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Heuristic estimation of dust devil vortex parameters and trajectories from single-station meteorological observations: Application to InSight at Mars

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ABSTRACT

A physically-realistic migrating vortex model is developed and applied to generate pressure and wind speed and direction histories for dust devil passage. The asymmetric character of wind histories is noted, and we examine how these combined data constrain the solution space of dust devil parameters (migration velocity, diameter and intensity), ambient wind, and miss distance. These histories are compared with a new terrestrial field dataset of high-time resolution pressure and wind measurements of over twenty dust devil encounters in New Mexico. This new dataset is made available electronically and it is found that model fits can be typically achieved with simultaneous root-mean-square errors of ∼0.05 hPa (∼5–10% of the peak pressure signature), ∼20°of wind azimuth, and ∼2 m/s windspeed. The fits are not unique, however, and some heuristic aspects of resolving the intrinsic degeneracies of the problem and nonideal features of real encounters are discussed. The application of this approach to the InSight lander is noted, offering the possibility of defining the context for any possible detections of electromagnetic and seismic signatures of dust devils on Mars.

1. Introduction

Dust devils are one of the most dynamic features of the martian near-surface environment, and have been the subject of many studies in their own right (e.g. Balme and Greeley, 2006). While individual meteorological measurements (e.g. pressure time series) have been used to catalog vortex encounters on Earth and Mars, the resulting statistics are a convolution of intensity (e.g. core pressure drop) and the effects of diameter and miss distance. There is value in independently identifying the diameter and intensity, since these are distinct properties of an individual vortex, and the possible covariance of these properties is not known (e.g. small devils are more abundant than large, but are small intense devils more abundant than large weak ones?). Furthermore, in the search for possible 'unconventional' signatures of dust devils such as electromagnetic or seismic emissions, it would be useful to also determine the vortex trajectory so that the dependence of such signatures with distance can be evaluated. This effort may be of importance in the context of the planned InSight mission to Mars, which carries a sensitive seismometer Lorenz et al. (2015a) and magnetometer as well as meteorological instrumentation suite that should conduct extended high-time-resolution measurements able to catalog vortex encounters.

In this paper I explore how well the diameter and intensity of a vortex, can be estimated from single-point measurements of pressure, wind speed and direction. An additional product of the estimation exercise is a simple model of the vortex trajectory relative to the measurement station. The estimation approach is validated against terrestrial field measurements, and applications are discussed.

2. Statement of problem

The problem of identifying the location, intensity and diameter of a dust devil at any instant from these three measurements is of course grossly undetermined. However, casual observation suggests most dust devils have quasi-constant diameters, and Large Eddy Simulations (LES) suggest that their intensity, as measured by core pressure drop, are relatively constant over most of the lifetime of the vortex (e.g. Raasche and Franke, 2011). It is also generally the case that dust devils migrate with the wind in somewhat straight lines, e.g. Balme et al. (2012).

Assuming a constant diameter, intensity and migration velocity then reduces the parameter estimation problem to a small set of unknowns, against which the full time series of the meteorological measurements can be applied. We apply a model of the pressure

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Nomenclature

β	Azimuth of vortex migration
ϕ	Azimuth of wind velocity at station (+ve clockwise from North)
θ	Azimuth of vortex as seen from station
θ_M	Azimuth of vortex at closest approach
Ω	Azimuth of ambient wind
d	distance of vortex
d_{min}	closest approach distance
D	vortex wall diameter
ΔP	pressure drop at measurement station
ΔP_o	pressure drop at vortex center
$t_{1/2}$	full-width half maximum of pressure signature
S	vortex advection speed
U	ambient wind
V	vortex tangential wind speed
V_T	tangential wind speed at vortex wall (+ve clockwise viewed from above)
W	wind speed at measurement station
W_N,W_E	North and East components of wind velocity at measurement station

and tangential wind of a vortex as a function of radial distance to develop the signatures of dust devil passage as a function of vortex parameters and encounter geometry. While the pressure is a scalar quantity with no directional information, the wind is directional and we assume that the tangential vortex wind adds vectorially with the ambient wind. This results in an asymmetric distribution of both wind speed and direction, which serves as a powerful separate constraint on the model parameters.

Vortex encounters were qualitatively sketched by Ryan and Lucich (1983) for Viking wind data on Mars, and also by Tratt et al. (2003) for terrestrial encounters; some quantitative speed and direction profiles were computed (albeit with little comment) in Ringrose et al. (2007) although there is more discussion in an unpublished thesis (Ringrose, 2003). Those studies, and earlier work by Sinclair (1973) used the idealized Rankine vortex model as a framework for discussion, but it is well-known (and Tratt et al.'s data show – see Lorenz, 2014) that the Rankine model has an unphysically-sharp peak in velocity at the wall, and that velocity in real vortices falls off more slowly with distance than that model (which after all is almost a century and a half old) predicts. Here for quantitative replication of field data, we use a more realistic vortex model, which has smooth functions of pressure and windspeed as a function of radial distance.

