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Buoyant thermal plumes from planetary landers and rovers: Application to sizing of meteorological masts

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ABSTRACT

Objective: Landers on Mars and Titan may have warm surfaces as a result of solar heating or the carriage of radioisotope power sources. This warmth can perturb downwind meteorological measurements, but cannot be modeled as a simple aerodynamic wake because buoyant forces can be significant.
Methods: We use an analytic model from the industrial aerodynamics literature on smoke dispersion from fires and smokestacks to evaluate the plume trajectories. Computational Fluid Dynamics (CFD) simulations are also performed for a Titan lander.
Results: CFD yields results similar to the analytic model. (Albeit with a possibly weaker dependence on windspeed than the classic model.) We apply the models to evaluate the probability of immersion of instrumentation in plumes from the Mars Science Laboratory (MSL) Curiosity and for a Titan lander under various wind scenarios.
Conclusions: Lander perturbations can be easily calculated.
Practice implications: None.

1. Introduction

It is an axiom of physics that any measurement perturbs the system being measured. This is particularly true for meteorological measurements on planetary missions, where the instrumentation is of necessity installed on a vehicle that must be powered and may have a rather different temperature than the surrounding environment.

Lander-induced thermal perturbations were noticed for some wind azimuths on the Viking and Phoenix Mars missions, as we detail in a subsequent section. Similar effects may be expected for the Mars Science Laboratory (MSL) Curiosity and for landed missions on Titan, such as the Titan Mare Explorer (TiME) mission (Stofan et al., 2013) that recently underwent a Phase A study.

The purpose of this paper is to lay out a succinct basis for estimating the geometry of a lander thermal plume. This approach allows an evaluation of the windspeeds and directions that might cause a given sensor location to be strongly perturbed, or can serve as a basis for specifying the height and location of a meteorological mast to achieve immunity from perturbation for a given condition. Ideally such analyses are performed using wind tunnel measurements or with elaborate computational fluid dynamics (CFD) models. Both approaches can entail considerable time and cost, as well as detailed design or operational details that may not be resolved when a mast design decision must be proposed. Thus we describe, and validate, a simple analytic approach to considering the problem.

2. Prior work on lander perturbations

The Viking lander was originally intended (Hess et al., 1972) to have a moveable arm on which meteorological instrumentation would be mounted, being able for example to move up and down to profile the boundary layer. It was recognized, even in this first meteorology campaign on another world that '*the lander will severely influence the wind field in its vicinity* (*especially in the downwind zone*) *and the various heat sources on and in the lander will influence the temperature recorded (downwind by convective transport and in all directions by radiation)*' (Hess et al., 1972). These effects were investigated with a 0.45 scale model of the lander in the 16 ft Transonic Dynamics Wind Tunnel at the NASA Langley Research Center (Fig. 1).

Although these wind tunnel tests quantified the perturbation (and indeed demonstrated that wind shields would be needed to prevent excessive chilling of the radioisotope generator fins) budget and weight constraints led to descoping of the meteorological instrumentation. One can sense the investigators' frustration in the Note added in proof in Hess et al. (1972) where it is

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reported that the moveable boom will be replaced with a shorter fixed boom, and that '*a portion of the data will be affected by the presence of the lander and will probably have to be discarded*'.

In spite of this compromise, the Viking meteorology experiment had its instrumentation some 1.6 m above the ground (0.7 m above the lander deck – see Table 1) and was very successful, and even 35 years later remains the longest meteorological record. That said, lander interference effects were observed when the wind came from a roughly 90° range of azimuths in both wind and temperature data (Hess et al., 1977). The lander effects were most obvious in the temperature data owing to the lander thermal plume – e.g. Hess et al. (1977), (their figure 11) shows a 2–5 K perturbation when the windspeed was below about 0.5 m/s and blowing across the RTGs and lander deck towards the sensors.

No lander plume effects were identified in the (solar powered) Mars Pathfinder lander data which saw considerable solar heating of the ground in any case (Schofield et al., 1997), although a dependence of aerodynamic roughness on azimuth was identified in the windsock experiment (Sullivan et al., 2000). The windsocks and temperature sensors were on a slender 1.1 m mast at the edge of one of its solar panel 'petals', and thus somewhat horizontally displaced (1.6 m) from the center of the main lander body.

As noted in an Appendix in Seiff et al. (1997), the Pathfinder mast was introduced only at the instigation of a Science Advisory Team (SAT) appointed to guide the development of meteorology measurements – the original proposal had been to have a single temperature sensor near the camera, high on the lander central body. The SAT was concerned that heat from the lander would perturb this measurement.

