The Titan Wind Tunnel: A new tool for investigating extraterrestrial aeolian environments

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A B S T R A C T

Aeolian processes occur throughout the Solar System and likely on extrasolar planets as well. Models based on data collected in boundary layer wind tunnels have contributed to understanding the physics of these processes. Planetary wind tunnels allow simulation of conditions (atmospheric pressure, density, or kinematic viscosity) on extraterrestrial bodies, and their use over several decades has demonstrated important differences between terrestrial and extraterrestrial aeolian processes. A high-pressure wind tunnel is now available in the Planetary Aeolian Laboratory (PAL) at the NASA Ames Research Center. Used up to the early 1990’s for Venus analog experiments, this wind tunnel has been refurbished and is now in use as the Titan Wind Tunnel (TWT) for Titan analog experiments. Initial results for threshold friction wind speeds at Titan analog conditions do not agree with models based on experimental data at terrestrial, Martian, and Venusian analog conditions (Burr et al., 2015). These results from the TWT work continue a history of wind tunnel experiments that show repeated under-prediction of threshold by models based on non-analog conditions. In addition to suggesting caution in extrapolating from one surface environment to another, this historical record highlights the utility of experiments in wind tunnels that provide closely analogous conditions to the environment of interest. The TWT, along with other PAL facilities, provides the means for further analog experiments by the scientific community to support continued advancement in understanding planetary aeolian processes.

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1. Introduction

Aeolian processes are common throughout the Solar System. Spacecraft exploration has revealed evidence for sediment transport and deposition by flowing gas on multiple planetary bodies beyond Earth (Fig. 1). Early missions to Mars returned images of dark aeolian deposits scattered across the planet (Breed et al., 1979; El-Baz et al., 1979). The most extensive deposits were identified as ergs (sand seas) that encircle the north polar cap (Tsoar et al., 1979; Thomas and Weitz, 1989). Subsequent higher resolution data from the Viking Orbiters, Mars Orbiter Camera, and the High Resolution Imaging Science Experiment revealed previously obscure dunes with length scales of kilometers that are globally distributed in fields (Hayward et al., 2007; Tirsch et al., 2011; Chojnacki et al., 2014). Also widely distributed are transverse aeolian ridges (TARs), which, with sizes and morphometric properties intermediate between terrestrial dunes and ripples, remain enigmatic in origin (Wilson and Zimbelman, 2004; Balme et al., 2008). Yardangs (wind-eroded landforms) are also common on Mars, with vast regional expanses in the Medusae Fossae Formation (units Htu and Ahtu; (Tanaka et al., 2014) and locally within some crater interiors (Malin et al., 1998; Bradley et al., 2002; Mandt et al., 2008, 2009; Zimbelman and Griffin, 2010). At the smallest length scales, ripples and ventifacts (rocks abraded by
windborne sand) are observed both by orbiting and surface spacecraft (Greeley et al., 1999; Sullivan et al., 2008; Silvestro et al., 2010, 2011, 2013; Bridges et al., 2013). High-resolution images obtained repeatedly over the same locations have revealed that many Martian dark dunes and ripples are forming, moving, and disappearing under the current atmospheric regime (Bourke et al., 2008; Silvestro et al., 2010; Chojnacki et al., 2011; Bridges et al., 2012a,b, 2013). Numerous aeolian wind streaks and a few fields of aeolian bedforms have also been inferred for Venus, based on low resolution imaging radar data from the Magellan spacecraft (Greeley et al., 1992; Weitz et al., 1994). In two static television camera panoramas by the Soviet Venera 9 and 10 landers, approximately sand-sized particles, theoretically transportable by the current atmosphere, were observed at the surface, along with measured wind speeds up to 1 m/s (Florensky et al., 1977). Although no evidence for aeolian sand movement was reported in those earlier images, an aeolian origin was suggested for the sediments in the rock formations imaged by Venera 13 and 14 (Florensky et al., 1983). In the Saturnian system, Titan, like Venus, has a thick atmosphere relative to Earth’s and hosts extensive fields of low-latitude longitudinal dunes (Lorenz et al., 2006; Radebaugh et al., 2008), as seen in the synthetic aperture radar (SAR) data from the Cassini spacecraft. These Cassini SAR data, like the radar data from the Magellan mission, are not adequate in quality and time-duration to directly evaluate current dune mobility; inferences of dune reorientation based on regional planview analyses suggest activity on long-term climate cycles (Ewing et al., 2015). Linear SAR-bright features on Titan have been hypothesized to be yardangs (Radebaugh et al., 2015). Dark markings seen in Voyager 2 data of the surface of Triton, the largest satellite of Neptune and
potentially a captured Kuiper Belt Object (Smith et al., 1989), have been interpreted as aeolian deposits from jets (Hansen, 1999). And recent images from the Rosetta mission to the comet P67/Churyumov-Gerasimenko show a particulate surface with dune- and ripple-like forms and wind streaks, suggestive of aeolian-driven sediment mobilization by flowing gas (jets) (Thomas et al., 2015), a process that has been substantiated theoretically for some comets (Cheng et al., 2013). Pluto, also a Kuiper Belt object, exhibits regions of lower and higher albedo (Buie et al., 2010a,b), which might be a result of spatial variability in sediment deposition by its atmosphere/exosphere at times of semi-annual perihelion. Finally, aeolian processes may occur on some extra-solar planets and other bodies, for which increasing data might be expected in the coming decades.

