Telltale wind indicator for the Mars Phoenix lander

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[1] The Telltale wind indicator is a mechanical anemometer designed to operate on the Martian surface as part of the meteorological package on the NASA Phoenix lander. It consists of a lightweight cylinder suspended by Kevlar fibers and is deflected under the action of wind. Imaging of the Telltale deflection allows the wind speed and direction to be quantified and image blur caused by its oscillations provides information about wind turbulence. The Telltale will primarily support surface operations by documenting the wind conditions to improve the efficiency of sample delivery to instruments on the lander deck. During the latter stages of the mission the Telltale investigation will focus on meteorological studies.

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1. Introduction

[2] The Telltale wind indicator was added to the payload of the Phoenix lander [*Smith et al.*, 2008] at a relatively late stage of the preparation for the mission. At that time a hot film anemometer had been deselected because of mass and cost constraints [*Taylor et al.*, 2008] and no wind measurements were planned during surface operations. It was, however, noted that even simple wind measurements would greatly enhance the efficiency of surface operations, particularly the precision delivery of samples to instruments on the deck of the lander, and also would significantly improve the scientific value of the meteorological data.

[3] An idea was put forward by C. F. Lange to add a simple mechanical wind indicator, consisting of a light weight object hanging in strings. The device would be imaged by the onboard camera "Surface Stereo Imager" (SSI) (M. Lemmon et al., manuscript in preparation, 2008), to provide approximate wind direction and speed. This idea eventually was introduced to the Mars Simulation Laboratory at the University of Aarhus in Denmark, where the low-pressure wind tunnel [*Merrison et al.*, 2002] could facilitate the design and the calibration processes. After some feasibility studies and testing of prototypes in Aarhus, the task of building the instrument was undertaken.

[4] The benefits of such a wind indicator are that no direct power or data transmission facilities would be required by the lander as opposed to, e. g. the hot film anemometers on the Viking [*Chamberlain et al.*, 1976] and Pathfinder missions [*Seiff et al.*, 1997]. It was furthermore clear that such type of wind indicator required only a very simple mechanical interface to the lander. Previous mechanical wind sensors operating on Mars [*Sullivan et al.*, 2000] were not designed to monitor the winds at the landing site, but used to monitor surface roughness.

[5] From a science perspective accurate measurement of wind speed, direction and turbulence are important to assess the accuracy of atmospheric models and interpretation of local aeolian features.

[6] However, the only direct Mars wind flow data are measurements by the Viking landers and Mars Pathfinder obtained relatively close to equatorial latitudes. The Telltale wind indicator has the potential to contribute significantly to the understanding of the environmental conditions at the Martian surface in the unexplored polar regions.

2. Design of the Telltale Experiment

[7] A picture of the Telltale system on the Phoenix lander is shown in Figure 1. In preliminary tests it was noted that the active part of the instrument (referred to as the Telltale) would have to be extremely lightweight. The basic problem is that moderate winds in the thin Martian atmosphere have only limited capability to move objects and the Telltale has to have observable deflection when subjected to forces of

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Figure 1. The Telltale assembly. The total height of the instrument is 83.1 mm. Lightweight Kapton tube (yellow) is suspended in braided Kevlar fibers (~40 fibers of 18 μm in diameter). The Kapton part is viewed both directly and by mirror image from the below. Note that in this image the (flight unit) Telltale is mounted on a threaded pin and not on top of the meteorology mast.

the order of μN. Early attempts to build a standing Telltale that would partly compensate the gravitational forces were dropped because of lack of robustness of such a design and the requirement that the instrument would have to operate flawlessly under up to 16° lander tilt.

[8] The final Telltale design employs rolled-up cylinders of 8 μm Kapton™ foil. Despite the thinness of the foil, in rolled-up form it has sufficient stiffness to maintain the desired cylindrical shape. Any modification such as e.g., perforation would, however, limit this capability. The total weight of the active part is of the order of 10 mg. It was found that any attempts to build a more complicated object would increase the mass of the active part too much for the required sensitivity. The open end of the tube represents a potential problem due to eddy resonances. Calculations and experiments, however, showed that eddy resonances have frequencies above 100 Hz, well above the sensitivity range of the Telltale, so eventually no attempt was made in changing the surface of the Kapton foil by e.g., punching holes into it or by equipping it with a conical end.

