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# Signal-adapted tomography as a tool for dust devil detection

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ABSTRACT

Dust devils are important phenomena to take into account to understand the global dust circulation of a planet. On Earth, their contribution to the injection of dust into the atmosphere seems to be secondary. Elsewhere, there are many indications that the dust devil's role on other planets, in particular on Mars, could be fundamental, impacting the global climate. The ability to identify and study these vortices from the acquired meteorological measurements assumes a great importance for planetary science.

Here we present a new methodology to identify dust devils from the pressure time series testing the method on the data acquired during a 2013 field campaign performed in the Tafilalt region (Morocco) of the North-Western Sahara Desert. Although the analysis of pressure is usually studied in the time domain, we prefer here to follow a different approach and perform the analysis in a time signal-adapted domain, the relation between the two being a bilinear transformation, i.e. a tomogram. The tomographic technique has already been successfully applied in other research fields like those of plasma reflectometry or the neuronal signatures. Here we show its effectiveness also in the dust devils detection. To test our results, we compare the tomography with a phase picker time domain analysis. We show the level of agreement between the two methodologies and the advantages and disadvantages of the tomographic approach.

## 1. Introduction

Dust devils are dust loaded convective vortices, with diameters of a few meters and heights of an order of magnitude larger. Their formation is favoured in conditions of strong insolation, low humidity environment, lack of vegetation and buildings or other high obstacles and gently sloping topography (Balme and Greeley, 2006). For these reasons, they are often observed in terrestrial deserts and are also very common on the surface of Mars.

Martian and terrestrial dust devils have a common formation mechanism and similar dynamics (Ringrose et al., 2003), but the Martian dust devils can be an order of magnitude larger than the terrestrial ones (Fenton et al., 2016).

Dust devils are one of the most efficient aeolian mechanisms able to lift material from the surface and inject dust into the atmosphere, through the combined effect of the vertical wind, saltation process and pressure-gradient force (Balme et al., 2003; Klose et al., 2016).

The relative importance of the three mechanisms is still unclear, but, their sum makes the dust devil a more effective dust lifting-phenomena compared to the common atmospheric boundary layer winds (Greeley et al., 2003).

On Mars, the optimum size of the grains lifted by the boundary layer winds is around 100 μm and the value of the friction velocity threshold grows rapidly for particles smaller and bigger than this optimum size. However, the typical size of grains that compose the observed Martian haze and the local and global dust storms is in the order of about 3 μm in diameter and even smaller in some cases (Pollack et al., 1979). Due to the low Martian surface pressure, the boundary layer wind required to mobilize such small grains exceeds the speed of sound (Iversen and White, 1982) and is much faster than the typical winds observed or predicted from climate models.

The small grains are indeed not directly lifted by the wind friction.

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The first particles to be mobilized by the wind are the ones whose size is around 115 μm. Bouncing on the surface, these grains (called saltators) start a chain process called saltation. At each impact with the soil other saltators are ejected and the bump can be strong enough to mobilize even the smallest particles (Greeley, 2002). The wind regime needed to start the saltation on Mars is quite uncommon, but, once started the process can be sustained by the typical Martian winds (Almeida et al., 2008; Kok and Renno, 2009; Kok, 2010).

The wind friction and the saltation processes represent the driving lifting mechanisms during the dust storm. However, the lifting power of dust devils appears to be effective in a range of grain size much larger than the one of the wind friction (Neakrase and Greeley, 2010a,b). In addition, the vortices are a continuous source of lifted dust also outside the dust storms season. For these reasons, the dust devils have been proposed as one of the main mechanisms able to sustain the dust haze of the Martian atmosphere (Neubauer, 1966; Thomas and Gierasch, 1985, Klose et al., 2016).

The pressure gradient force is due to the low-pressure core at the centre of the dust devil. In the simplest and most common case, when the vortex has a single core, the pressure profile can be approximated by a Lorentzian function (Ellehoj et al., 2010):

$$P(t) = \frac{-\Delta P}{1 + \left(\frac{t - t_0}{1/2\Gamma}\right)^2} + B$$

where P(t) is the pressure as a function of time, ΔP is the magnitude of the pressure dip at the centre of the vortex, $t_o$ is the time instant relative to the peak, B is the background pressure value and Γ is the full width at half maximum (FWHM) of the event. The cumulative distribution of the ΔP can be described by a power law function, the magnitude of the drop usually ranges from 0.1 to 1.5 mbar (Lorenz and Jackson, 2016).

