TOWARD POWER- AND DATA-EFFICIENT SURFACE SCIENCE ON SMALL LANDED MISSIONS: DETECTING AND CHARACTERIZING MARTIAN DUST DEVILS.

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Introduction: The Mars community is moving towards an exploration strategy that involves more regular launches of small spacecraft. Such a strategy could dramatically advance our understanding of surface-atmospheric conditions and phenomena (e.g., of dust devils and dust lofting) and a broader collection of surface observations would inform both past and present climate processes [1] as well as surface operations. However, this will present an engineering challenge as resources on small landers (e.g., power and data bandwidth) would be much more constrained compared to previous Discovery- and Flagship-class missions. One way to mitigate this issue is through adaptive sampling – autonomously change data collection in response to the science environment. Compared to continuous or pre-scheduled observations, the capability to respond to the environment allows missions more efficiently spend resources when it's most scientifically valuable [2-5]. Such schemes are especially important for investigations of rare, transient phenomenon, such as Martian wind vortices (including dust devils).

Toward this goal, we developed algorithms to identify vortices in real time pressure timeseries data. Deployment of such algorithms on a future mission would enable a lander to trigger high volume data collection at the first sign of a vortex and stay in a quiescent, monitoring state otherwise (saving resources). Using existing Mars rover observations, we seek to quantify the science return achieved and power/data savings with this approach compared to conventional observation schemes. Once complete, this information can be used to inform future small lander mission concepts.

Detection Methodology: We developed computationally light models (meant for onboard use) to detect dust devils in 1 Hz pressure sensor data from the M2020 Mars Environmental Dynamics Analyzer (MEDA [6]). Previous studies have analyzed the pressure sensor data (along with other sensors) to identify nearby dust devils, which appear as dips in pressure signal [7] with varying durations (Figure 1). Using these results as ground truth, we developed four algorithms to identify dust devils from real-time observations *as early in the encounter as possible,* with the timescale of the encounter represented as the start of the full-width-half-max (FWHM) window of the pressure dip. Observations triggered before the FWHM window are of high importance as wind, camera, and/or dust sensor observations during this window are required to accurately assess the dust flux.

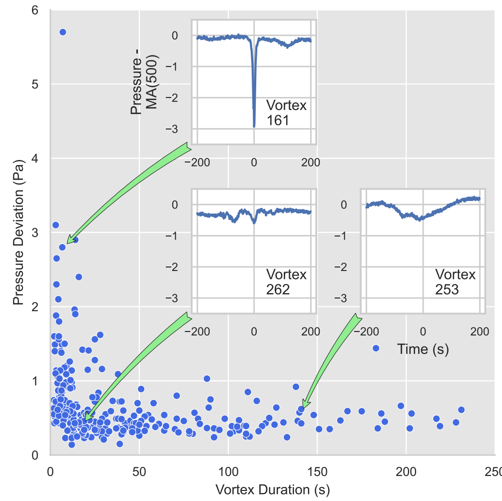

Figure 1. *Vortex events span a range of pressure deviations, durations, and shapes. Three examples of vortex-related pressure dips are shown in the insets.*

Statistics-based detectors. We developed two statistical-based detectors; the simple approach fits a normal distribution to the observed distribution of pressure deviations. Deviations large enough to exceed a tunable threshold (e.g., a large dip) trigger detections. The second statistical method adaptively tunes a threshold in a sliding window. It fits a line to historical data (previous 1000 seconds), uses this to detrend the data (subtracting the best fit line), and fits a normal distribution to the residual. As before, a tunable threshold is set on this distribution, which triggers when exceeded (Figure 2).

