NASA PLANETARY WIND TUNNEL FACILITIES

White Paper for 2023-2032 Planetary Science and Astrobiology Decadal Survey

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EXECUTIVE SUMMARY

- Aeolian processes are pervasive in our Solar System.
- The use of planetary wind tunnels has provided fundamental insights and quantification of these widespread aeolian processes, which both produce and reflect geologic evolution and critically influence robotic and human exploration.
- The NASA Ames Research Center Planetary Aeolian Laboratory is a unique wind tunnel facility capable of simulating aspects of extraterrestrial aeolian processes.
- The facility is also aging and presents barriers to reliable usability.
- The importance of planetary wind tunnel work impels investigation of avenues to revitalize the technique of laboratory aeolian investigation.

The white paper ends with recommendations to NASA to advance our community's capability in planetary wind tunnel experimentation

IMPORTANCE OF WIND TUNNELS IN PLANETARY RESEARCH

Aeolian geomorphology is pervasive throughout the Solar System, and likely on exoplanets planets with atmospheres. Once described only on larger planetary bodies with atmospheres (e.g., Greeley and Iversen, 1985), aeolian landforms are now interpreted in spacecraft images of smaller bodies with transient atmospheres or jets (e.g., Burr et al., 2015b). Understanding the processes that led to these landforms informs our understanding of planetary systems by elucidating patterns of aeolian erosion and deposition that may construct significant portions of the sedimentary and climatic record. These interpretations also help validate atmospheric models that are used for Mars surface operations and potentially for Titan missions.

Boundary layer wind tunnels simulate aeolian processes that produce aeolian landforms. Such wind tunnels have a well-established history of use in the terrestrial and planetary science communities (e.g., Bagnold, 1941; Greeley et al., 1974; Rasumussen et al., 1996; McKenna-Neuman and Sanderson, 2008; Rasmussen et al., 2015).

Boundary layer wind tunnels that simulate extraterrestrial near-surface flow were developed at the NASA Ames Research Center in Mountain View, CA (Greeley and Iversen, 1985; Rasmussen et al., 2015). The Planetary Aeolian Laboratory (PAL) hosts the Mars Surface Wind Tunnel (MARSWIT; Greeley, 1977) simulates aeolian flow at pressures down to those on the Martian surface. A relation for the minimum (threshold) wind strengths required to initiate particle motion, measured for Mars at the MARSWIT have also been applied to model aeolian-like transport produced by jetting on comets (Cheng et al., 2013).

Following evidence of aeolian processes on Venus, the Venus Wind Tunnel (VWT) was also established in the PAL (Greeley et al., 1984). This high-pressure wind tunnel was a closed structure with a fan that pushed pressurized air. VWT data were used to determine the threshold wind strengths for Venus and extrapolated to Titan atmospheric conditions (Greeley and Iversen, 1985). Evidence of aeolian dunes on Titan from the Cassini-Huygens mission led to its refurbishment into the Titan Wind Tunnel (TWT; Burr et al., 2015b). TWT data support previous predictions though aspects of the wind tunnel conditions are uncertain (Burr et al., 2015a, 2020).

This synopsis of wind tunnel usage raises two salient points (Burr et al., 2015b):

1. **The use of the NASA planetary wind tunnels has provided fundamental insights and quantification of aeolian processes across the Solar System.** Results have advanced understanding of entrainment, transport, and deposition from the dense atmosphere and high gravity of Venus to the gaseous jets and low gravity of comets, as well as bedforms, aeolian erosions, saltation trajectories, mass fluxes, and effect on missions.
2. **Accurate results require correct boundary conditions.** Threshold wind speeds derived from wind tunnels in which the boundary conditions did not match planetary conditions under study were shown in subsequent experiments not to accurately predict the threshold wind speeds of interest, and some certainties remain in the wind tunnel environment.

In summary, the NASA planetary wind tunnels have been critical – but also insufficient -- resources for understanding aeolian movement and bedforms across the Solar System.

NASA REVIEW OF PAL:

A review of SMD planetary facilities in 2015 included assessment of the PAL facilities (Mackwell, 2016). The findings of the review include the following significant **strengths**:

- The PAL facilities are uniquely capable of addressing questions in planetary aeolian science. The panel noted that large volumes at low pressure in the MARSWIT are a consequence of its relationship with the Ames Research Center steam plant, which can provide low pressure at no extra cost. The parameter range was noted as “a significant and unique capability for understanding the fundamentals of fluid-surface interactions.”
- PAL capabilities are directly relevant to past, present, and prospective missions.
- Efforts to solicit wider utilization (including a user guidebook) and archive prior work (Burr et al. 2020) were significant improvements over previous practices. Generation of a User Guidebook was a “tremendous” step of progress in supporting prospective users.

