helium pressurized vessels. The cold compartment is similar to a thermal cocoon. This tighten spherical structure, containing mainly the scientific payload, ensures a thermal control of its internal volume within an acceptable range (up to 40°C). The thermal shield is designed to absorb the thermal flux due to the entry of the probe from the upper Venusian atmosphere down to the altitude measurement. The shield concept could be based on the technology retained for the Huygens probe front shield sub-system. Its weight can be evaluated to 15 kg.

At an altitude of about 20 km, slightly higher than the measurement altitude, the thermal shield is released, the balloon envelope is deployed from the gondola and begins to be inflated with Helium. The balloon envelope is designed to receive a total Helium mass of 6 kg, corresponding to an inflated volume of about 2 m^3, in order to stabilize the 60 kg gondola at the measurement altitude of 10 km. The Helium gas is contained in pressurized vessels made of metallic insert (Titanium thin wall sphere) reinforced by an external carbon composite thermo structure. Two vessels of 40 cm diameter, pressurized at 60 MPa, are required per balloon probe. The estimated mass of a single vessel is 20 kg. After complete inflation of the balloon envelope, the vessels are released from the gondola in order to remove their 40 kg mass and to reduce the total mass to 60 kg. After altitude stabilization of the balloon probes, the operational phase can start. The objective is to have 20 hours of scientific operations at 10 km altitude, and then to allow the descent of the gondola down to the surface by venting the Helium content of the envelope. This phase will take about 2 hours, the estimated science operation phase of the balloon probes is then close to 24 hours.

The descent probe is designed to perform scientific measurements during its 1 hr (or 2 hrs) descent time through the Venusian atmosphere from 80 km altitude to the ground. The concept is similar to the balloons probes, but with increased system dimensions (hemisphere of 160 cm diameter instead of 80 cm diameter sphere) and weight (250 kg instead of 115 kg) in order to accommodate the specific payload. The structure is an hemispherical thermal cocoon and an outer balcony protected by a thermal shield. The shield is used both to absorb the thermal flux due to the atmospheric descent and to allow aerobraking of the probe. A parachute could be eventually added to reach the best compromise between scientific return optimization and system constraints such as system thermal behavior and power resources. Some of the instruments require windows to look towards the ground. A first option could be to integrate these optical windows to the shield. A second option could be to integrate the windows on the bottom part of the probe and to release the shield during the descent. The outer balcony "hot compartment" is dedicated to sub-systems which can be in isothermal conditions with the probe environment (mainly telecom parts such as antenna, batteries, ..). The thermal insulation of the cocoon is designed to limit the internal temperature to acceptable value (about 40°C) during the 1 hr to 2 hrs lifetime. The internal cold compartment receive the complete payload and the other sub-systems (electronics, ..).

Both the balloons and descent probes have a complex and variable thermal environment during their operational phase. All the parts which can withstand this environment are not thermally protected in order to reduce the size of the temperature controlled area. This is the case in particular for the hardware components of the telecom s/s and for the batteries (described below). The temperature controled area is designed to keep all the thermally sensitive equipments below 40°C. This task is more critical on the balloon probes, because of their 24 hours lifetime, than in the descent probe. Taking into account the limited power resources, a concept of a passive thermal cocoon made of concentric layers of PCM (Phase Change Materials) have then been validated for the balloon probes.

The thermal dynamic simplified model is based on a spherical gondola. A preliminary thermal study has been led. The concept of the gondola consists of a spherical cocoon with a series of concentric layers having the following characteristics (from the outer edge to the inner edge) : insulating layer, liquid water layer, insulating layer, paraffin layer, inner compartment with the payload. The thermal conductivity of the insulator has been assumed to be 0.04 W m^{-1} K^{-1}. For the paraffin, a calorific capacity of 1000 J kg^{-1} K^{-1} is assumed, for a volumic mass of 800 kg m^{-3}. Melting temperature is 40°C, and the latent heat of fusion is 260,000 J kg^{-1}. About 4000 configurations have been analyzed. The better compromise consists of a 80 cm diameter cocoon, with successive layers, from the outer to the inner, of thickness : 8 cm (insulator), 2 cm (water), 8 cm (insulator), 4 cm (paraffin) (see Fig. 5). The volume of the central compartment is 24 l and the time of survival about 32 hours. This time has been obtained with conservative assumptions, in such a way to account for the necessary weakening of performances due to thermal "leaks" (entry gas and optical lines, structure). The weight of the cocoon, including insulator, water and paraffin, and payload (20 kg) is 60 kg.

