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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), $\sim 20^\circ$ 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.

Keywords

Mars Atmosphere; Experimental Techniques; Atmospheres; dynamics

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’

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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 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 Francke (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 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.

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

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

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

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

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 P (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 P_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

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

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

We illustrate this superposition effect in figures 2, 3 and 4. In the far field, $W=U$ and the direction is uniform. Close to the wall, however, the vortex wind can become important or even dominate. In particular, because the vortex wind and ambient wind can be near-opposite and equal, such that the resultant is near-zero, the direction can change by 180 degrees essentially instantaneously as the velocity field is advected over a point. This effect occurs only to one side of the devil passage : on the other side, the vortex winds and ambient sum together and only a small direction change is produced.

This model, while simple, displays a wide range of possible histories as shown in figure 4. The model allows us to predict the time histories of P , W and ϕ , as a function of the vortex properties D , V_T and P_o , the geometric properties of the encounter $d_{\min}$, S and β , and the ambient wind speed and direction U , Ω . This set of eight parameters is grossly undetermined, but we can find U and Ω by examining data long before or after the dust devil passage ($t \rightarrow \infty$, $x \rightarrow \infty$), where the vortex wind V falls to zero, thus $W \sim U$ and $\phi \sim \Omega$ making the assumption that the background wind vector is constant with time.

We can reduce the pair of intensity parameters by invoking cyclostrophic balance (where the pressure gradient provides the force needed for the centripetal acceleration of the rotating air) then we have

$$V_T^2 = \Delta P_o / \rho \quad (9)$$

where ρ is the density of the air. Note that the two variables are not completely dependent, in that we must retain the sense of rotation, since sign information is not captured in a physically-meaningful (i.e. negative) P_o . We thus book-keep separately whether the circulation is clockwise or anticlockwise.

The variable set is still challengingly large. For the moment, although it will be useful in future to retain the full model as specified above, we will take advantage of the approximation that the vortex is advected in the wind field. This restricted version of the model has $S=U$ and $\beta=\Omega$. Field observations by Balme et al. (2012) show that in general dust devil movement is within 20% of the wind speed, and the direction within about 30° (see later), so this restriction has some justification.

From inspection of the restricted model, some useful identities emerge. From the geometry of the problem,

$$\theta(t = \infty) = \Omega, \theta(t = -\infty) = \Omega - \pi \text{ and } \theta(t = 0) = [\Omega - \pi/2 \text{ or } \Omega + \pi/2]$$

i.e. the ‘vanishing point’ perspective. Also, algebraic manipulation yields the following useful relation for the full-width half-maximum $t_{1/2}$ of the pressure dip.

$$t_{1/2} = (1/U) \left[d_{\min}^2 + D^2 \right]^{0.5}$$

This relationship underscores that the characteristic timescale of the event is of the order of D/U , and in principle some degeneracy between a large devil making a fast passage, and a small devil moving slowly, exists. However, in the restricted model, the advection speed is in principle known ($S=U$) so this degeneracy disappears.

We can fit the wind azimuth and speed histories similarly, but the dual solution remains (since the vortex motion can be clockwise or anticlockwise – in our formalism the latter solution has a negative $d_{\min}$). Note that while we have developed the model with the intent of fitting individual events and estimating distance histories to assess seismic or magnetic signatures, there are other studies on the vortex population for which $d_{\min}$ is merely a ‘nuisance variable’. In these instances we might expect a large population of events to have an essentially random $d_{\min}$ distribution, and thus in studies of the ensemble of events $d_{\min}$ can be marginalized out, unless some terrain feature like a ridge led to preferential miss distances.

With perfect instrument data and with real-world vortices and ambient wind acting according to the model, we should be able to solve for all the model and geometric parameters. However, in practice, wind speed data recorded with a cup anemometer (which has a response time of a few seconds) is a low-pass filtered version of the actual wind speed history, and all data have sensor or digitization noise, so some degeneracy emerges. A more severe limitation, however, is the extent to which real winds are nonuniform, and real vortices have time-varying properties, azimuthal variations or other deviations from the idealized model. We therefore now examine some field data to test the model.