These several planetary bodies have a range of conditions that control the production, entrainment, transport, and deposition of aeolian material. The very different gravitational, atmospheric, and sedimentary conditions (Table 1) on these bodies point to the diverse yet pervasive nature of aeolian processes. The sediment properties on each body are distinct and, in some case, uncertain; sediment particle sizes, densities, and shapes remain to be determined for the more distant and exotic bodies. However, some constraints can be put on these properties through remote sensing and laboratory experiments. For example, the density of atmospheric tholins, which have a similar composition to aeolian sediments on the surface of Titan (Barnes et al., 2008), has been estimated based on tholins created in a laboratory setting (Khare et al., 1984; Trainer et al., 2006) and an optimum aeolian particle size has been inferred from threshold friction wind speed experiments (Burr et al., 2015). And spacecraft exploration of Comet P67 is providing constraints on those sediments (Fulle et al., 2015).

Compared to inferred sediment properties, the boundary conditions of gravitational acceleration and atmospheric density vary more widely. Thus, examining the effect of this wider variation on aeolian sediment movement provides an idea of the diverse conditions for aeolian sediment transport on these bodies. The dependence of aeolian sediment movement on these boundary conditions can be seen through the expression for the threshold friction wind speed (Bagnold, 1941; Iversen and White, 1982; Greeley and Iversen, 1985):

\[
u'_t = A(\frac{\rho_e}{\rho} g D_p)^{1/2} \approx A(\frac{\rho_e}{\rho} g D_p)^{1/2},
\]

where \(\nu'_t\) denotes friction wind speed, the subscript ‘\(t\)’ indicates threshold, \(\rho\) and \(\rho_e\) are the atmospheric and particle densities respectively, and \(g\) is gravity. \(A\) is a dimensionless empirical coefficient dependent on the interparticle forces (\(I_p\)) and particle friction Reynolds number (\(\text{Re}_p^*\)), given as:

\[
\text{Re}_p^* = \frac{u'_t D_p}{v} = \frac{u'_t D_p \rho}{\mu},
\]

where \(v\) is kinematic viscosity, the ratio of molecular viscosity (\(\mu\)) to gas density (\(\rho\)). The effect of the boundary conditions on threshold can be seen by plotting the threshold friction wind speed for constant sediment properties as a function of these two boundary conditions (Fig. 2A). These two conditions may be combined into a single parameter, based on Eq. (1), thereby ignoring any interparticle forces or Reynolds number effects. These idealized results show that threshold should increase exponentially from Venus, to Titan, to Earth, to Mars conditions, due to the combined effects of atmospheric density and gravity.