[9] In preliminary testing, it was noted that the telltale could act as an uncontrolled pendulum when the airflow contained turbulence frequencies close to the natural oscillation frequency of the (movable) Kapton part of the Telltale (few Hertz). Though a time average of such a motion should in principle give information on wind velocities, reduced image contrast due to the movement during exposure and the chaotic movement of the active part clearly showed that some moderate damping of the motion of the active part was required. Different approaches were employed to obtain the necessary damping properties of the active part. Of the many possible solutions tested, braided Kevlar fibers were selected, because they have the necessary damping properties, strength, and robustness to be reliable in this context. Kevlar fibers are still the cause of many problems in the design, they exhibit static friction that give hysteresis and they can become brittle when bent under a critical radius. To minimize weight, the Kevlar fibers were glued directly to the Kapton tube.

[10] Originally, placement of the Telltale on the lander deck as part of the radiometric calibration targets [*Leer et al.*, 2008] was considered, so that the Telltale could be imaged on a regular basis together with them. Because of the very complex surface structure of the lander deck, including all the science instruments, it became clear that this placement would not give reliable wind data. Instead, it was decided that the Telltale should be moved to the top of the meteorological mast. This position posed its own challenges. The top of the mast is at a height similar to the SSI so Telltale deflections toward or away from the imager would be ambiguous in SSI images. Second, the expected vibration levels on top of the MET mast during launch and landing were unfavorable for such a sensitive instrument. The orientation problem resulted in the addition of a mirror made from polished titanium mounted below the active unit to enable observation of the tilt direction of the Telltale clearly within the same image. An orientation marker was added to provide a coordinate system in the mirror frame. The marker is apparent in the mirror in Figure 1.

[11] The relatively harsh vibration environment expected during launch and landing added significant constrains to the design. It soon became clear that the final design would be a compromise between sensitivity and robustness. The Telltale failed during vibration testing just before scheduled delivery in May 2006. The lessons learned from this test led to overall redesign of the instrument. The titanium structure was significantly strengthened and softer glue was applied to the tube to avoid critical bending of the fibers. This new design passed vibration tests made at iABG Gmbh, Germany in late 2006, two units were subsequently calibrated and the unit selected for flight is shown in Figure 1.

3. Calibration Data and Extrapolation to Martian Conditions

[12] As seen from Figure 1, the braided Kevlar fibers do not lie evenly. This is partly due to intrinsic tension (bending) of the braided fibers and as there is only a minute amount of force pulling the strings. Moderate vibrations (previbration testing) make the fibers come to rest in a slightly bent configuration as the one seen in Figure 1, and additional vibrations did not alter this configuration. The offset of the Kapton part was carefully calibrated together with the influence of lander tilt. The description of calibration given below emphasizes treatment of the wind influence.

[13] The Telltale can be described generally as a damped oscillator with two degrees of freedom. Wind information is obtained by comparing the forces of the gravity to the wind drag force. The calibration is performed under terrestrial gravity so an accurate description of the Telltale on Mars

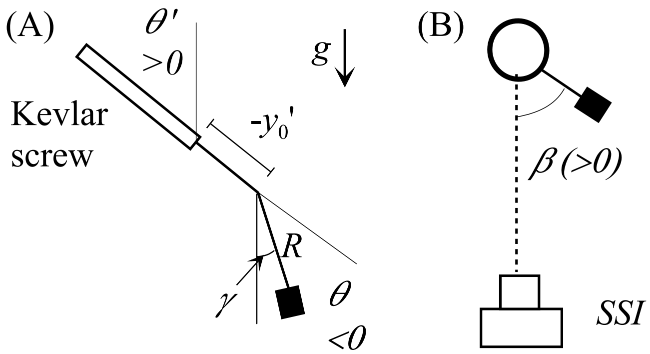

Figure 2. Illustration of the parameters used in description of the dynamics of the Telltale. (a) Side view. (b) Top view.

requires a theoretical study of the effects of the gravitational force. The description given below is restricted to one dimension in order to illustrate the necessary theory behind the use of the Telltale. The calibration results presented here are based on a preliminary calibration report (C. Holstein-Rathlau et al., Mars Simulation Laboratory, University of Aarhus, calibration report (version 1), technical document, May 2007).