3. Field data

We will investigate the application of the model to field data obtained in summer 2014 at La Jornada Experimental Range, 37 km north of Las Cruces, New Mexico in the northern part

of the US Chihuahuan Desert. This field site (figure 5) has noted dust devil activity, and was the site of a previous investigation using a line array of pressure loggers (Lorenz et al., 2015b).

In the present experiment, a Davis instruments wind vane and cup anemometer (figure 6) were installed at 1.8m height on a fencepost at a flux tower installation near Taylor Well at La Jornada, together with two custom modified Gulf Coast Data Concepts B-1100 pressure loggers. These loggers have been augmented with extended battery power supplies (Lorenz, 2012) and the ability to record an analog voltage once a second (Lorenz and Jackson, 2015) in addition to pressure recorded digitally with a 1 Pa resolution at 2 samples/second. The potentiometer output of the wind vane was recorded by one B-1100, while the pulse output of the anemometer was converted by small circuit using a PICAXE-08 microcontroller which was programmed to count pulses and generate an analog voltage via pulse-width modulation on an output pin, smoothed with an R-C filter. The wind speed and direction were recorded at 1-s intervals ; while the two pressure records were sampled at 2 Hz, we averaged only one down to 1-s for computational convenience.

The experiment was installed in late April 2014, and operated for several weeks before the alkaline D-cell batteries expired. Inspection of the pressure record by semi-automated methods (e.g. Lorenz and Jackson, 2015; see also Jackson and Lorenz, 2015) revealed some dozens of negative excursions attributed to boundary layer vortex passages. Since the two pressure loggers were co-located, the wind vane direction and the anemometer wind speed could be synchronized by matching the pressure loggers. Some small differences in the pressure histories existed at the ~ 0.1 hPa level, so that not every vortex event identified with a 0.3 hPa threshold in one logger was also detected in the other. For the present analysis we examine only the set of events (27) which were detected reliably in both records. The two largest events (by pressure and by windspeed) are shown in figure 7.

We may note here that although there exist in the literature a handful of vehicle-borne pressure and wind signatures, dating back to Sinclair (1973), and a couple of collections of event summaries (e.g. peak windspeed) from fixed stations at White Sands (Lambeth, 1966) and in the Mojave desert (Carroll and Ryan, 1970), there is not until now a generally-available set of time-histories of vortex encounters of wind and pressure data. The present paper provides such data for the 27 events as ASCII files in the Supplemental Information. We note, however, a few analogous datasets recorded in tornados (Karstens et al., 2010). A large set of pressure-only records (e.g. Jackson and Lorenz, 2015), including measurements from an array (Lorenz et al., 2015b) have been made available.

4. Model Fitting to Data

The model described in the previous section was fit to the time series by using the root-sum-squared weighted errors in the three signals (pressure, direction and speed) as a cost function to be minimized. Clearly, one might choose parameters in the model that fit the pressure better than the wind speed, or vice versa, so errors in the three histories were first considered separately to assess how good a fit to each variable individually could be obtained. Informed by this exercise, the characteristic accuracy of model fits was found (for a 4-minute period

centered on the dust devil passage, i.e. 240 samples of each variable) to be ~0.05 hPa (typically 5–10% of the peak pressure signature), ~20° of wind azimuth, and ~2 m/s windspeed. The final cost function to be minimized therefore used the sum of the square of the error in each variable divided by these scale quantities to achieve a satisfactory overall fit, i.e. the quantity J is minimized, where J is defined as a function of the rms errors σ_π , σ_ϕ , σ_Ω in pressure, azimuth and windspeed respectively with units as above, as follows

$$J = (\sigma_\pi/0.05)^2 + (\sigma_\phi/20)^2 + (\sigma_\Omega/2)^2 \quad (12)$$

After some initial experimentation in trial-and-error fits, automated fitting using the downhill simplex method was used. As starting values, the average windspeed in the first minute of the record was used for S, U and the direction similarly for Ω, β . The pressure was adjusted to have the average P for the first and last minutes of the record to be zero. The half-width $t_{1/2}$ of the pressure signal was calculated from the time series, and the diameter D estimated to be $U t_{1/2}$. The miss distance was guessed at $0.8 D$, and the core pressure drop was estimated at 1.5 times the minimum value measured in the time series. Clockwise and anticlockwise senses were both tried for each event. In general this heuristic procedure gave reasonable fits when the simplex process converged on local minima of the cost function. Anticipating these to be nonunique, a Monte-Carlo approach using 40 random starting values (multiplied or divided by factors of a few from the estimates above) was also used, and in some cases yielded appreciably better fits.

