OBSERVATIONS OF WINDS AT GALE CRATER: PRELIMINARY COMPARISON OF RESULTS FROM MARS SCIENCE LABORATORY’S NAVCAM AND REMS INSTRUMENTS  

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Introduction: Since the Mars Science Laboratory (MSL) rover’s landing in Gale Crater in August 2012, the mission science team has used the rover’s instruments to monitor and study the atmosphere and environment at the landing site [1]. The Rover Environmental Monitoring Station (REMS) instrument was included on the rover for this purpose [2], but the rover’s Navigation Cameras (NavCam) have proven useful for observing atmospheric dynamics, particularly winds aloft [3].

Winds from REMS and NavCam: NavCam has been used to supplement REMS wind observations by taking sequences of images of the sky, in which the motions of clouds or suspended dust can be tracked, and used as a proxy for wind [4]. Whereas REMS measures surface winds at the position of the rover [5], these Atmospheric Monitoring Movies give the bulk motion of the air parcel above the rover’s position – essentially the wind at the cloud altitude. While the absence of an atmospheric lidar or similar instrument on the rover means that it isn’t possible to directly observe the altitude at which the observed clouds have formed, they can in principle be inferred to occur at the condensation level. This altitude ambiguity results in a consequent ambiguity in the horizontal wind speed, even if the the direction and speed in the image space are known very well.

Of the Atmospheric Monitoring Movies, the NavCam zenith movies, in particular, allow the most direct estimation of the wind direction at the cloud altitude. When visible cloud is present – even if so optically thin that image filtering is needed to make it apparent – the motion of the air mass can be observed by the translation of the clouds through the frame of the zenith-facing camera. Pointing the camera at zenith avoids variable-range distortions, and removes the need for complex geometric transformations of the observed wind vectors; if the wind is assumed to be horizontal in the atmosphere, the motions in the image plane can be assumed to correspond directly to motions in a horizontal plane at the cloud altitude.

The movies are typically eight frames in duration, with an image spacing of approximately 12 seconds (varying based on exposure requirements).

Observations: REMS measurements have been regularly made throughout the mission (where not precluded by mission constraints). Typically a five-minute monitoring of the REMS sensors (including wind measurements) is made every hour, with several extended observations of one hour or more each sol. The NavCam movies are obtained periodically when operational conditions permit – typically zenith movies have been obtained every 3–4 sols.

Each type of wind observation has its limitations. The REMS sensor has ambiguities in the observed wind direction because of incomplete azimuthal coverage. This is due to the malfunction of one of the wind sensor on one of the two sensor booms, meaning that for directions sensed primarily from that boom, direction uncertainties of +/- 90 degrees exist.

For NavCam movies, the reliance on feature-tracking requires that visible, wind-borne features must be present for the motion to be estimated. This means that cloud, or at least dust billows of sufficient heterogeneity in optical thickness, must be present. In most cases, elementary image pre-processing (generally mean-frame subtraction) is used to enhance optically thin features; where these features are sufficiently contrasting and robust across movie frames, an automated processing algorithm is employed to obtain the wind vector to high precision [6]. Unfortunately, such visible features are not always present, and they have been observed less frequently during the first 360 sols of the MSL mission than they were during the Phoenix mission [7].

A further limit of the zenith movies is their timing. Since they image the sky at zenith, they cannot be used to observe winds near solar noon, to protect NavCam from directly imaging the sun. This limits their use to periods from shortly before sunrise to late morning, and mid-afternoon to shortly after sunset. Timings are also often driven by accommodation of other rover activities.

REMS winds are here specified to the nearest 5 degrees; NavCam winds to the nearest sixteenth of the azimuth range (360°/16 = 22.5°), due to the limits of visual estimation of angles.