3.1. Theoretical Considerations

[14] In two dimensions, the position of the Kapton part of the Telltale can be described using a single variable, as the angle of deflection θ as illustrated in Figure 2. The tilt of the Telltale θ' (>0 in Figure 2) is the lander tilt angle. It turns out that the position of the Kapton part (black box in Figure 2) can be described mathematically as bent around a point at a distance $|y_0'|$ in the prolongation of the Kevlar screw, and tilted at angle θ (<0 in Figure 2). The distance R (~20 mm) depends slightly on orientation. The direction of Telltale deflection is related to the line of sight of the SSI. An orientation angle β is set to 0° in line of sight of the SSI increasing counterclockwise (see Figure 2b). The potential energy of the Telltale can be written as

$$U = U_G + U_K + U_W,$$

where U_G is the contribution from gravity, U_K the contribution from the Kevlar fibers and U_W the contribution from the wind action. Taking the derivative with respect to tilt angle θ and solving for

$$\frac{dU}{d\theta} = 0$$

to minimize the Telltale energy we can determine θ. The potential energy term can be written as

$$U_{\mathrm{G}} = \rho^{(1)}(R)g(1 - \cos\theta),$$

where $\rho^{(1)}(R)$ is the so-called mass density integral, that would be mR for a simple pendulum of length R and mass m. The Kevlar term can be written as

$$U_K = A_K^{(1)}\theta^2 + A_K^{(3)}\theta^4,$$

where $A_K^{(i)}$ are parameters determined from the calibration data. The wind term has been described in a general manner as

$$U_W = C_1 C_D \rho \nu^2 f(\theta),$$

where C_D is the drag coefficient, depending on the Reynolds number $Re = C_2(\rho\nu/\mu)$, and C_1 and C_2 are fitting variables. It is sufficient to know the derivative of $f(\theta)$. Analysis of the wind tunnel data leads to

$$\frac{\mathrm{d}f(\theta)}{\mathrm{d}\theta} = -1 + ae^{-k\theta}$$

with a and k empirically determined variables. This form is sufficient to describe the deflection of the Telltale up to ~40°.

3.2. Calibration Data

[15] A series of measurements were performed to calibrate the Telltale, and to derive the parameters necessary to describe its movement. Most of these tasks were performed on Telltale elements dismounted from the gallows structure.

3.2.1. Tilt Measurements

[16] The Kevlar screw was tilted (θ', see Figure 2a) and imaged with a digital camera. From the image, the values of θ' and θ were determined and for a range of θ' values the stiffness of the Kevlar fibers (U_{K}) could be evaluated.

3.2.2. Oscillation Measurements

[17] The Telltale was placed in a vacuum chamber pumped to pressures lower than 10^{-2} mbar. The Kapton part was then set into oscillatory motion and filmed at 30 frames per second until the Telltale came to rest. These experiments were performed at different air pressures. Figure 3 shows a typical data set from these measurements. The natural oscillation frequency and intrinsic damping properties can be calculated from the data.

3.2.3. Wind Tunnel Measurements

[18] Wind tunnel measurements were performed at four different pressures, for more than 10 wind speeds and seven different orientations. At each setting, a 35 s video movie at 30 frames per second was taken to get time series of the oscillations. Figure 4 shows a portion of a typical time series.

[19] The zero wind speed curve represents how accurately the position and angle of the Kapton part of the Telltale can be determined with the imaging system. With highly compressed images (compressed to 2% of full size) and flat background the position of the Telltale can be determined with accuracy better than 0.3 pixels, corresponding to ~0.1 mm movement on Mars or a deflection angle of ~0.3°. At the highest wind speed presented in Figure 4, wind tunnel turbulence causes fluctuations. Deflection curves like those presented in Figure 5 were generated from the averages.

