VENUS PATHFINDER : A STAND-ALONE LONG-LIVED VENUS LANDER MISSION CONCEPT

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ABSTRACT

A concept for a long-lived Venus lander mission, without support from an orbiter, is discussed : the principal goals are to measure Venusian seismicity, meteorology over a solar day, and to demonstrate active cooling. Astronomical drivers for logical mission duration are considered, and expected meteorological and seismic events are discussed. The effective heat leak observed during the descent of the Pioneer Venus Large probe is evaluated and is used as a basis for defining cooling power requirements.

1. INTRODUCTION AND SCIENCE GOALS

This work examines how a lander mission on Venus might look if it could survive indefinitely. While there has been discussion elsewhere (e.g. the Venus Flagship study [1]) of top-down scientific goals for Venus exploration, the novel paradigm considered here is a technology demonstrator for a Radioisotope Stirling generator and cooler. While the concept of a long-lived lander has been advanced before (e.g. the VISM Discovery concept of 17 years ago [2]) it is worth considering anew, and in particular, how long should such a mission last?

The science enabled by long duration falls into two principal categories: that science enabled by duration directly, and that enabled by mobility which is in turn enabled by duration. This exercise considers only the first : there has been ample consideration before of mobile science on Venus and elsewhere, yet introducing mobility brings substantial technological requirements with their attendant costs and risks. A further refinement of the science goals is that they should not be attainable by a short-lived lander. This, then, opens four main avenues:

- Allow larger data return (e.g. acquire descent imagery, then trickle data back to Earth - this may allow a much higher imaging science content than is typically considered)
- Improved signal-to-noise for counting measurements (e.g. gamma ray spectroscopy or neutron-activated measurements)
- Observe dynamic phenomena such as weather, seismic activity and magnetic fields
- Allow time for ground control interaction e.g. acquire sample with an arm from a spot near the lander identified in panoramic imagery.

The third of these considerations argues for the longest duration, and in principle has fairly modest instrumentation requirements, so is an attractive framework for the 'technology demonstrator' paradigm. Descent imagery is likely to be of high interest, and documentation of the landing site is likely to be considered essential in any case. Gamma-ray or similar measurements are improved by longer counting intervals (only ~1-2 hours on missions to date, which rely on the thermal transient from an initial cool state) but the incremental science value is modest compared with e.g. making the first seismic measurements on the Earth's sister planet.

The payload resource requirements for meteorology and seismology etc. are not especially demanding, and have been considered in various Mars network missions, both conceived and flown (e.g. Viking, Mars-96, Netlander, etc.). ~10W and ~10kg should be adequate, including a descent camera.

The most crucial accommodation consideration is likely to be isolating a seismometer from the lander (to mitigate vibrations from the Stirling converter and refrigeration system) and from wind-induced disturbances which plagued Viking. Simple release onto the ground beneath the lander, with a wind cover, will likely suffice. Anemometer measurements can be strongly influenced by lander effects : a deployable mast is likely an expensive challenge; an alternate approach (as implemented on Venera 9 and 10) is to install two or more body-fixed sensors at different azimuths, such that one is always 'upwind' and thus only modestly perturbed by the vehicle.

For climate studies and to understand the Venus global circulation, the most relevant timescale is the solar day (i.e. noon to noon) of 117 Earth days. Even though the surface temperature changes are not expected to be large (e.g. models by Dobrovolskis [3] suggest ~ 0.3K) there may be significant changes in windspeed and direction since slope winds are likely to be a major controlling factor.

As for seismicity, this is difficult to estimate. In principle we can expect the overall heat flow, and thus the driving force for seismicity, from the Venusian interior to be similar to that of Earth. However, plate tectonics on Earth leads to a rather efficient heat engine, developing considerable mechanical power, but concentrating that at plate margins. Venusian seismicity may be quite different, especially if the planetary heat flow is released more episodically (as the 'catastrophic resurfacing' paradigm of surface age might suggest.)

However, for the present analysis let us assume that the population of seismic events observed on Earth overall is also seen on Venus (i.e. roughly 10 magnitude-7 events per year, 100 magnitude-6 events, and so on) and that these events are randomly distributed across the planetary surface. Examining some empirical data on ground motion suggests that at a given point, a ground motion of 10nm should be encountered some ~600 times a year. For comparison, the seismometer on the Viking lander had a sensitivity of ~1nm, although the detection threshold for seismic events was often much higher due to wind noise. Since the Venus atmosphere is very dense, wind loads will likely be a concern, so we adopt for now the conservative threshold of 10nm. (These values are explored in more detail in a separate paper [4]).