The Bagnold parameter, \(A\), was parameterized in terrestrial and Martian wind tunnel experiments, resulting in complex (transcendental) expressions (Greeley and Iversen, 1985). As a deliberate simplification of this complex parameterization, a second threshold model was developed that ignores any Reynolds number effect (Shao and Lu, 2000):

\[
u'_t = A_0 \left( \frac{\rho_e D_p}{\rho} \right)^{1/2} \left( \frac{\nu}{\rho D_p} \right)^{1/2},
\]

where \(A_0\) is a constant value, derived from the observation (Shao and Lu, 2000) that \(A(\text{Re}_p^*)\) lies between 0.011 and 0.013 (Iversen and White, 1982). The values from these two models (Bagnold (1941), Shao and Lu (2000)) may be compared to the values derived from friction threshold experiments in planetary wind tunnels (Fig. 2A). The difference between the model values and wind tunnel results illustrates the utility of wind tunnel experiments for investigating factors in planetary aeolian processes. The orders-of-magnitude range of threshold wind speeds (Fig. 2B) shows the strong effect of these boundary conditions on aeolian processes.

The preceding review of discoveries made from spacecraft data and wind tunnel experiments illustrates the multiple approaches required for understanding extraterrestrial aeolian processes (Greeley and Iversen, 1985; Bourke et al., 2010; Lorenz and Zimbelman, 2014). Physical simulations of aeolian processes are accomplished primarily in boundary layer wind tunnels, which enable accurate measurements under controlled experimental conditions to reveal or quantify controls on these processes. Experiments in terrestrial wind tunnels were first used by Bagnold (1941) to advance understanding of the physics of sand-sized grain entrainment and movement by the wind and the small- and

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Relevant surface and atmospheric parameters for planetary bodies, including Earth, with aeolian bedforms.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>Venus</td>
</tr>
<tr>
<td>Surface gravity, g (m/s²)</td>
<td>9.81</td>
</tr>
<tr>
<td>Surface pressure, P (bar)</td>
<td>1.0</td>
</tr>
<tr>
<td>Surface atm. density, (\rho_g) (kg/m³)</td>
<td>1.2</td>
</tr>
<tr>
<td>Representative surf. temperature (K)</td>
<td>295</td>
</tr>
<tr>
<td>Predominant sedimentary material</td>
<td>Silicate, felsic</td>
</tr>
<tr>
<td>Particle density, (\rho_p) (kg/m³)</td>
<td>2650</td>
</tr>
<tr>
<td>Atm. viscosity* (Pa·s)</td>
<td>~1.85 × 10⁻⁸</td>
</tr>
<tr>
<td>Atm./gaseous comp.</td>
<td>~79% N₂, ~96.5% CO₂, ~95% CO₂</td>
</tr>
</tbody>
</table>
large-scale effects of that movement. Likewise, physical simulation of extraterrestrial aeolian processes is accomplished in planetary wind tunnels but at conditions that simulate the relevant extraterrestrial environmental parameters (Greeley and Iversen, 1985; Lorenz and Zimbelman, 2014). Over decades of planetary wind tunnel experiments, such similitude parameters have included pressure, density, gas composition, and kinematic viscosity, depending on which are most relevant for the aeolian processes under investigation (Eqs. (1) and (2)).

The development of planetary boundary layer wind tunnels was prompted by the discoveries in the 1970’s of aeolian bedforms and sand-sized sediments on Mars and Venus, respectively (Greeley and Iversen, 1985). The recent discovery of dunes on Titan prompted refurbishment of the high-pressure wind tunnel for Titan analog experiments (Burr et al., 2015). Here we describe this unique high-pressure wind tunnel in its current configuration for Titan work, along with recent and planned improvements. To provide context, we begin with some background information about the use of wind tunnels for planetary investigations. We then address our main topic, which is this newest addition to the suite of planetary wind tunnels.