3.2.4. Tilt Images

[20] Tilt images were taken in the following way: The Telltale was mounted on a rig with one camera mounted in the same geometry as the SSI. The whole setup was tilted, giving ~150 orientations of the Telltale. Tilt angles and the absolute orientation of the Kapton part of the Telltale were recorded using cameras mounted behind and beside the rig. These data will be used to evaluate the mirror image of the

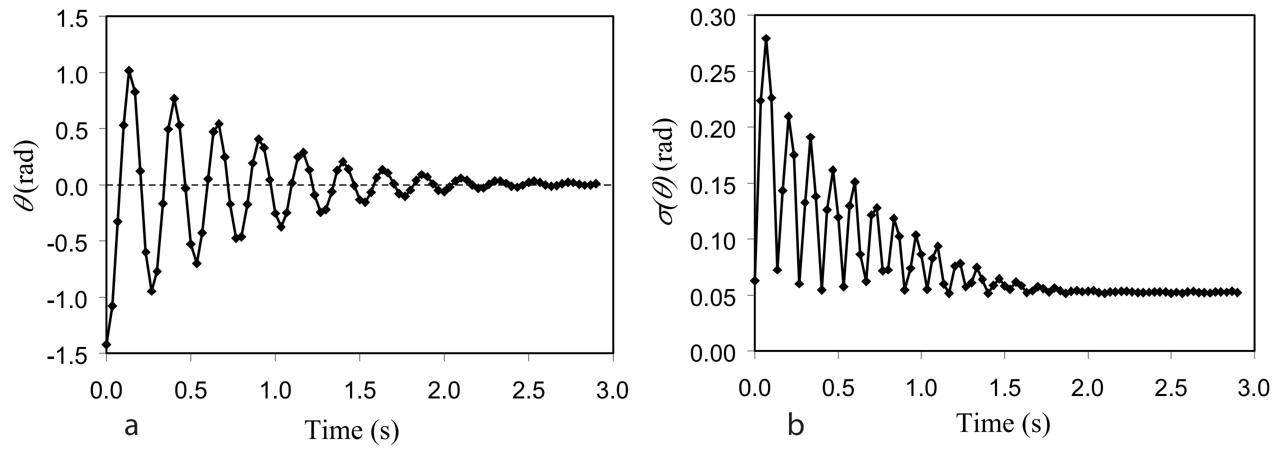

Figure 3. (left) Deflection angle θ as a function of time during an oscillation measurement of the Telltale. (right) Standard deviation of the position of the Kapton part of the Telltale (blur), in the same measurement. This quantity should be proportional to the angular velocity of the Kapton part of the Telltale.

Kapton part of the Telltale. Figure 1 is an example of tilt image with zero degrees of tilt.

4. Obtaining Wind Data on Mars

[21] The parameters of the model outlined above were optimized using the whole calibration data set. To extrapolate to Martian gravity it is straightforward to change the gravitational parameter in order to obtain the predicted deflections for Mars. The air density and viscosity of the atmosphere are needed and can be calculated from temperature and pressure data obtained on the lander at high frequencies and at good accuracy [see *Taylor et al.*, 2008]. In this way, deflection maps such as those presented in Figure 6 are generated. Further work with the model and fine tuning taking into account also the gallows structure are being undertaken. The frequency response of the Telltale is shown in Figure 7. At low frequencies, the Telltale will follow the flow (normalized response of unity). It has a resonance at 3 Hz on Mars, where variations in the wind speed are amplified by a factor ~6.5. If there was no turbulence in the airflow, or variations in wind speed during image exposure, the Telltale would respond with a single deflection representing the forces from the wind. All variations lead to blurring of the Kapton part of the Telltale in the images, and any wind variations with ~3 Hz characteristics will enhance the blur by a factor of ~6.5. Blur of the Kapton part in the images or deviation from the average position, will give the magnitude of the ~3 Hz turbulence (amplified by factor ~6.5), and the average position will give the average conditions during exposure. At higher frequencies, the sensitivity of the instrument is somewhat lower. Calculations of eddies generated in the airflow around the Kapton part have high frequencies (~100 Hz) and such eddies do affect the performance of the instrument.