As a test case, we generated a synthetic time series of pressure, wind direction and speed, and added Gaussian white noise to each series, with a standard deviation of 0.02 hPa, 5 degrees and 1 m/s respectively. The Monte-Carlo process resulted in reasonably accurate recovery of the model parameters (figure 8) : while in this instance the miss distance, bearing and speed were recovered correctly (10.2 m vs 10 m; 269 deg vs 270 deg, 2.98 m/s vs 3 m/s) the diameter was slightly underestimated (9 m vs 10 m) and the core pressure drop overestimated (2.42 hPa vs 2.00 hPa). These errors of 10 and 20% can be considered somewhat representative of good results from the procedure, recognizing that nonGaussian and/or larger noise (or model deficiency) will yield larger errors. It may be noted, and will be discussed later, that some of these errors are strongly correlated - the effects of the larger pressure drop and smaller diameter largely compensate for each other in the modeled pressure and windspeed time series.

Given the reasonable success of this exercise, we now apply the fitting procedure to the field data : some examples of the best fits are shown in figure 9. The fits to the set of events, together with the rms errors in the three variables, using a slightly different cost function $J = (\sigma_\pi/0.03)^2 + (\sigma_\phi/15)^2 + (\sigma_\Omega/2)^2$ are listed in Table 1. A complete set of field measurement plots, and ascii time series of field data and model histories, are given in Supplemental Information.

Note that in table 1, event 24 converged on a negative diameter, since the optimization was not constrained. In this instance in fact the sense should be reversed to anticlockwise since

the model formulation incorporates a wind term that depends on the sign of the distance normalized to diameter. One could alternatively force the diameter to be positive ; another approach might be rather than book-keep sense as a separate binary variable, use a signed pressure or signed diameter to retain the sense information.

Event 21 is a ‘textbook’ vortex encounter, with the presence of a local minimum in windspeed indicating a diametric passage of the ‘eye’ of the vortex where winds drop almost to zero. The heuristic fit fails to capture this particular feature because it is so short in duration, so the failure on that handful of windspeed datapoints is compensated by better fit elsewhere and/or with other parameters . By choosing model parameters appropriately (sacrificing the fit quality in pressure, for example) the model can recover this shape quite well – see figure 10. Performing the fit to data more closely centered on the event (e.g. ± 40 s) might also more robustly recover such structure in automatic fitting. Note that close inspection of figure 10 shows that part of the difficulty in fitting may be because the windspeed minimum is slightly offset from closest approach, perhaps because of a failure to correctly account for the finite time response of the cup anemometers : a thermal anemometer (as carried on InSight) or an ultrasound system with a faster response would be easier in this respect. In any case, it must be recognized that simultaneous fitting to three different datasets entails some judgement if particular phenomena are being explored, although the methodology described here overall yields reasonable overall estimates of the vortex parameters.

5. Future Elaborations and Applications of the Model

In the interests of developing a viable solution from modest data, the vortex and trajectory models are essentially as simple as can be contrived and yet still capture the key physics. This restricted model has 6 principal parameters, of which 2 (wind speed and azimuth) are essentially specified directly from the data; further, the cyclostrophic balance assumption relates the tangential windspeed directly to the core pressure drop, eliminating another degree of freedom. Thus the unknowns are the diameter, the intensity (e.g. core pressure drop), the rotation sense and the miss distance. The latter variable is not of general interest, and can be marginalized (in a Bayesian sense – i.e. ‘averaged out’) in studies of large populations.

A first, obvious model constraint that might be relaxed is that the vortex is advected at the ambient wind velocity. While a defensible first approximation, there are documented to be ~ 30 degree differences in migration direction, and perhaps 20% differences in migration speed (Balme et al., 2012), with migration tending to be 10–20% faster than ambient wind at the surface. This bias may be different at Mars, of course. It is notable, examining the data from Balme et al. (2012) that there is a systematic improvement to the agreement between surface windspeed direction and dust devil migration direction when the windspeed is higher (see figure 13). This is consistent with a ‘random’ component of motion associated with boundary layer convection, which is vector-added to a prevailing wind.