Results to date: The malfunction of the REMS wind sensor has led to a need to update the sensor calibration, an effort which is still in progress, so data is available only for a limited number of observations at present. Combined with the sparsity of cloud as im-
aged by NavCam in the early period of the MSL surface mission, this means that we report here only the results from four sols early in the mission. NavCam-derived winds are available from a larger number of sols, and increased frequency of visible cloud is expected as we enter a cooler season at Gale Crater [4], but comparison to REMS winds for these awaits the release of the updated calibration. The results available at the time of writing are shown in Table 1.

<table>
<thead>
<tr>
<th>Sol</th>
<th>NavCam wind direction</th>
<th>REMS wind direction</th>
<th>NavCam time</th>
<th>REMS time</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>315</td>
<td>130</td>
<td>15:41</td>
<td>16:00-16:05</td>
</tr>
<tr>
<td>49</td>
<td>315</td>
<td>145</td>
<td>15:59</td>
<td>16:00-16:05</td>
</tr>
<tr>
<td>56</td>
<td>270</td>
<td>100*</td>
<td>15:25</td>
<td>15:00-15:05, 16:00-16:05</td>
</tr>
<tr>
<td>100</td>
<td>90</td>
<td>95*</td>
<td>14:36</td>
<td>14:00-14:05, 15:00-15:05</td>
</tr>
</tbody>
</table>

Table 1 - Wind direction from NavCam and REMS
Wind directions indicate the angle in degrees, clockwise from true north, that the wind is observed to come from. Times are local mean solar time (LMST). *Indicates wind direction has an ambiguity of ±90°.

In each case, the REMS observation closest to the time the NavCam zenith movie was acquired is used; the average wind direction seen by REMS is given in the table. For sols 56 and 100, where the zenith movie was midway between two REMS measurements, both REMS observations were used, and for both sols the winds were consistent in the two sampled periods (to within 5°, subject to the ±90° ambiguity).

**Interpretation:** While the data set is as yet limited, it’s clear that in the available instances, the wind directions observed by REMS and NavCam are not similar. There are nonetheless some consistencies among the four sets of observations.

All of these instances are of mid-afternoon winds, with local times from 14:36 to 15:59 LMST. Surface winds are in all cases from the southeast, while winds aloft as seen by NavCam are from the northwest and west, except on sol 100.

Differences between surface and upper-level winds are to be expected, in general. Such significant differences in direction indicate that the winds at the two levels are on these occasions dominated by different influences. It is possible that winds very close to the surface are strongly influenced by topographic features. Indeed, the observed direction has the surface winds coming from the general direction of Gale Crater’s central mound, informally called Mount Sharp by the science team. This mound rises some 5 km above the crater floor, and would be expected to significantly affect local winds. A downslope wind from the mound which then moves across the crater floor is one potential origin for surface winds from the southeast seen by REMS.

Regardless of whether the clouds seen by NavCam are above or below the approximately 4.5 km height of the crater rim, the air flow at the cloud altitude may well be (and is observed in these cases to be) very different from the winds at the surface. This is particularly true if a downslope wind from the mountain is in fact occurring on these afternoons. Whether these clouds are drifting as part of an internal crater flow, or the overall regional circulation around and above Gale Crater, is unclear from this limited dataset. The coming availability of the complete REMS dataset and continued NavCam movie campaign, along with comparisons to numerical models of the flow in and around Gale Crater, may give greater context for these observations.

**Conclusion:** Both REMS and NavCam, through the Atmospheric Monitoring Movies, have successfully observed winds at Gale Crater. The two datasets are distinct, but complementary, with NavCam giving periodic observations of winds aloft and information about the motion at the condensation layer, and REMS giving instantaneous surface winds on a regular basis. The MSL science team plans to continue observing the atmosphere with both instruments as the surface mission continues.

As the improved calibration for REMS data becomes available, a much larger set of near-contemporaneous NavCam and REMS wind observations will be analyzed, potentially shedding more light into the wind patterns observed here, particularly the differences between the surface and wind aloft observations. Comparisons to atmospheric circulation modeling work currently in progress by members of the science team are also planned, to help validate possible descriptions of the winds in and above Gale Crater.