2. Boundary layer wind tunnels

2.1. Simulation of natural conditions in boundary layer wind tunnels

Wind tunnels are chambers in which natural atmospheric flow are simulated, characterized, and controlled, such that the effects of conditions on aeolian processes can be assessed. Although wind tunnel environments are clearly distinct from natural environments, the similitude of key characteristics allows for extrapolation from the former to the latter. Boundary layer wind tunnels simulate the surface-layer flow of the atmospheric boundary layer (ABL) for neutral stability conditions. The surface layer, comprised of the lowest tens of meters of the ABL, varies in height largely as a function of surface roughness, the speed of the geostrophic wind above the ABL, and the stability of the planetary atmosphere. Typical heights of the surface layer range up to ~50 m on Earth, ~10 km on Mars in the daytime (Petrosyan et al., 2011), and possibly 3 km on Titan (Lorenz et al., 2010). These heights have yet to be determined for other planetary atmospheres.

The ABL surface layer has certain fundamental characteristics that can be simulated in an atmospheric boundary-layer wind tunnel. The surface layer is two-dimensional in nature, i.e., wind speed varies with height above the surface, and so is not complicated with the Coriolis effects that result in the Ekman spiral layer above the ABL. The relevant part of the ABL for studying most atmosphere/ground interactions is the lowest part of the wind profile, the surface layer, where surface roughness drags on the flow of atmosphere. This drag increases turbulence there, causing a downwind velocity deficit, which, in the absence of thermal instabilities or flow obstacles, can be described by a logarithmic wind speed variation with height (e.g., Bagnold, 1941; Schlichting, 1968).

An important difference between wind tunnel conditions on Earth and natural conditions on other bodies is temperature. For example, the conditions at the surface of Venus include temperatures of ~735 K, whereas on Titan, the ambient temperature is ~94 K. Achieving these temperatures in wind tunnel experiments is not currently possible. In modeling physical processes, temperature (T) is most relevant to its inverse effect on gas density: \( \rho = p/RT \), where \( p \) is pressure and \( R \) is the gas constant. Therefore, adjusting the pressure within the wind tunnel on Earth can yield the correct similitude for planetary surfaces (e.g., Greeley et al., 1984; Burr et al., 2015). In doing so, the choice can be made whether density on its own, or the density/viscosity ratio, which has a different temperature dependence, is used as the similitude parameter. As discussed here, recent work in the Titan tunnel (Burr et al., 2015) has advocated the latter approach for threshold experiments. Another important difference is gravity, which is accounted for by numerically adjusting the wind tunnel data to planetary conditions using Eq. (1).
Following this ground-breaking work, wind tunnels have been used for investigations into the effects of wind on both terrestrial and extraterrestrial land surfaces. Although more commonly used to study processes on Earth, terrestrial or ambient wind tunnels and related facilities have also been used for investigations into the physics relevant to extraterrestrial aeolian processes. For example, the University of California at Davis (UC Davis) has two ambient wind tunnels that have been used to make discoveries regarding the magnitude of the Magnus effect during saltation (White and Schulz, 1977) and the physics of aeolian sand transport around dunes (White and Tsoar, 1998; White, 1996), relevant for transport around dunes on other bodies (e.g., Fig. 1B, C). At the Arizona State University, a vortex (dust devil) generator (ASUVG), consisting of a 0.5 m with variable speed motor above a moveable table with distributed pressure transducers, has provided information on the surface pressure profiles and threshold wind speeds for sediment transport by dust devils on Earth for comparison to similar data under Martian conditions (Greeley et al., 2003).

Wind tunnels and related facilities have also been used to simulate extraterrestrial environments (Table 2). Although not all aspects of extraterrestrial planetary surfaces can be simulated on Earth, the controlling conditions may be approximated, and the results of experiments under those approximated conditions, especially when combined with modeling or fitting of the data to models, provide insight into specific processes. The use of planetary boundary layer wind tunnels has led to major findings in understanding and quantifying sand movement on Mars (Greeley et al., 1980; Iversen and White, 1982), Venus (Greeley et al., 1984; Iversen et al., 1987) and Titan (Burr et al., 2015). Studies in wind tunnels and related facilities have also contributed to understanding dust movement (White et al., 1997; Greeley et al., 2003). Planetary wind tunnels are also used for atmospheric instrument calibration (Merrison et al., 2008; Wilson et al., 2008) and to investigate the effects of atmosphere on sea-surface wave growth (Lorenz et al., 2005). Wind tunnel experiments have been used to quantify abrasion rates (Bridges et al., 2004, 2005) and to determine the effects of various processes, e.g., rolling, on detachment thresholds (de Vet et al., 2014).