In fact, while the straight-line trajectory model is reasonable for situations where there is an appreciable wind, dust devil tracks often reveal a rather cycloidal or trochoidal migration

path. Such curved migration paths often give multiple local minima in distance to a measurement station, and thus multiple dips in observed pressure time series (e.g. Lorenz, 2013). While such cycloidal functions can be specified with a modest number of parameters, there is likely a danger of overfitting.

Multiple pressure dips (seen in field measurements of pressure on Earth – Lorenz, 2012) can also be caused by multiple-cored vortices. This underscores the more general point that a single, axisymmetric vortex structure is assumed in the present model, with specified radial functions of velocity and pressure. In principle, other functions could be used (e.g. choosing an exponent other than 2.0 in eqs. 4 and 5). Furthermore, we explicitly relate the core pressure drop and peak tangential windspeed, collapsing two parameters into one. That link could be relaxed (we in fact experimented with altering the prefactor in eq.9, but fitting was not noticeably better overall, although of course gave different results from pressure and wind in a given fit attempt).

An additional modeling aspect is perhaps the most obvious, that the model assumes a single vortex is responsible for the observed perturbations. Multiple vortices could be present. This sort of model selection question is confronted in other fields, notable examples being the detection of exoplanets in transit lightcurve data, and in target tracking by radar or sonar methods in military applications, most particularly in submarine warfare. A powerful approach in these situations is to use Bayesian methods to judge whether additional model parameters (e.g. multiple vortices) are justified by the resulting improved fit to the data, and methods such as Markov Chain Monte Carlo (MCMC) or particle filters are used to manage the multiple hypotheses considered.

The model can also be expanded to accommodate additional observational constraints. For example, an image might show a dust devil on the horizon, therefore giving a fixed azimuth value at a given time, and also the width of the feature constrains the ratio diameter/distance at that instant. Such constraints can powerfully resolve the meteorology-only ambiguity. If a stereo camera is available, or the camera is high enough off the ground, the range to the devil can be estimated, and thus the diameter as well. In the context of the InSight mission, the seismometer may provide vortex trajectory constraints – if the ground elastic response can be estimated, the tilt magnitude (Lorenz et al., 2015a) may be an indication of the vortex core pressure drop divided by the square of the normalized distance r . Even if the elastic properties of the ground are not known, the direction of tilt provides a direct estimate of the azimuth of the vortex as a function of time, unless there is a viscoelastic lag. It may be that these properties could be introduced as model parameters to be estimated, e.g. by comparing the tilt azimuth history with camera azimuth constraints.

7. Conclusions and Model Applications

We have reported a high-quality data set of wind and pressure measurements from ~27 vortex encounters from a field campaign in New Mexico, and shown that not only can these encounters be reproduced well with a simple model, but the model can be fit to recover estimates of the vortex and encounter geometry parameters. This model may be useful to reconstruct the encounters with vortices on Mars, and thereby derive quantitative

relationships for seismic and magnetic signatures. In future work we will evaluate the improved constraints that seismic tilt histories and/or camera data might provide.

While dust devil encounters on Mars have been documented with pressure data (Murphy and Nelli, 2002; Ellehoj et al., 2010) and with winds (Ryan and Lucich, 1970), the InSight mission promises to measure both wind and pressure data at a suitable cadence to detect vortices (e.g. Banfield, 2014) : the pressure sensor in particular is the fastest-response highest-sensitivity continuously-recording pressure instrument ever sent to Mars. It may be natively sampled at 20 Hz and may have a noise level on the order of ~ 10 mPa (i.e. $\sim 0.002\%$ of ambient). Further details of the frequency-dependent noise and downsampling strategies are given in the InSight Participating Scientist Program Proposal Information Package November 2015, (<http://nspires.nasa.gov>, downloaded January 11, 2016). That document indicates that wind measurements will be made at up to 1 Hz, with a precision of about 1.5 m/s below 5.5m/s, and 2.8m/s at 15 m/s.