2. EARTH VISIBILITY AND COMMUNICATION

Earth visibility may be critical - it is of course easy to relax this constraint by introducing an orbiter relay, but for the most affordable mission concept, we consider direct-to-Earth communication. For simplicity, we consider that Venus has zero obliquity and that the heliocentric Earth and Venus orbits are coplanar. Furthermore, let us assume our lander sits at the Venusian equator (visibility of Earth will degrade at higher latitudes). Then the Earth elevation simply relates to the longitudes of Earth and the lander, the former obtained from an ephemeris.

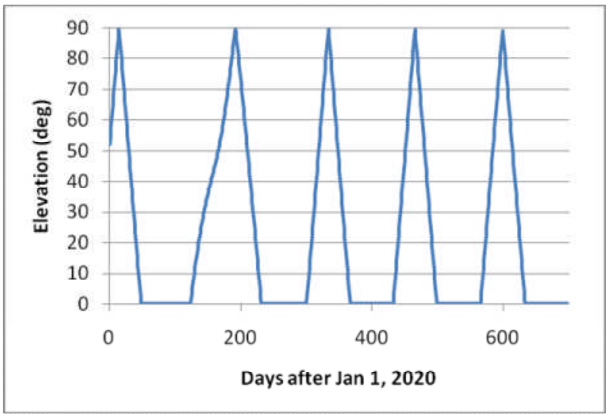

Figure 1. Earth elevation from a point on the Venus equator.

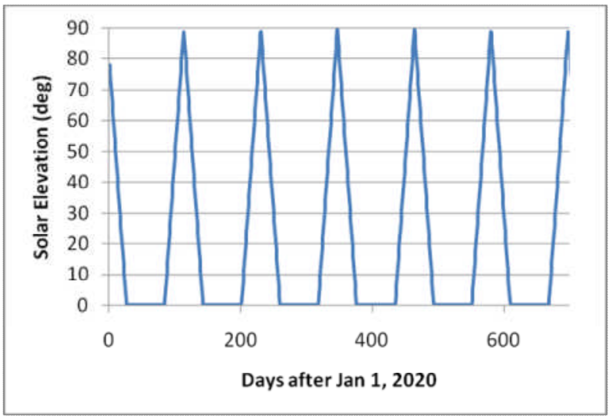

Figure 2. Solar elevation from the same point on the Venus equator. Clearly, Earth visibility from a given point and its solar time history are related

Earth is typically (see fig.1) above the horizon for ~100 days: applying a 20^{o} elevation mask reduces the usual window for communications to ~50-60 days, with intervals of usually ~80 days between opportunities. Note, however, that judicious choice of coupled timing and longitude can increase the window to ~90 days or interval can increase to ~120 days around opposition). However, if strong scientific constraints on these choices (either for specific geological provinces, or for local solar times) exist, these advantageous opportunities may not be available over a desired mission epoch.

The combined solar and communications geometry is such that the shortest communications range occurs near local midnight. Assuming daylight measurements are desired, simultaneous communication will require transmission over distances that may exceed 1 AU (fig 3: NB conjunction must be avoided too). Note that while temperature variations over the course of a Venus day will be small, they are likely not zero, and winds (especially slope winds) may vary substantially. (Note that a Venus solar day is ~117 Earth days).

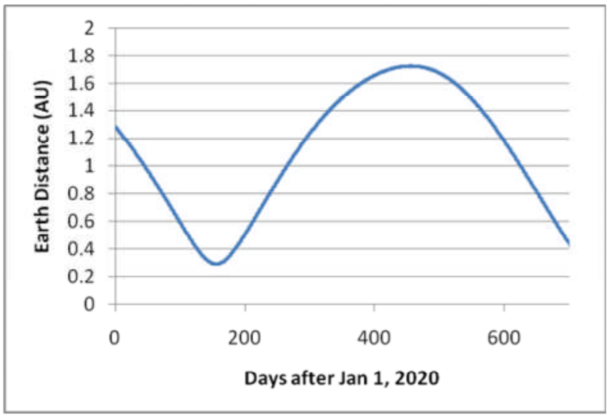

Figure 3. Distance to Earth. Naturally, closest approach occurs at opposition (here, day ~155), where by definition if a lander can see the Earth, it cannot see the sun.