Spacecraft images showing aeolian-like features on Mars motivated construction of the first planetary boundary layer wind tunnel, designed to simulate the low-pressure conditions of the Martian surface (Greeley et al., 1980; Greeley and Iversen, 1985). This Mars Surface Wind Tunnel (MARSWT; Fig. 3) is an open-circuit atmospheric boundary-layer wind tunnel, measuring 1.3 by 1.3 by 13 m and having operating pressures ranging from 1 bar to 5.5 millibar. Located at the Planetary Aeolian Laboratory (PAL) at the NASA Ames Research Center in Mountain View, CA, it is housed in a silo previously used for testing of rocket electronics at low atmospheric pressures, with low gas densities achieved by evacuation of the silo. This silo has also enabled experimental investigation using the ASUVG of dust devils under Martian atmospheric conditions (Fig. 3), providing data on the effects of surface roughness and sediment flux of dust devils on Mars (Neakrase and Greeley, 2010b,a).

A more recent example of a Martian surface wind tunnel is the Aarhus Wind Tunnel Simulator (AWTS) located at Aarhus University in Aarhus, Denmark (Merrison et al., 2008). This ESA Mars facility enables simulation of atmospheric pressure, composition, temperature, wind, and sediment transport at the Martian surface. It is comprised of a closed (re-circulating) wind tunnel, 0.4 m in
diameter and 1.5 m long, housed within a larger chamber for environmental control. The simulator is instrumented to quantify aeolian processes and is in use for studying aeolian transport of granular material (Merrison et al., 2007) and for testing of flight instruments (Merrison et al., 2008). A larger facility (the Aarhus Wind Tunnel Simulator II) has more recently become available for testing meteorology sensors for Earth and other planetary bodies, although the facility is not designed to support investigation of aeolian processes (Holstein-Rathlou et al., 2013).

3. The Titan Wind Tunnel

3.1. History as the Venus Wind Tunnel

Surface images of Venus showing sand-sized sediments (Florensky et al., 1977) initially motivated the construction of the high-pressure Venus Wind Tunnel (VWT) (Greeley et al., 1984); later orbital images interpreted as showing wind streaks behind craters (Greeley et al., 1992) and dune fields (Weitz et al., 1994) substantiated that motivation. Co-located with the MARSWIT in the PAL, the VWT was constructed in the early 1980’s of schedule 40 steel pipe as a closed-circuit chamber 6×2.3 m in size. CO2 was used for most of the Venus-analog experiments, as well as with N2 and air. These gases were moved through the wind tunnel by a fan at one corner. The test section, measuring 20 cm in diameter and 122 cm long, housed the experimental particles. The test section interior was accessed through removal of the section from the rest of the enclosed circuit. Wheels on a track assembly enabled this movement of the section out of line with the rest of the wind tunnel structure and then back into line for conducting the experiments. The first instrumented operation of the VWT was in 1981. Consistent operation took place until 1988, when the tunnel was removed and rebuilt. It was returned to service in late 1990 and was last used in late 1994.

3.2. Current TWT configuration

The discovery in Cassini SAR data of pervasive low latitude dunes on Titan motivated the refurbishment of the VWT for Titan analog work (Burr et al., 2015). This refurbished facility is now designated the Titan Wind Tunnel. Although a brief description of the TWT was provided in our initial report of results from the facility (Burr et al., 2015), space limitation precluded a complete description. The remainder of this paper focuses on a description of the unique and newly available facility, along with information about its operation and availability.