It has been demonstrated (Lorenz et al., 2015a) that dust devil vortices on Earth produce a surface tilt signature that is detectable by a long-period seismometer, and can be interpreted by a simple model of a point load on an elastic half-space. A constant of proportionality exists between the total load applied by the devil (proportional to the product of core pressure drop and the square of diameter), and the tilt observed : this constant captures the elastic modulus of the regolith, which is of more general geophysical interest. With known vortex encounter geometry (the tilt varies as the inverse square of distance) this constant can be estimated. Higher-frequency seismic signals from dust devils also exist (as also noted from tornadoes, e.g. Tatom et al., 1995) but have not yet been well-characterized.

Additionally, whirling grains in dust devils can be electrically charged. While DC electric fields (which for terrestrial devils can reach many tens of kV/m) are not measured directly by InSight, the circular motion of these charged grains can generate a magnetic field (as if the charges were moving along the wire in a solenoid). Variations in the circular velocity, radius or amount of charge may lead to variations in the associated vertical magnetic field. Furthermore, if the dust devil has azimuthal structure – as many are observed to have, e.g. with double or multiple vortex cores – then AC magnetic fields and horizontal field components may be generated. At present these fields have only been detected, and their relationship to vortex parameters and dust loading has not been quantified on Earth or Mars.

Finally, in addition to a quasi-static dip in pressure associated with the nearby passage of a vortex (the signature by which most vortices are identified), dust devils may generate audible noise and low-frequency pressure fluctuations (i.e. infrasound). Infrasonic records of dust devil vortex passage at monitoring stations of the Comprehensive Test Ban Treaty Organization (CTBTO) show rapid fluctuations (Lorenz and Christie, 2015), as do tornadoes (e.g. Bedard, 2005) : sufficiently high-rate sampling of a pressure sensor on InSight might be able to detect similar infrasonic emission.

In each of these cases, the interpretation of these ‘unconventional’ signatures of dust devils would benefit from an estimate of the distance, direction, diameter and intensity of the vortex, as described in the present paper.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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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
P	Pressure drop at measurement station
P_0	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

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Highlights:

- Applies analytic vortex model to generate encounter signatures
- Examines solution space constraints from data and fitting accuracies
- Demonstrates model with new high-quality terrestrial field data
- Considers optimal camera views for InSight mission

Figure 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 $\beta=\Omega$.

Figure 2.

Vector addition of the ambient and vortex winds produces a slightly asymmetric velocity field, shown as arrows, centered on the 10m diameter dust devil. Arrow length equal to cell spacing (5m) corresponds to winds of 5 m/s : at the edge of the field the wind is simply the ambient, 5m/s top to bottom. Left of center, winds are slightly weaker due to the cancellation of part of the ambient wind by the vortex wind (clockwise), whereas right of center they are slightly enhanced, but in both cases the direction is that of ambient. Just below (i.e. before the dust devil passage) winds deviate to the left, and above to the right. In this weak-vortex example, the deviations are similar either side of the devil.

Figure 3.

As figure 2, but with comparatively weaker ambient wind $U=2 \text{ m/s}$ (here the circumferential wind at the wall VT is 5 m/s as before). Again an extended region of weak winds to the left is formed due to the opposite direction of vortex and ambient flow, while they add to the right. Because the vector subtraction to the left of center leads to such small winds overall, the direction is very easily modified and the vortex component causes a complete and instantaneous 180° reversal in left-right direction as the vortex passes. This dramatic azimuth change is observed in field data.

Figure 4.

Simulated measurement histories of windspeed and direction measured at a point as the superposed vortex and ambient wind fields are advected over a fixed meteorological station (essentially up-down cuts through figures 3, although in this instance with a larger vortex). The curves are labelled by the x-distance at which the cut occurs (negative to the left). Along the centerline the wind direction (upper panel) shows a slight deviation to higher azimuths, then a rapid veer to the other direction, and then a slow decay (to show the details, the plot is not wide enough to show a completely unperturbed wind). To the right (10, 20m) the direction change is muted, but to the left (-10, -20) the wind azimuth veers strongly, rotating completely around. The lower panel shows the wind speed histories, with stronger peaks to the right and almost constant values to the left : where the vortex makes a diametric crossing of the station (0) the 'eye' is resolved, with a local minimum in windspeed flanked by two local maxima.

Figure 5.

Aerial view of the field site, taken with a GOPRO digital camera lofted on a parafoil kite (the kitestring is visible just left of center). The area is flat, with partial cover of scrub and bushes. The anemometer and wind vane were mounted on a fencepost of the square corral visible at bottom just left of center. A vehicle and a few persons offer a sense of scale.