The findings of this review also include the following **weaknesses**:

- The community of users is very small and “a vicious cycle may emerge wherein R&A proposals from prospective users may be seen as risky if the proposers have no experience... and prospective users do not get the funding to acquire such experience.” Realistic avenues for training the next generation of experimentalists are not available.
- Transparency into Ames support of the facility is limited. Budgetary data indicated “significant attribution of Ames FTEs to the facility without detailed justification. The general lack of engagement of Ames management in facility operation, or of Ames scientific personnel in PAL experiments, was noted with some concern.”
- The facility cannot fully replicate planetary conditions—“only room temperature operations are possible, Venus pressures and temperatures cannot be attained, and of course gravity cannot be matched”.

Lastly, this review includes the following **comments to Facility Leadership and NASA**:

- The panel suggested that having a research scientist on campus or nearby with an active interest in wind tunnel work could be beneficial. Also suggested were a User Workshop and advertising post-doctoral positions to work in the wind tunnel to increase the user base, although potential funding sources for these ideas were not suggested.
- Improvements to the facility, so far handled by the PIs (past and current), might be better addressed through a small committee appointed to seek community input.
- A PAL website could be used to track utilization and impact via publications.
- Risks to the facility include overturn in staffing and the nature of the relationship with the steam plant (from which vacuum is derived). As stated in the PAL Proposers Guidebook, “[t]he vacuum necessary to simulate Mars is a by-product of other NASA/Ames Research center facilities and cannot be guaranteed. . .” (https://rpif.asu.edu/documents/PAL_Proposers_Guidebook_2015_v6.pdf). For the TWT, the tank that had previously enabled 20 bars of pressure has recently been limited to 15 bars, a factor that is not within direct control of the PAL management team.

PAL USER EXPERIENCES SINCE NASA SMD REVIEW:

From our experience, we note additional aspects regarding community use of the PAL facilities:

- Gas flow in the TWT appears to be unevenly distributed, potentially invalidating results. Pinpointing the cause for this issue, e.g., by tracing the air flow with smoke, would be challenging, given the small sizes of the test section and the observation ports.
- A second issue with gas flow is achieving sufficient speed to initiate sediment transport in the TWT. The fan and/or fan motor are not able to move all desired experimental materials at pressures that give kinematic viscosities corresponding to lower-density atmospheres under paleoclimate conditions on Titan (cf, Charney et al. 2014). While it would also be desirable to conduct ambient experiments in the TWT for cross-calibration with data from other wind tunnels, some experimental sediments cannot be moved in the TWT under low-pressure conditions that overlap with those of other wind tunnels.
- As noted above, the co-location of the MARSWIT with the Ames Research Center steam plant provides opportunistic low pressure at no cost to PAL, but the continued availability of this low pressure is uncertain and of uncertain time-duration. In addition, access to the wind tunnel during those low-pressure conditions is not possible, constraining the types of potential investigations.
- Knowledge of turbulence is limited in space and time, and instrumentation used to characterize gas flow in the wind tunnel is not consistent with contemporary best practices. Contemporary wind tunnels are commonly outfitted with non-invasive wind velocity measurements such as Laser Doppler Anemometry (LDA) (e.g. McKenna Neuman and Bédard, 2015) or Particle Image Velocimetry (PIV) (e.g. Zhang et al. 2008), whereas wind speed measurements in the PAL are taken using Pitot tubes at a single streamwise location and introduce multiple issues and uncertainties. For example, while the Reynolds number values derived from velocities at the pitot tubes may indicate turbulent flow at that location, the characteristics of 3-D flow structures are not detectable, challenging our ability to characterize the boundary layer and spatial flow variability, an important determinant for simulating flow around objects such as scaled landforms (e.g. craters, dunes, ventifacts, yardangs, and spacecraft components).
- Instrumentation to characterize sediment behavior – including fundamental parameters such as grain trajectories or sand fluxes – is currently limited.
 - Sand fluxes: Of principal importance in aeolian studies is the estimate of sediment transport rate (Q), or the mass of sediment transported across a line perpendicular to the wind direction ($\text{kg m}^{-1} \text{s}^{-1}$). Q is normally measured using one of a variety of sediment traps. The TWT does not have any sediment traps, due to size limitations and the resultant flow interference. The MARSWIT could be outfitted with passive sediment traps, but such devices would be impractical as they would require human access to the evacuated silo to empty and weigh the contents
 - Grain trajectories: Trajectories are another basic parameter of aeolian sediment transport, as they determine the kinetic energy of the grains. Terrestrial wind

tunnels use non-invasive instrumentation such as laser Particle Tracking Velocimetry or Particle Image Velocimetry (*Figure 6*; O'Brien and McKenna Neuman, 2017) to document grain behavior to unobtrusively measure a 2D profile of transport flux along with 2D components of grain velocity and 3D components of fluid velocity. With its larger size, the MARSWIT might support such instrumentation, although it is not currently available to PAL users. The size of the TWT would make such instrumentation a challenge.

