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Touchdown on Venus: Analytic wind models and a heuristic approach to estimating landing dispersions

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ABSTRACT

The 'landing ellipse' or region of uncertainty within which an unguided probe to Venus may be expected to land is calculated. The region can be usefully seen as the convolution of three different factors: an initial circular delivery uncertainty which is smeared at a grazing entry angle onto the planetary sphere, an along-track uncertainty due to atmospheric density and vehicle aerodynamic variations during hypersonic entry, and a descent dispersion due to uncertain and/or variable zonal and meridional winds. This decomposition allows the various contributions to be instructively exposed and conveniently traded-off, without conducting explicit entry and descent dynamics simulations. It is seen that for descent durations and delivery errors typical of past Venus missions, the zonal wind contribution (determined with an analytic fit to Pioneer Venus tracking data) generally dominates, causing a ~200 km E–W (99%) dispersion, with meridional dispersions being about 4 times smaller. However, when entry angles become shallower than about 8°, the along-track dispersions may dominate, with the resulting ellipse becoming longer or wider depending on the entry azimuth. The analytic wind descriptions presented here may be applied to scientific problems, such as the dispersal of volcanic plumes or impact ejecta.

1. Introduction

The uncertainty of the position on a planetary surface on which an unguided probe may land can be important for the scientific success of a mission. It may be required to reach a specific type of terrain for safe landing (such as splashdown in a sea on Titan) or it may be desired to study a target of particular scientific interest, such as tessera on Venus. A second question is the uncertainty with which the landing point can be determined after the mission.

These problems are quite different for worlds with thick atmospheres, where the terminal descent may last tens to hundreds of minutes and winds may give an appreciable horizontal displacement, than for Mars, where there is substantial recent experience but where the rapid entry and descent through a thin atmosphere ('seven minutes of terror') do not allow wind to have an effect.

We consider in this paper the question of delivering a lander to Venus' surface. Among concepts for future missions are landers to answer scientific questions such as the origin of the tessera (e.g. the Venus Intrepid Tessera Lander 'VITaL' study, NASA, 2010) or to exercise surface mobility (e.g. a Venus rover concept by Landis et al. (2011)). In both cases, specific landing sites are required, and the likelihood of landing within a certain area is of critical importance, but landing uncertainties at Venus have not been widely considered to date.

Often in early mission formulation (pre-Phase A) it may be desired to evaluate these landing uncertainties without performing a full end-to-end Monte Carlo simulation that explicitly models the dynamics of entry and descent (such analyses being typical for missions being actually implemented, but demanding a significant level of effort). The present paper decomposes the landing point uncertainty into three major contributions which can be considered semi-analytically. This approach exposes the contributing terms and allows a straightforward assessment of how reductions in these factors (either by a priori reduction in dispersion, or by post-hoc estimation of the actual trajectory by measurement) can reduce the uncertainty in the final landing point and/or knowledge thereof. The scientific value of improved knowledge, or the reduction in mission risk by improved targeting, can thereby be traded off against the cost of implementing narrower uncertainties or improving measurement precision.

The various contributions of entry and descent dispersion will be discussed: at Mars the thin atmosphere and resultant short descent mean delivery/entry errors dominate, whereas at Titan, with a thick atmosphere allowing steep entries and long descent, the winds dominate. Venus is in fact an interesting hybrid of these two end members. As we shall show, the major contributing factor at Venus

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in most practical cases is the displacement by the wind, and thus the estimation of landing dispersions requires a close estimate of the winds and their variability. Following an approach similar to that applied at Titan (Lorenz et al., 2012) we therefore first develop an analytic specification of zonal, meridional and vertical winds to use in trajectory models, and compare it with a range of spacecraft data. This wind specification may be convenient for use in scientific applications, e.g. in modeling the dispersion of impact ejecta to form dark parabolic fallout features (Vervack and Melosh, 1992).

2. Wind model

2.1. Zonal winds

As at Titan, which like Venus is a slowly-rotating world with an optically-thick atmosphere, the dominant wind throughout most of the atmosphere is in the zonal direction (see e.g. Del Genio et al., 1993): major reviews of Venus winds are given by Schubert (1983) and Gierasch et al. (1997). Thus a planetary probe descending by parachute is displaced Westwards, with only a modest north–south movement.

We use the measured motions of the four Pioneer Venus probes (Counselman et al., 1979, 1980) as a metric of the expected displacement of a probe during descent, and the differences between the four descents as a guide to the possible dispersion in values. The velocities reported by VLBI (Very Long Baseline Interferometry) in Counselman et al. (1980) have been digitized and following Lorenz et al. (2012) analytic functions of wind vs. altitude are developed for nominal, minimum and maximum cases (q.v. a similar exercise for Titan by Flasar et al. (1997)).

Fig. 1 shows the zonal wind profiles determined from the Pioneer Venus tracking, together with analytic functions that envelope the data. A pronounced wave structure is evident in the measurements – see also Del Genio and Rossow (1990). It might be that a more elaborate wind profile specification could take this structure into account. This would allow a tighter dispersion on the overall displacement, in that the min/max envelopes must span the positive and negative perturbations due to the wind, but an individual descent may see these perturbations partly cancel each other out. However, the present approach is conservative and convenient.