As a refurbishment of the VWT, the TWT (Fig. 4) has the same physical dimensions. The wind tunnel is a closed-circuit, high-pressure chamber that was hydrostatically tested during refurbishment to 300 psia (‘pounds per square inch absolute’ or ~20 bar). In one corner of the tunnel, an upgraded 1490 W (2.0 hp) motor rotates an 8-bladed fan at rates up to 2500 rpm. In the two corners downwind of the fan motor, ten curved tubes, each 5 cm in diameter, reduce separation of the gas from the wind tunnel boundary and thereby minimizing turbulence induced by lateral flow. Downwind of these flow straighteners is a 47-cm-diameter settling chamber, containing Hexcel honeycomb followed by four 180-mesh screens, which further dampens turbulence and traps and prevents material from entering the test section. In the test section at pressures necessary to simulate Titan kinematic viscosity (12 bars; Burr et al., 2015), the fan drives air flow at freestream velocities ($u_f$) of up to ~6.5 m/s. A diffuser expansion section downstream of the test section improves the efficiency of flow through the tunnel and prevents material from recirculating with the air and impinging upon the fan. This removal of material from the gas flow also prevents plugging of the fixed pitot tube, which is located in the straight section downstream of the fan.

The test section is 122 cm long with an interior diameter of 20.3 cm and moves laterally on rails into or out of its position within the wind tunnel. Floor plates include (i) the calibration plate with a traversable pitot tube and (ii) the experimental test plate with no pitot tube. These plates have the same length as the test section and, with widths of 18 cm, rest against the inside walls of the tunnel when inserted into the test section (Fig. 5A). In this position, their horizontal upper surfaces are approximately two-thirds of the test section diameter below the top center of the tunnel. In cases where bedforms develop during the experiment, the test plate may be extracted from the test section without their disruption so that they may be analyzed (Fig. 5B).

The test section has two stations for observing the test bed. The upwind station consists of a single observation port located on the outside and 30 cm from the upwind end of the test section. The window is 7.6 cm in diameter and consists of a curved inner window of tempered glass and a flat outer window of safety glass. The downwind station consists of three viewing ports, located 30 cm upwind from the end of the test section, including two ports identical to the upwind port and a smaller (5-cm-diameter) port on the top, which enables additional illumination of the test bed.
The TWT operates with pressurized air supplied from a tank outside the building that is desiccated to dew point at –40°C. This line air is supplied at 150–165 psig (‘pounds per square inch gauge’ or ∼1.15 × 10^6 Pa) to the wind tunnel, where a booster pump may be used to augment the static pressure up to higher values; maximum pressure is 300 psig (2 × 10^6 Pa), at which pressure the safety relief values opens. Total pressurization time is ∼5 min. Temperature variations during pressurization are negligible due to the large fluid mass within the tunnel. Besides air from the facility tank outside the building, other gases can be supplied from cylinders, which serve as a backup pressurizing system and as a source of extremely dry gas if the facility air drying system becomes non-operational. Static pressure is monitored visually using a calibrated gauge (manufactured by Wika Instrument Corp., + or –1 psig) attached to the front of the tunnel pressurization control panel.

As part of its refurbishment, the TWT was fitted with a custom-made transducer manufactured by the Tavis Corporation. This high-pressure transducer is an important augmentation to the facility, as it records very low differential pressures at high static (ambient) pressures. The reliable operation at high static pressures is enabled by the all-metallic diaphragm, which is not in contact with the sensing elements. This non-contact operation (or variable reluctance sensing), in conjunction with the all-welded construction, allows for the low differential pressure capability of the instrument and the resultant high accuracy (∼2% error) of its data. The metallic, all-welded construction also provides long-term accuracy. Thus, the transducer operates robustly and provides high-accuracy data even under the high pressures in the TWT during Titan analog experiments, a technologically difficult capability that was not documented in available records for the VWT transducer. This transducer supplies data at high frequency (high-temporal resolution data) and is calibrated for high ambient pressure conditions up to 20 bar. For TWT usage, the transducer sits immediately outside the test section, and is
is the dynamic pressure of the gas (air). In the TWT work, the parameter of kinematic viscosity was used as the condition to simulate the detachment of grains on Titan (Burr et al., 2015). Past wind tunnel investigations into saltation have used a variety of similitude parameters, including atmospheric density and atmospheric pressure (Table 1). In the TWT work, the parameter of kinematic viscosity was used as the condition to simulate the detachment of grains into saltation. The results from that work show that threshold wind speeds on Titan are not accurately predicted by models based on data from the MARSWIT and VWT experiments. Inclusion of a density ratio term reconciles the TWT data with the models, although the physical basis for that term is uncertain.