The sand and dust grains mobilized by the vortex collide with each other and with the surface, acquiring charge by triboelectricity (Eden and Vonnegut, 1973). When the composition of the colliders is approximatively heterogeneous, the charging process is size-dependent, the smaller grains tending to acquire a charge opposite to the larger ones (Inculet et al., 2006; Duff and Lacks, 2008; Esposito et al., 2016; Harrison et al., 2016; Neakrase et al., 2016). The smaller grains are lighter and are driven upwards in the dust column by the air flow, while the larger ones stay closer to the ground producing a charge separation. The dust devil can acquire a strong electric field in this way, as firstly reported by Freier (1960), Crozier (1964, 1970). Farrell et al. (2004) has reported for terrestrial dust devils a vertical electric field over 4000 V/m. Taking into account that usually the background absolute value of the terrestrial atmospheric electric field is below 100 V/m, the electrical variation due to the passage of a dust devil is a clearly recognizable feature of the event.

As already mentioned, the role and importance of dust devils in the Martian climate is a highly studied and debated subject. The study of dusty vortices is one of the scientific questions to be pursued by the next Mars space missions, such as the ExoMars 2020 and InSight 2018 (Lorenz, 2016). Therefore, the ability to discriminate dust devils in the acquired data becomes of great importance.

Overall, the main signatures of the passage of a dust devil are (Balme and Greeley, 2006):

- a peak in wind speed,
- a change in wind direction,
- a drop in pressure,
- a peak in the electric field,
- a peak in concentration of the lifted dust and sand,
- a raise in atmospheric temperature.

Depending on the distance to the dust devil and on its magnitude, these features can be more or less evident and some of them may be totally hidden. Clearly, the simultaneous occurrence of all of them strongly indicates the passage of a dusty vortex. The detection of dust devils starts from the search for one of these features. Usually, the variation in the pressure signal is chosen as the main parameter to investigate (Murphy et al., 2016).

Methods based on the comparison between a short-term and a long-term average are used to detect the isolated drops. This approach is called "phase picker". In dust devils the long-term average is usually in the order of ten minutes, while the short-term is in the order of ten seconds or less. When the difference between the two values exceeds a chosen threshold the event is counted as a possible dust devil. The threshold depends on the fluctuations around the long-mean value, namely, on the variability and noisiness of the signal. Subsequent check of the other physical parameters allows the elimination of non-significant events. This method is used, with some variants, both on terrestrial (e.g., Jackson and Lorenz, 2015) and on Martian (e.g., Ellehoj et al., 2010) measurements.

Here we want to propose an alternative technique based on a time-signal adapted operator analysis, instead of the direct time analysis. This technique allows us to deal with very noisy signals and it is less sensitive to the duration and magnitude of the dust devil's signal, leading to a detection much less sensitive to the choice of arbitrary thresholds. This tool also allows to filter the signal eliminating any component that does not belong to the dust devil.

The pressure profile of the vortex has a clear shape in the time domain but has no characteristic track in the frequency domain. Therefore, we need a signal transform that takes into account transients and allows the extraction of the signal components that are related to the characteristic behaviour of the dust devils. For this purpose, we decided to adopt a bilinear transformation called tomogram, improving the technique and adapting it to the specific case of the vortices detection.

The analysed data were acquired during a field campaign performed in Morocco in 2013. The campaign was carried out in the frame of the DREAMS project, the meteorological station on board of the Schiapparelli lander of the ExoMars 2016 space mission (Esposito et al., 2017). We show the results of the application of this new methodology to the data acquired during five days of measurement. We show the results of the application of this new methodology to the data acquired during five days. We have also analysed the same days with a time-domain technique. Comparing the corresponding results obtained by the two methods, we can test the effectiveness of the tomographic technique.

## 2. Material and methods

### 2.1. Field campaign

The field campaign took place in 2013 in the Tafilalt region (Morocco) in the north-western Sahara. This area is characterized by an arid environment, it is rich in both sand and dust, and is very active from an aeolian point of view. Measurements have been performed during the dust storm season in a period between July and September at geographical coordinates 4.113°W, 31.161°N, elevation of 797 m a.s.l.

From the geological point of view, this site is a flat Quaternary lake sediment bed. The sand, silt and clay fractions of the soil have similar composition consisting of detrital shale grains, quartz and carbonates. The position near the centre of the lake made the site rich in hygroscopic and soluble minerals. For this reason, most of the soil grains are aggregated in an extended saline crust.

A fully equipped meteorological station (Fig. 1) was deployed consisting of:

- soil temperature (CS thermistor) and moisture (CS616-C) sensors,
- three 2D sonic anemometers (Gill WindSonic) placed at 0.5, 1.41, 4 m,
- one temperature and humidity sensor (Vaisala HMP155) at 4.5 m