The Huygens dataset (~100 Mbit) defines a basic descent/landing data volume 'debt' which should be worked off over the duration of the surface mission, plus ~ 3Mbit per day (as for Mars network missions) for magnetic, meteorological and seismic monitoring.

An efficient, novel and scientifically-worthwhile mission can be conducted on Venus with a modest payload and direct-to-Earth communication. A natural timescales for such a mission are ~50 days (the length of a communications window) or ~200 days (embracing two such windows) or more. Science return, due to both observing opportunity and downlink capability, increases with time. Thus if a radioisotope power source and cooler is used (so incremental resource demands for increased duration are minimal), there seems no logic in a mission duration of less than 50 days. A 200-day mission, to observe and transmit meteorological variations over a full solar day would be a worthwhile goal.

If the data volume suggestions above are adopted, the corresponding scientific data rate requirements to Earth (assuming a ~6 hour DSN pass per visible day) are 250 bps for a 50 day mission, and ~350 bps for a 200 day mission (wherein the data acquired while out of contact is stored onboard until the second window opens). Of course, scientific return is increased if realized data rates - which will depend on the distance (fig 3) - exceed these minimum requirements.

If the landing site on Venus sees a level of activity comparable with the 'average' Earth discussed previously and an event detection threshold of 10nm is used, then a 50 day mission should see ~100 events (and thus the rate of events to ~10%). A lower detection threshold would increase the number of events, but intelligent data handling need not demand a corresponding increase in volume since merely counting events of a given size may convey much of the desired information.

3. COOLING REQUIREMENTS

Various insulation strategies have been proposed to mitigate against harsh planetary environments, from fibrous insulation like glass wool, to foams or aerogels, multilayer blankets, or even vacuum bottles (Dewars). Insulation performance can be strongly temperature-dependent, and (except in the latter case) affected by the internal atmosphere of the probe, but effective values of thermal conductivity below ~0.1 $Wm^{-1}K^{-1}$ can be realized. However, it quickly becomes apparent to the designer that the driving factor for cooling performance requirements (or for lifetime, in the case of Venus probes without active cooling) is the parasitic heat leaks that bypass the insulation.

Specifically, instrument windows and apertures, some structural components (since the insulation rarely has the capability to bear >100g entry loads encountered at Venus), and cabling all introduce conductive heat paths that can be significant compared to the insulation, even though the latter occupies a much larger solid angle of the vehicle. Desirably this should be determined by a full-scale environmental test, but clearly this is only effective at a late stage in design, when it may be too late to be useful. One way of estimating this heat leak is by a 'bottoms-up' method, book-keeping each window or wire and its area, length and thermal conductivity. However, such an estimate at an early stage is likely to be incomplete, since many little details such as fasteners, cables for ground test, may not be included, so healthy margins should be applied.

A useful quantity to bear in mind may be what the as-built (and indeed as-flown) performance of previous missions has been. Although this level of engineering detail is difficult to recover, it is possible to reconstruct the performance of, for example, the Pioneer Venus Large Probe (PVLP). This used a 1-inch thick 41-layer aluminized Kapton MultiLayer Insulation (MLI), with a performance at these temperatures of ~0.06 $Wm^{-1}K^{-1}$ [5] For the 72cm spherical probe and the temperature difference of ~450 K at impact, the heat flow through the insulation would be ~610W.

The internal temperature history [6] just prior to impact shows a rise of ~ 1.2K/min (see figure 4). We can estimate the total heat gain by multiplying by the heat capacity. Specifically, the design [7] suggests masses and materials for the internal equipment as follows :

Communications (6kg, Al), Data handling (5kg, Al), Internal Structure except shelves (10.5kg, Al), equipment shelves and heatsinks (33kg, Beryllium), Harness (2kg, Copper), Battery (partly decoupled from shelf, so adopt 9kg, Al) and instruments (35kg, Al). Applying typical specific heat capacities suggests an overall capacity of ~125 kJ/K. Thus 1.2 K/min implies a ~2500 W heat gain. When we subtract the expected 1700W of insulation flow, and the 481W of internal dissipation, we find no less than ~300W of heat leak through parasitic paths, i.e. a 0.5 W/K conductance or the equivalent of a 0.5cm^2 aluminium short circuit across the insulation. (A comparable calculation for the Huygens probe gives leak conductance a factor of several higher for that vehicle). Clearly, enhancing the insulation performance without addressing these heat leaks would be futile effort.