Figure 6.

Field installation on a T-post supporting the wire fence. Note the scale of the scrub in the background and the dessicated mud which in fact had only modest dust availability. The datalogging box with the two pressure loggers and D-cell batteries is seen at the base of the fencepost. The anemometer cable is coiled near the top of the fencepost to prevent rodent damage to wiring.

Figure 7.

Profiles of the two largest vortices detected in terms of wind speed (event 7, ~20 m/s) and pressure drop (event 14, 1.4 hPa). The panels (left to right) are pressure, wind direction and wind speed : the event time and optimized model parameters are shown at left ; the rms errors in each fit are noted at the right.

Figure 8. Synthetic model time series with Gaussian noise added, and the result of the Monte Carlo fitting procedure. The recovery of model parameters is overall good, but not perfect.

Figure 9.

Field data of four vortex encounters that are particularly well-described by the vortex model described in the text. The panels (left to right) are pressure, wind direction and wind speed : the event time and optimized model parameters are shown at left ; the rms errors in each fit are noted at the right. Despite the great diversity in wind direction histories, the model can be adapted to achieve very good fits. Note also that the windspeed record tends to have variations that are not captured by the smooth model functions, and that event 21 (3rd line)

has a local minimum in windspeed at the center (i.e. the ‘eye’) that is only hinted at in the model fit.

Figure 10.

An alternate fit to Event 21. Here the diameter is larger, but the migration speed is increased to compensate, so the duration of the event is comparable. Here, however, the miss distance is made small enough compared with the diameter that the ‘eye’ of the devil is resolved.

Figure 11.

Poorer automatic fits to the data result in some other encounters, generally as a result of non-simple fluctuations in windspeed. In some cases (e.g. events 3, 19, 25) the pressure record is appreciably nonsymmetric, perhaps indicating a multi-core vortex, which our symmetric model cannot hope to capture ; in another case (Event 8) there is clearly a second vortex in the record at about 1.5 minutes, which again our single-vortex model cannot capture. Although the rms errors are generally rather poorer than those in figure 8, the retrieved

parameters are not unphysical, and it is not clear that any simple model could do much better.

Figure 12.

Solutions for Event 20 and 21 plotted on the Diameter-Advection speed plane of the solution space. Squares denote solutions which best match the pressure history – the slope of unity highlights the diameter/speed degeneracy in these parameters. The wind direction constraint (plus signs) has a shallower slope, and therefore together with the pressure defines a rhomboid solution. The boomerang shape of the wind speed constraint (X) is usefully different, being near-orthogonal to the long axis of the direction/pressure rhombus. Event 21 has a longer duration, so the diameter/speed band allowed by the pressure history is displaced to the right compared with Event 20. In this instance, the windspeed constraint is less useful. Clearly, the best-fit solution overall will be close to the centroid of the intersection region of these constraints – the actual solution area shown is only intended to illustrate the relative shapes, not the size of an ‘acceptable’ region.

Figure 13.

Variation of dust devil migration direction from the wind direction as a function of wind speed U , reported by Balme et al. (2012). Superposed are the deviations expected from a constant 'random' windspeed R – an arctangent (R/U) model captures the field data behavior.

Table 1.

Event summary and model fit results, using a cost function . Columns are the Event number and date, the approximate time (Eastern daylight time, 2 hours ahead of local mountain time), the lowest pressure excursion recorded, the maximum wind speed recorded, the difference between the largest and smallest wind azimuth, the ambient windspeed and azimuth. Then follow the recovered best-fit parameters, namely core pressure drop, miss distance, diameter, rotation sense (1=clockwise, -1 anticlockwise) and the root-mean-square differences between observations and fit for pressure, wind azimuth and windspeed.