A similar solar petal location (but without the mast) was intended for one air temperature sensor the very tightly constrained Beagle-2 lander (Towner et al., 2004) and would have been perturbed by heating of the solar panel. An additional sensor was located (with a wind sensor) on the end of a 1 m long robotic arm (much as had been originally intended for Viking). This would have allowed measurement of the near-surface temperature gradient and the plume above the lander by moving the sensor around. The nominal position of the arm would place the temperature sensor at one edge of the lander, 1 m above the ground, which would keep the sensor free of lander perturbations over a 270° arc of wind directions.

Fig. 1. A 0.45-scale model of the Viking lander is tested in a Langley wind tunnel in 1970. NASA image L-70-7351 from Hansen (1995).

The Mars Phoenix lander, with low sun angles at high latitude and with a slender mast deployed 1 m above the lander deck and it was recognized that thermal plumes might be observable (Taylor et al., 2008). Computational Fluid Dynamics (CFD) simulations were conducted (e.g. Gendron et al., 2010) although much of that work emphasized the horizontal flow pattern across the deck and estimation of heat transfer coefficients from lander deck equipment (boxes ~0.25 m), found to be ~0.1 $Wm^{-2}K^{-1}$ for free (still air) convection and 1~2.5 for forced convection (4–15 m/s wind). Closer study of the perturbations (Davy et al., 2010) on the meteorology measurements found that the upper temperature measurements (0.5 m and 1 m above the deck, which itself was ~1 m above the ground) were unaffected by the lander, except over a very narrow azimuth range when they were in the wave of the camera and its mast. The lower temperature sensor (at 0.25 m) was affected, especially in the wake of the warm antenna and lidar boxes. The sensed plume perturbation (Davy et al., 2010, their figure 13) was ~2 K, whereas lander deck temperatures were typically perhaps ~15 K warmer than the unperturbed atmosphere (Davy et al., 2010; their Fig. 1). Phoenix also carried a thermal and electrical conductivity probe (TECP) at the end of its robotic arm: this did record evidence of air temperature fluctuations (Zent et al., 2010) although profiles or wake measurements have not been reported. A limiting factor is that the arm was used primarily for surface sampling functions, restricting its use for atmospheric functions.

In passing we note that CFD has also been applied to notional Mars landers (Lenoir et al., 2011), with a view to optimally locating an anemometer to minimize the speed and direction perturbation. That work, however, considered flow perturbation by obstruction around a hemispherical lander, without any buoyant effects. Some wind tunnel tests were made to evaluate the (significant) perturbation of pressure and temperature measurements on Pathfinder in its parachute descent configuration (Rivell et al., 1997).

The locations of various meteorological measurements on landers are summarized in Table 1. Some wind speed measurements have been made on the surface of Venus by the Venera landers: these had cup anemometers mounted on the drag plate at the top of the probe. The flow obstruction by the probe and antenna was recognized, and thus two anemometers were installed, at azimuths separated by 120° such that one would always be somewhat upwind – an interesting solution to the wake problem that avoided deployable masts. It is curious to reflect that Venus landers to date, which have relied on the transient tolerance of the hot environment by insulation and heat capacity, would introduce a negatively-buoyant cold plume into the

Table 1
Meteorology sensor installations on landed spacecraft. References (a) Hess et al. (1977), (b) Avduevsky et al. (1977), (c) Schofield et al. (1997), (d) Harri et al. (1998), (e) Towner et al. (2004), (f) Davy et al. (2010), and (g) Gómez-Elvira et al. (2012).

Name	Height above ground (m)	Height above vehicle (m)	(Reference) Arrangement and heating considerations
Viking Lander (VL1, VL2)	1.6	0.7	(a) On deployed boom, 0.3 m out from lander. 2 × 700 Wth RTGs
Venera (V9, V10)	1.3	0.1?	(b) On braking disk at top of lander
Mars Pathfinder (MPF)	1.1	1.1	(c) On slender deployed mast at edge of solar array petal
Mars 96 Penetrator (M96P)	~0.5	~0.4	(d) On small mast above aftbody
Mars 96 Small Station (M96SS)	0.7	0.3	(d) On tripod above lander
Beagle 2 (BGL)	1.0	~0.8	(e) Mounted on 'paw' on robot arm – height variable up to 1m
Mars Phoenix (PHX)	2.0	1.0	(f) On slender deployed mast on lander deck
Curiosity (MSL)	1.7	0.6	(g) On stub booms on camera mast at corner of rover. 2000 Wth RTG