2.1. Model formulation

As discussed above, we model the vortex as an invariant entity, with a constant migration velocity and intensity (Fig. 1).

We assume generally the vortex moves at speed S in an azimuth direction Ω (although the restricted model sets $\Omega=\beta$ and $S=U$) and we define time t and a coordinate x to be zero at closest approach

$$x = St \quad (1)$$

where the instantaneous distance d is simply

$$d = \left({d_{min}}^2 + x^2\right)^{0.5} \quad (2)$$

Clearly $d=d_{min}$ at closest approach, by definition. Vortex models are typically described in terms of a nondimensional radius r

$$r = 2d/D \quad (3)$$

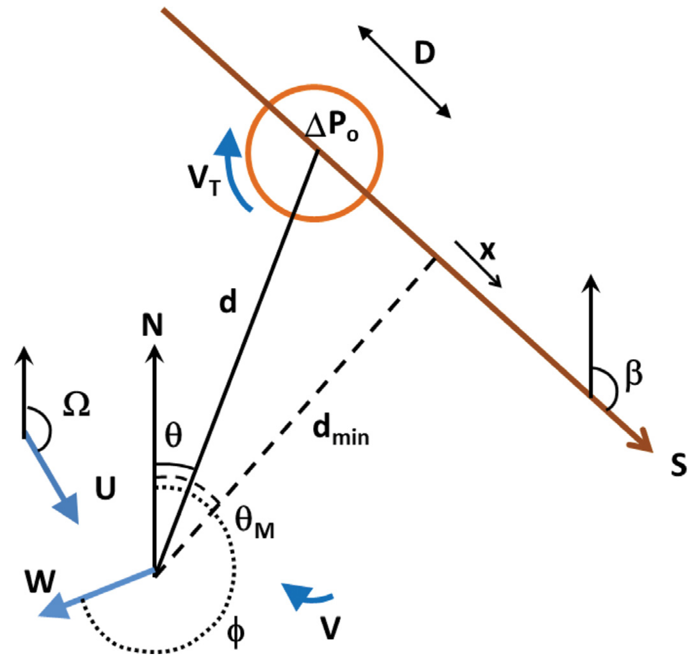

Fig. 1. Schematic of the encounter geometry of a vortex with a measurement station, seen from above. The vector addition of the vortex wind V (determined by the tangential wall speed V_T) and the ambient wind U (at azimuth Ω) yield the measured wind speed W (these vectors shown with blue arrows) which blows at azimuth ϕ. The observed azimuth θ of the dust devil has a value θ_m when range to the vortex d has a minimum d_{min}; at this moment, coordinate x is zero. x increases with time due to migration speed S in direction β. The vortex has a wall diameter D and core pressure drop ΔP_o: in the model V_T is determined by D and ΔP_o. In a restricted version of the model (vortex advected in wind), $S = U$ and $\beta = \Omega$.

where D is the wall diameter (commonly the visible radius of a dust-laden vortex) at which the windspeed is a maximum. Various vortex models exist. Here a Lorentzian profile of the pressure drop ΔP (used, e.g. by Ellehoj et al., 2010 to model martian dust devils) is algebraically convenient

$$\Delta P = \Delta P_o/(1 + r^2) \quad (4)$$

With ΔP_o the core pressure drop. We use the corresponding relation for the velocity field

$$V = 2rV_T/(1 + r^2) \quad (5)$$

which more smoothly describes the velocity-radius relationship than the Rankine model which is not differentiable at the wall. Our smooth profile also falls off more slowly in the far field than the $1/r$ dependence in the Rankine model : this slower fall-off was noticed by Tratt et al. (2003) in their field data (see also Lorenz, 2014) and thus overall these functions appear more suitable to describe real dust devils.

The wind vector at the measurement station is the superposition of the ambient wind U (at azimuth Ω), and the local tangential wind V calculated above, and is resolved into east and west components as follows

$$W_E = U \sin\Omega - V \cos\theta \quad (6)$$

$$W_N = U \cos\Omega + V \sin\theta \quad (7)$$

From these, the wind speed W and direction follow

$$\phi = \arctan(W_E/W_N) \quad (8)$$

$$W = \left({W_E}^2 + {W_N}^2\right)^{0.5} \quad (9)$$

We illustrate this superposition effect in Figs. 2–4. In the far field, $W=U$ and the direction is uniform. Close to the wall,