Event #	Date	Time (EDT)	P _{min} (hPa)	W _{max} (m/s)	$\phi_{\max}-\phi_{\min}$ (deg)	U (m/s)	Ω (deg)	P _o (hPa)	d _{min} (m)	D (m)	Sense CW=1	σ_p (hPa)	σ_ϕ (deg)	σ_W (m/s)
1	4/23/2014	17:10	0.49	18.6	59.0	8.47	73.35	0.50	-47.96	142.16	-1	0.059	17	1.8
2	4/26/2014	14:11	0.46	15.6	73.3	9.49	68.20	0.42	-19.01	97.51	-1	0.057	19	1.7
3	4/26/2014	14:47	0.47	18.9	57.7	12.36	63.93	0.97	-48.53	330.29	-1	0.069	21	3.2
4	4/27/2014	14:43	1.32	15.0	308.2	7.77	39.59	0.30	-371.93	1107.98	-1	0.115	24	3.3
5	4/28/2014	17:35	1.29	21.5	99.7	7.50	94.37	1.03	16.66	76.69	1	0.078	19	1.8
6	4/29/2014	17:10	1.07	12.1	358.3	5.21	128.86	1.23	5.01	18.45	1	0.058	30	1.5
7	5/3/2014	17:46	0.79	18.8	358.3	1.62	333.94	3.59	14.48	13.96	-1	0.094	27	1.6
8	5/4/2014	15:25	0.53	10.8	217.7	2.78	69.46	0.58	-6.14	31.66	-1	0.063	51	2.3
9	5/4/2014	18:32	0.40	10.9	351.1	7.26	61.30	0.35	1.97	94.75	-1	0.058	19	3.4
10	5/5/2014	14:11	0.39	10.1	112.4	5.34	64.60	0.35	-11.11	147.74	-1	0.047	37	2.7
11	5/7/2014	14:22	0.33	16.3	354.4	9.97	59.36	0.35	-37.78	127.55	-1	0.044	12	2.0
12	5/7/2014	17:32	0.28	16.2	57.8	12.38	60.15	0.19	11.97	107.25	-1	0.092	13	1.9
13	5/8/2014	12:01	0.65	9.4	63.4	7.41	88.64	0.70	-11.11	57.28	1	0.056	16	1.7
14	5/8/2014	16:10	1.52	17.9	358.9	7.49	92.73	1.34	5.95	69.09	1	0.077	26	2.2
15	5/8/2014	17:40	0.89	21.7	144.5	8.70	74.00	0.85	-14.91	64.40	-1	0.063	12	1.4
16	5/11/2014	17:34	0.30	17.7	74.9	12.25	67.28	0.19	-10.14	133.196	-1	0.092	16	2.4
17	5/11/2014	17:41	0.36	16.8	91.4	11.43	77.33	0.31	-24.97	256.61	-1	0.085	16	2.4
18	5/13/2014	18:23	0.34	7.6	358.9	1.16	195.98	0.32	2.44	10.92	-1	0.048	24	2.2
19	5/13/2014	20:26	0.61	14.9	359.5	5.59	233.30	0.47	-18.64	149.20	-1	0.067	32	2.3
20	5/13/2014	13:55	0.65	9.3	272.3	3.05	98.14	0.58	1.14	24.77	1	0.036	14	1.4
21	5/17/2014	17:48	1.27	15.8	264.1	0.69	331.68	1.37	4.10	18.88	-1	0.091	33	2.6
22	5/17/2014	18:41	0.42	8.5	245.3	5.97	35.71	0.20	-57.19	348.22	-1	0.058	28	3.1
23	5/20/2014	13:19	0.42	10.3	81.5	5.59	86.08	0.37	12.02	84.77	1	0.040	17	1.4
24	5/20/2014	15:22	0.18	12.2	89.3	5.50	98.71	0.22	-13.51	-34.67	1	0.100	23	1.5

Event #	Date	Time (EDT)	P _{min} (hPa)	W _{max} (m/s)	Φ _{max} -Φ _{min} (deg)	U (m/s)	Q (deg)	P _o (hPa)	d _{min} (m)	D (m)	Sense CW=1	σ _p (hPa)	σ _θ (deg)	σ _w (m/s)
25	5/21/2014	15:09	0.50	8.8	284.6	7.12	63.12	0.35	15.69	190.77	-1	0.052	39	3.1
26	5/21/2014	17:36	0.67	13.4	120.3	6.60	39.67	0.71	18.42	65.86	-1	0.054	28	3.1
27	5/21/2014	19:03	0.76	9.6	346.7	7.60	14.86	1.17	-116.51	288.60	-1	0.064	40	3.8