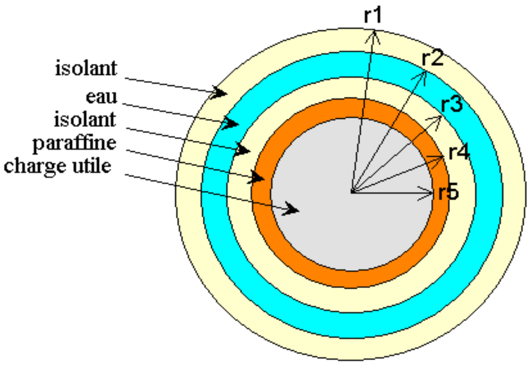

Fig. 5. Schematic view of the cocoon with concentric layers consisting of (from the outer to the inner) : insulator, water, insulator, paraffin, central compartment for payload.

The use of high temperature batteries aboard the balloon and descent probes is an important key to solve the thermal control requirement by reducing the mass located in the cold compartment and the volume of this compartment. It means that the power sub-system should work at about 700 K. Both lithium and sodium batteries are under development. These batteries allow a stable energy storage at ambient temperature, it means that no significant energy loss is expected after integration of the power s/s and during the cruise to Venus. They can then be operated in the range 600-800 K. The lithium-sulfur batteries are commonly operated in the range 620-670 K. Practical energy densities in the range 100-150 Wh/kg are reported on the optimized couple Li/FeS_2 batteries. The sodium-sulfur (Na/S_2) batteries have a similar operating temperature range and practical energy densities of 100 Wh/kg are reported. A technological trade-off is required between these technologies but a mean energy density of 100 Wh/kg, compatible with the Venus environmental constraints, can be retained for the power s/s mass and performance estimation.

7. TELECOMMUNICATIONS

A detailed scenario of the telecommunication sequence has been established.

- Phase 1: When the bus is still at large distance from Venus (> 100,000 km), BPs directly transmit to the Earth. For an emitted power of 10 W, which requires an input power of the order of 30 W (30% efficiency), the small, omnidirectional, antenna of the BP allows transferring 10 to 100 Bits per second (Bps) to the Earth.
- Phase 2: When the bus/ probe distance falls below 100,000 km (last 6 hrs), the data transmission rate from the probes to the bus becomes significantly larger than the probe/ Earth data transmission rate,

increasing from 0.25 kBps to about 10 kBps at 5,000 km, in the final stage of data transmission. Note that the emitted power can be 10 times greater on the DP, because of the larger amount of energy available (due to its shorter journey in Venus atmosphere: 2 hrs versus 24 hrs), allowing emitting up to 100 kBps in the final stage. With such a high data rate, all DP data can be transmitted in real time. For BPs, it is possible to transmit a substantial fraction of data collected during the one-day mission in the last hours of operations by using an onboard memory of a few hundred Mbits. Note that the totality of BP data (about 100 Mbits with a compression factor of 5) may hardly be recovered, which therefore requires onboard electronic intelligence (compression, detection of rare events…) in order to select data to be transmitted.

8. CONCLUSION

Deploying balloons at low altitude (typically 10 km) rather than at middle altitudes (30-60 km), would be of high interest for several reasons. First, at 10 km altitude, the probe has a direct optical access to the surface in the visible range (τ<1 in the 4 visible windows) for morphology/ mineralogy purpose. Second, at only 1/2 atmospheric scale height above the surface, the surrounding atmosphere is at chemical equilibrium with the surface, which is of great interest for geochemical measurements. Furthermore, the probability to detect chemical, radioactive, thermal, acoustic signatures of surface activity (volcanism, quakes, …) is increased near the surface. Finally, if it is possible to design a balloon system able to sustain these harsh environmental conditions, this system can be operated, without further substantial modification, during descent and landing if balloons are deflated in a final stage. Using balloons as descent probes in a multi-site perspective is an attractive possibility that deserves to be studied. Because temperature sharply decreases with altitude, it might be possible to relax constraints by deploying balloons at higher altitude (i.e. 20 km). A trade-off will have to be found, in terms of deployment altitude, between science return and technical difficulties (and risk).

The proposed flotilla of balloons may provide interesting network science, in the case a single event may be detected simultaneously in different regions of Venus: acoustic/chemical/ radioactive signal due to surface activity (volcanism, quakes,…), electromagnetic signal produced by storms (lightning), chemical horizontal gradients due to atmospheric circulation etc… Balloons, used as local probes and/or as a network, and complemented by a descent probe (possibly also by an orbiter), will bring unprecedented information about deep atmosphere, surface mineralogy, geochemical cycles and, ultimately, Venus history and evolution. Note that a detailed knowledge of deep atmosphere and surface is required for preparing a Venus sample return mission on the long term. A number of R&T studies have to be led about sensors, onboard data treatment, thermal insulation, heat-tolerant components,… From preliminary studies, a 1-day-lived balloon seems thermally and energetically possible. Note that active cooling (using radioactive thermonuclear generators) might allow to increase the lifetime of balloons, provided thermal insulation, and tolerance to pressure and chemical environment, are sufficiently performing. For the descent probe, the heritages from Russian Venera missions, NASA Pioneer Venus mission and ESA Titan Huygens probe may certainly be used with benefit.

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