5. Operation of the Telltale on Mars

[22] The data from the Telltale is in the form of images. Significant image compression is possible but the feasibility

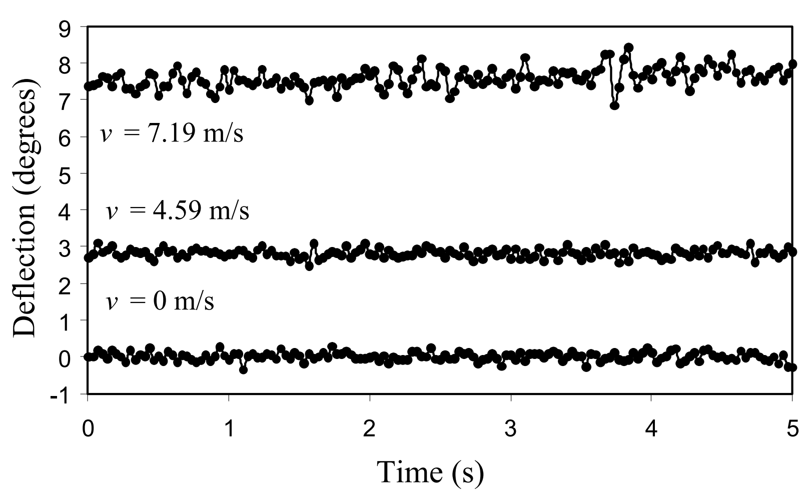

Figure 4. Typical time series from wind tunnel experiments obtained at the wind speeds indicated. These data were taken at orientation $\beta = 39.2°$ and $P = 14$ mbar air.

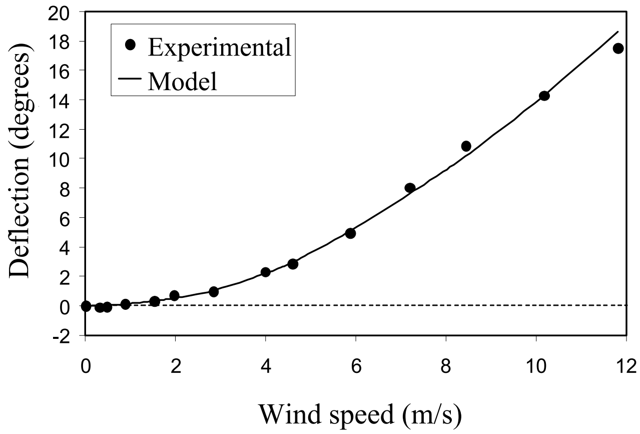

Figure 5. Representative deflection as a function of wind velocity. Data were obtained at orientation $\beta = 39.2°$ and P = 14 mbar air. The solid line shows model prediction as described in the text.

of a heavy compression without undesirable deterioration of the images depends on the contrast of the images. The compression will be optimized after landing and characterization on Mars. Exposure times should be longer than the time constant of the Telltale (>0.3 s) to avoid the risk of images reflecting only a part of an oscillatory motion. Good contrast is expected with the 440 nm diopter filter of the SSI and with exposure times of the order of seconds. The presence of atmospheric turbulence on Mars benefits the experiment, as it will reduce the effect of hysteresis in the Kevlar fibers to negligible levels, because the system will be able to find the energy minimum.

[23] The maximum possible data frequency will depend on the SSI read-out time, which is of the order of 45 s. Additional subframing during high-frequency exposures of the Telltale may reduce this time slightly.