On-going investigations in the TWT are focusing on refining these initial results. Specific topics to be addressed include, the wind speeds needed to maintain saltation, how these wind speeds compare to model wind speeds for saltation vs suspension, and how threshold wind speeds have varied under hypothesized past climate change on Titan. Other planned experiments will address the mechanisms by which the ratio of particle to gas densities can be used to reconcile experimental data from low density-ratio environments to threshold models (Iversen et al., 1987; Burr et al., 2015). Wind tunnel data, in conjunction with modeling (e.g., Kok and Renno, 2007), will also enable quantification of saltation paths and energetics, sand transport rates, and landscape modification.

3.4. Recent and planned improvements

Since the first published work accomplished with the TWT (Burr et al., 2015), we have continued to make improvements to the facility. These improvements include an additional transducer, which, like the previous model, will provide high-pressure, high-frequency data but will have greater precision at lower wind speeds. The previous model spanned a pressure range whose lower end coincided with the threshold wind speeds derived for the experimental sediments used in the previous work. Thus, a transducer with increased sensitivity at low wind speeds will improve the future results of upcoming threshold experiments. In addition, the TWT is being instrumented so that pressure and temperature data can be recorded during experiments, along with the transducer and fan motor voltages.

3.5. Access to the TWT and other PAL facilities

The TWT, along with all PAL facilities, is currently funded by NASA’s Planetary Science Division and is open to all investigators through various pathways. The first path, which is available to scientists from U.S. institutions, is to successfully propose to NASA’s Solar System Workings (SSW) program to conduct experiments using the PAL facilities. Under such circumstances, the PAL PI will provide a letter of commitment for inclusion in the SSW proposal acknowledging the proposal and stating the general availability of the PAL to support the proposed experiments. Specific dates for the experiments would be worked out after proposal selection. Access to the facility is then free of charge, except for the cost of consumables (e.g., sand) and any specialized equipment or photographic services. The second pathway, available to U.S.-based researchers who are not funded by SSW (e.g., to test instruments for future Titan missions), is use of the facility at a daily rate of $600/day, plus the cost of consumables and any specialized equipment or photographic services. Foreign investigators may also get access to the facility at the same daily rate by meeting NASA security, safety, and procedural regulations, and being granted permission from NASA. For these researchers, the PAL PI would provide a commitment letter both acknowledging the desired investigations and setting down the required fees for PAL usage to complete those investigations. The PI home institution would be invoiced by NASA Ames for these fees.

4. Importance of planetary boundary-layer wind tunnels

Findings from wind tunnel experiments can lead to increased understanding of the physics of aeolian processes. The importance of planetary wind tunnels is illustrated by considering the
evolution of our understanding of threshold wind speeds required to entrain surface grains on Mars, Venus, and Titan (Table 3). Initial predictions for Mars threshold speeds were derived by extrapolating wind tunnel results conducted at Earth conditions (Iversen et al., 1976). However, these predictions were not borne out when experiments were conducted in a Mars-pressure wind tunnel (Greeley et al., 1984; Iversen et al., 1987). Predictions for Titan were made using these previously developed models (Greeley and Iversen, 1985; Shao and Lu, 2000). However, these predictions for threshold of motion behavior on Titan were not confirmed by initial wind tunnel experiment results from the TWT (Burr et al., 2015). This sequence of development in our understanding of threshold of motion behavior in different planetary environments indicates some of the challenges posed by the complex gas/grain physics involved, and suggests that caution is warranted in extrapolating from one surface environment to another. This history also highlights the importance of conducting planetary environmental wind tunnel experiments.

5. Conclusions

Terrestrial and planetary boundary-layer wind tunnels have been used over many decades, resulting in substantial contributions to our understanding of the physics of aeolian sediment transport. The TWT is the latest addition to this family of wind tunnels available to the aeolian planetary community for such investigations, and provides unique capabilities for simulating aeolian processes in high-pressure, high-density atmospheres. Such atmospheres are found not only in our Solar System on Venus and Titan, but likely also on extrasolar planets. The TWT is available for investigators to use to advance our understanding of aeolian processes on these worlds.

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