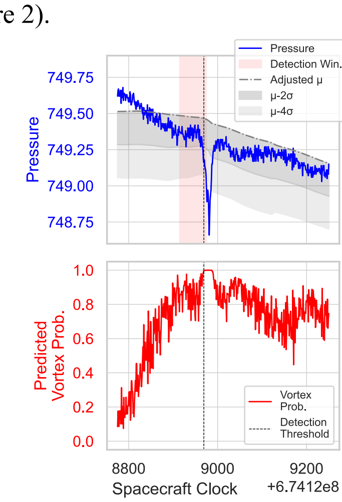

Figure 2. *Adaptive distribution fit of the pressure timeseries data to mean-subtracted pressure data (top) can be used to estimate the probability of an ongoing anomaly (e.g., a dust devil). Detection of a vortex event is triggered when a probabilistic threshold is exceeded (bottom).*

Machine learning-based detectors. We also tested two machine learning architectures: a long short-term memory (LSTM) model and a transformer model. For both, we used overlapping 60-second windows of pressure sensor data as input paired with ground truth labels indicating whether or not the final data point fell within the 4x FWHM window of a vortex. A standard 80/20 train/test split was used along with 5-fold cross-validation to identify the best model hyperparameters. The models generated a confidence value on the interval [0, 1], which was also used with a threshold to generate binary detections.

Detection Evaluation. We assessed the efficacy of the models in two ways. First, we evaluated their ability to identify whether each timepoint fell within the 4x FWHM window using detection-error tradeoff curves (Figure 3). This indicates how well each detector performed in identifying vortices in pressure data irrespective of exact timing. Second, we evaluated how early each model identified dust devils relative to the FWHM window – triggering before the FWHM window is desired to maximize science, but we also tracked near misses (triggering during the FWHM; Figure 4). Overall, the ML-based approaches tended to perform better, but future work is needed to assess the tradeoff between the power required to run each algorithm and detection performance (as the ML models will likely require more resources).

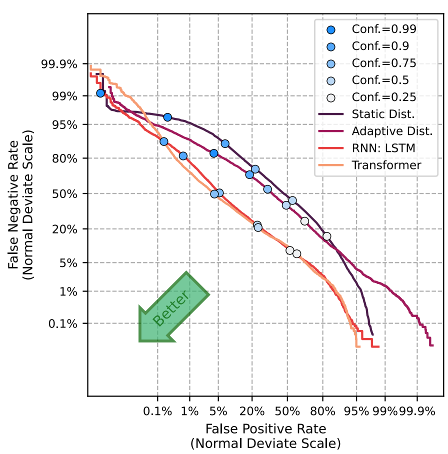

Figure 3. *Point prediction performance for all detectors. By tuning confidence over a range of thresholds, ground teams can tune the expected balance of false positive vs. false negatives.*

Assessing Science Value and Power: With the detector evaluation recently completed, our next steps are to assess the simulated science return for each algorithm. This analysis will use each detector's vortex triggers to quantify how the timing of each detection would impact the inferred dust flux and related uncertainties had each been deployed on M2020. The science value will be compared with power and data volume needs for each algorithm to assess tradeoffs. We anticipate having early results in the coming weeks (in time for LPSC) and then plan to submit the results to a *Planetary Science Journal* focus issue [8] to inform small lander mission concepts to Mars.

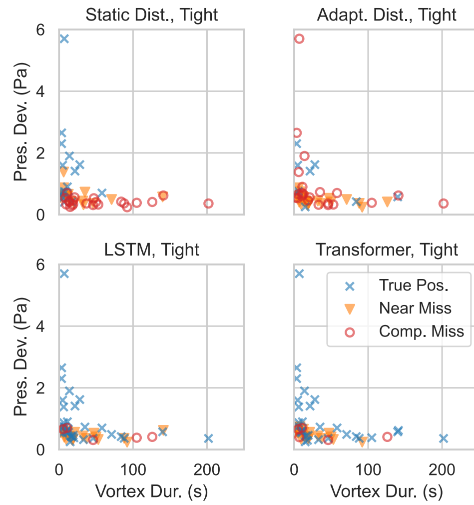

Figure 4. *Vortex event detections for all four detectors using a tight filter (high trigger threshold). Different models tend to capture different types of vortices.*

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