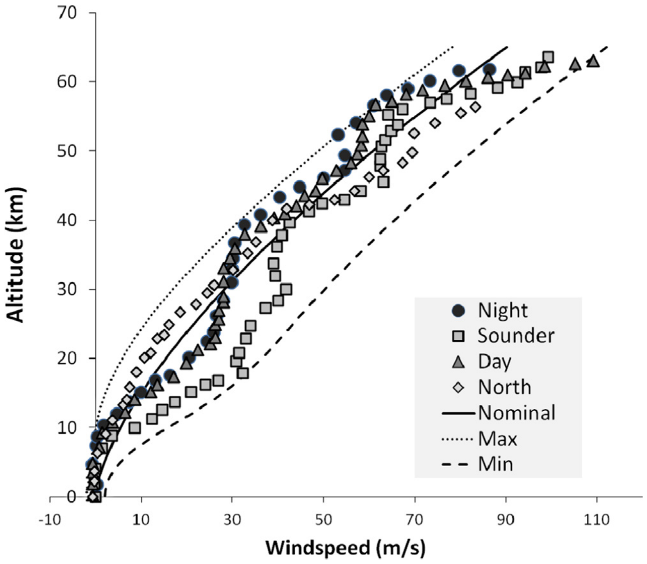

Fig. 1. Zonal winds indicated by the descent of the four Pioneer Venus probes, as measured by radio tracking by Counselman et al. (1980).

Table 1
Wind model parameters. Speeds U_o, U_s, U_t are in m/s, scale heights H_t and zonal and meridional displacements D_z, D_m for a Pioneer Venus descent (see later) are in km.

Profile	U_o	U_s	U_t	H_t	V_o	V_s	D_z	D_m
Nominal	0	80	0	1 (n/a)	0	0	89	0
Minimum	−2	80	−10	15	−1.5	−6	61	−9.5
Maximum	2	80	20	7	1.5	10	142	12.5

It is found that the wind altitude profile is not linear in altitude, but can be well-described over the 0–60 km range with three terms as

$$U(h) = U_o + U_s (h/60)^{1.5} + U_t \{\tanh(h/H_t)\}^2 \tag{1}$$

where $U(h)$ is the zonal windspeed in m/s at height h (km). U_o is the surface windspeed, nominally zero, U_s and U_t are scale speeds, 80, and 0 m/s respectively, and H_t is a scale height. The nominal profile is simply $U(h)=80(h/60)^{1.5}$, but the maximum and minimum envelopes are best specified by including the additional two terms. Note that because a descending probe spends proportionately longest at low altitude, it is important not to over-generously specify the speeds in that part of the atmosphere. Table 1 shows the parameters to specify the nominal, minimum and maximum profiles (U_{o_nom}, U_{o_min}, U_{o_max}).

These envelope functions are useful for general purposes, and for low to mid-latitude work specifically. As is well-known from telescopic and spacecraft cloud-tracking (e.g. Limaye et al., 1988; Hueso et al., 2012), the zonal winds at the cloud-top altitude are approximately constant between +45° and −45° latitude, declining roughly linearly with latitude to zero at the pole. The extent to which this latitude dependence may be reflected throughout the atmosphere has not been robustly measured, although Global Circulation Models (e.g. Lebonnois et al., 2010) could give some useful insights.

Note that in the lowest part of the atmosphere, boundary-layer circulations and wind diversions around topographic obstacles may dominate over the generally retrograde zonal circulation. Substantial deviations from the zonal direction were observed in the lowest few km of the Huygens probe descent at Titan (e.g. Bird et al., 2005; Karkoschka et al., 2007) – hence the 2 m/s variation imposed by the U_o terms in the model. The displacements that result, however, are relatively small.

In addition to confirming the overall magnitude of the winds (80–100 m/s at 66–72 km) the large amount of cloud-tracking data from Venus Express reported by Hueso et al. (2012) allow some insights into the variability of the zonal winds at these heights. They report rms variations of about 10 m/s at each latitude.

These variations were seen over several years, and such a large time span may not be merited to evaluate dispersions for a single descent, especially if some remote sensing data can constrain the overall wind field near the time. At the other end of the timescale spectrum is the history of zonal winds recorded at more or less a single altitude by the VEGA balloons. These were tracked over a couple of days, also by groundbased radio tracking (Doppler and VLBI), yielding a measure of short-term variations which are unlikely to be predictable even with proximal observations. Fig. 2 plots the deviation from the mean value, indicating almost all data falling within 2–4 m/s of the mean value. Note that the VEGA measurements are pseudo-Lagrangian – the balloons are being advected in a parcel of air which is transiting different locations in phase space (specifically longitude and local solar time). Nonetheless the data give some context and confidence to the analytic envelope specification.

Considering these data in aggregate, the min–max dispersions in the model profiles in Fig. 1 of ~30 m/s at the top of the profile (~60 km) should be appropriate for general analysis of individual descents. Were one to contemplate e.g. how closely two identical