[24] The measurements performed with the Telltale will be influenced by the boundary layer turbulence and convective turbulence due to solar heating of the surface. From atmospheric scaling laws [*Larsen et al.*, 2002], a basic turbulence intensity of 22% (one sigma) is expected at a height of z = 2 m of the Telltale above the surface, somewhat higher at daytime and somewhat lower at night. The power spectrum of the basic turbulence is flat below frequencies of $0.06U/z$ and decreases exponentially above. Therefore, an instantaneous measurement (~1 s exposure time) under the steady state conditions of 5 m/s can give values in the range of 3–7 m/s and multiple images are needed to obtain reliable average wind speeds. Exposure times less than 0.3 s may give images of the Telltale in a middle of an oscillation due to turbulence and thus will not reliable.

[25] Midday measurements will be dominated by convective turbulence. These fluctuations have time constants of the order of minutes. Images taken to document wind conditions during sample delivery have to be taken within this range before and after the sample delivery to be of use for interpretation of potential sample loss. Extensive systematic measurements are needed in order to get statistics of such fluctuations and reliable information on the diurnal cycle.

6. Conclusions

[26] Wind measurements on the Phoenix Mars lander, even though performed with a passive wind sensor, will significantly support the scientific output of the mission, by determining the best time of day to do sample delivery and/or documenting the wind conditions during sample delivery. It will be possible to obtain reliable wind information at a location in the north polar region of Mars, where the wind patterns may be substantially different from those at midlatitudes.

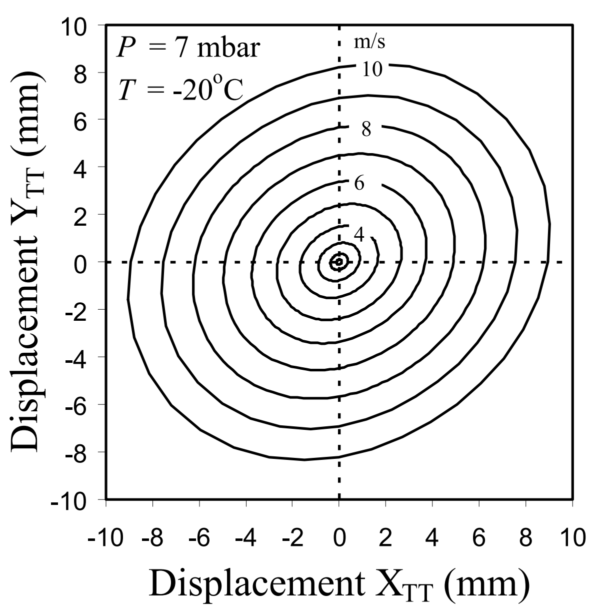

Figure 6. Displacement diagram for the Kapton part of the Telltale on Mars, under the conditions indicated. The negative Y_{TT} axis represents $\beta = 0°$ orientation.

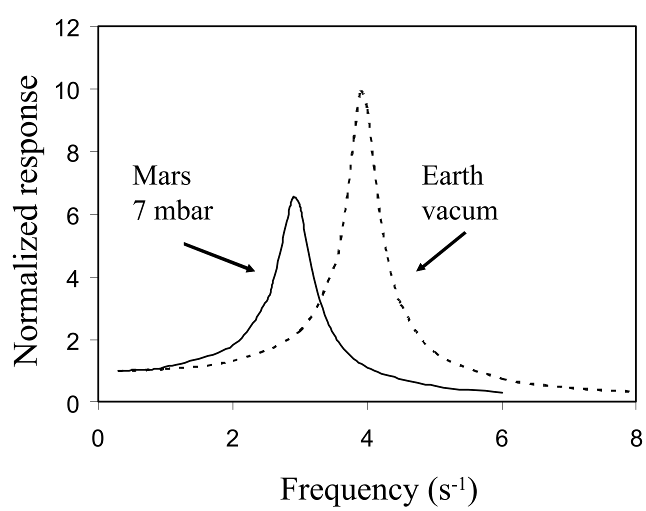

Figure 7. Calculated frequency response of the Telltale deflection under vacuum conditions on Earth and in 7 mbar pressure on Mars.

[27] Wind measurements will be possible with a rate of up to 1 per minute using the onboard camera. Reliable wind information will be obtained in the 2–10 m/s wind speed range.

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