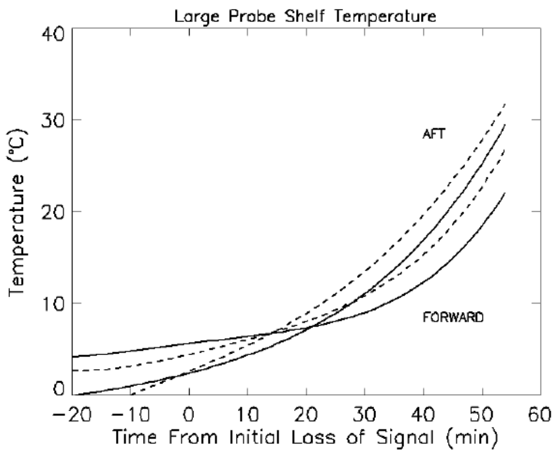

Figure 4. Pioneer Venus Large Probe Temperature history (from [6])

On the other hand, Pioneer Venus had no less than 7 science instruments, many with demanding optical view requirements such that significant insulation penetrations were unavoidable. The payload described here has essentially no such demands, although cabling and one fiber optic light guide are required. It seems plausible to consider that the heat leak could be reduced by an order of magnitude. The insulation performance should be commensurately improved by a factor of 2-4. Even so, cooling requirements of the order of 100-200W result. This makes the internal power dissipation required for payload operation and data transmission somewhat insignificant.

4. COOLING TECHNOLOGY

Radioisotope-powered cooling for long-lived Venus missions has been considered for several years at NASA Glenn Research Center (e.g. [8,9,10,11]).

One design [8] suggests a combined Stirling generator and cooler, using some seven GPHS (General Purpose Heat Source) Pu-238 'bricks', i.e. 1750 Wth to generate 478W of mechanical power. This is applied to an alternator (providing 100W of electrical power) and to a Stirling cooler, able to lift 100W of heat from the vehicle interior and reject it to the Venus environment at about 770K. This performance assumed the vehicle interior temperature at 473K, a high value by typical spacecraft standards but a reasonable extrapolation to aim for, given the considerable influence of cold-end temperature on the efficiency of refrigeration. The mass proposed for this system was 21kg.

This mass value appears somewhat unrealistic compared with the current ASRG (Advanced Stirling Radioisotope Generator) performance. The ASRG, which has been developed and life-tested to the point where Discovery missions in Phase A are expecting to launch ASRGs in 2016, have a quoted mass (as at June 2010 [12] of 28kg. This includes two GPHS units, two converters and the housing required for launch safety etc. Given that the number of converters will not increase (although the piston size etc must be larger) a factor of ~2 seems a reasonable, if somewhat optimistic (taking no account of any mass growth needed to address operation at Venus ambient conditions), estimate of a plausible mass. On the other hand, if 200W of thermal cooling power is indeed needed as suggested by the foregoing section, this cooling system would need to be doubled (i.e. ~120kg total, with ~16 GPHS modules, just under the 18 used in each Cassini RTG. (It may be noted that some previous Venus studies [see 11] suggested 8 to 40 GPHS units.

An obvious apparent issue of concern is the possible influence of an engine/cooler with reciprocating pistons on a nearby seismometer. In fact analysis [4] shows that this effect should be rather small, using data from the Viking lander to estimate ground/landing system compliance. Furthermore, the typical operating frequency of ~100 Hz of Stirling engines is well outside the 0.1-5 Hz band of teleseismic interest, and the mechanical filtering by means of suitable absorbing mounts and/or electrical filtering of the signal (6-th order filters are not uncommon in this application) assures the vibration effects should be minimal. On the other hand, in the dense Venus atmosphere, wind loads on both the lander itself, and a deployed seismometer package, could be a major disturbance. A wind shield, and wind measurements, will mitigate this issue somewhat.

5. CONCLUSIONS

A rationale for a Venus geophysics/meteorology mission has been presented, with a modest payload and a justification for a 50-200 day mission duration.

With a somewhat conservative (10nm) seismic detection threshold, such a duration should lead to ~100 seismic event detections if Venus is as active as Earth overall.

Considerable technical challenges exist. 100-200W of cooling power, requiring perhaps 100kg of power generation and cooling equipment, appears necessary to support extended surface operations.

6. ACKNOWLEDGEMENTS

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