- Data from the TWT suggest that the length of its test section may be inadequate for simulating natural two-phase (gas and sediment) flow conditions. Although test sections can be hydrodynamically lengthened by increasing gas density, an approach that might have been used for the Venus Wind Tunnel (Greeley et al., 1984), analysis of unpublished data from our TWT threshold experiments suggests that the boundary layer might *not* have been fully developed at the Pitot tube.

In summary, extant NASA planetary wind tunnel facilities, while offering unique and significant research opportunities, have technological, logistical, and administrative barriers to effective future community use.

POTENTIALITIES FOR PLANETARY WIND TUNNELS

The potential of planetary wind tunnels to further understanding of planetary aeolian processes can be achieved only through broad community availability and access. A small number of possible wind tunnel uses include:

- Construction of bedforms: Correct interpretation of bedforms is a critical enabler within geomorphological studies of extraterrestrial bodies, as these are a basic embodiment of aeolian processes. Although the underlying physics is thought to be consistent across planetary bodies, the exact morphologies and sizes likely develop differently on extraterrestrial bodies (e.g., formation of microdunes on Venus, inferred from work in the VWT; Greeley, Marshall and Leach 1984). Experimental studies of interplanetary polymorphism of aeolian bedforms support more accurate interpretation of mission data.
- Surface erosion rates and processes from abrasion: Work in the MARSWIT investigated ventifact formation under Mars analog conditions (Bridges et al. 2004, Bridges et al. 2005). Yardangs on Mars (e.g., Mandt et al. 2008, Ward 1979, Zimbelman and Griffin 2010) and inferred on Titan (Paillou et al. 2016, Radebaugh et al. 2015) give important information on paleoclimate wind directions and speeds, the locations and availability of sediment, and atmospheric circulation patterns. Wind tunnel experiments into the formation conditions of these landforms would make that information accessible.
- Aeolian dust activity: Dust is a driver of planetary surface and atmospheric processes, as inferred for both Mars (e.g., Kahre et al. 2017) and Titan (Rodriguez et al. 2018). Yet the current parameterizations of dust lifting on both Mars and Titan require testing. The results have important implications for (paleo)climatic processes and conditions.
- Forward contamination by missions: Wind tunnel experiments could address critical questions, such as, how far would leaked terrestrial contaminants be carried by the wind? This information is of great importance to missions seeking life on Mars.

- Astrobiological considerations: Finding organic molecules in the martian geologic record is dependent on exposure to cosmic rays. While recently abraded surfaces are more likely to expose organics, accumulation of dust and sand deposits could help to preserve organics, protecting them from destruction from cosmic rays. Wind tunnel experiments into both abrasion (second bullet above) and deposition could address these issues.

RECOMMENDATIONS REGARDING NASA WIND TUNNEL FACILITIES:

The above information summarizes the importance of planetary wind tunnels, while also pointing out some challenges to PAL wind tunnel use by the planetary community. Here we summarize some of these challenges, and then give recommendations to address them:

- Limited instrumentation within the NASA PAL wind tunnels leads to uncertainty in understanding flow conditions in the wind tunnels, adding some uncertainty into the resultant data and findings. Outdated instrumentation both presents a challenge to wind tunnel users and limits the amount of information that can be gained during experiments. Both the TWT and the MARSWIT lack a detailed design/performance assessment. ***We recommend 1) that NASA consider providing funding and other support to accomplish the characterization of wind tunnel flow as a function of space and time, and 2) that NASA then consider additional funding to bring the instrumentation and capabilities of the NASA Planetary Aeolian Laboratory in line with modern, commonly used instrumentation and capabilities found at other wind tunnel facilities.***
- The PAL wind tunnels present significant technological challenges to their use. The feasibility of removing or mitigating these challenges is not known, due in part to lack of a detailed design/performance assessment (as recommended above). ***We recommend 1) that NASA conduct a comprehensive evaluation of both the technological aspects of the current facilities (including the flow characterization recommended above) and administrative issues, and 2) that NASA conduct a feasibility study, to include a cost-benefit analysis, on refurbishing the PAL wind tunnels in accordance with contemporary best practices or building one or more modern planetary wind tunnels.***
- As noted by the review panel, there is a lack of transparency into Ames support of the facility and a general lack of engagement of management in facility operation or experiments. In addition, community use of the PAL is limited by administrative issues (e.g., access to NASA Ames Research Center, training opportunities). ***We recommend that NASA engage the planetary aeolian community in an evaluation of the prospects for locating and operating a NASA wind tunnel facility at an institution with more transparency, managerial engagement, and/or proximity to aeolian researchers, including an assessment of whether the high- and low-pressure capabilities currently housed together in PAL should more effectively remain together or be housed in different facilities / locations.***

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