Mobile ground-based SMART radar observations and wind retrievals during the landfall of Hurricane Harvey (2017)

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INTRODUCTION

High-frequency weather radar observations are commonly used to characterize severe weather phenomena in both operational and research settings. Dual- and multiple-Doppler radar analyses have advanced the understanding of storm-scale structure and evolution of tornadic supercells (Wurman et al., 2007; Skinner et al., 2014; DiGangi et al., 2016; Betten et al., 2018) and midlatitude mesoscale convective systems (Biggerstaff and Houze, 1991, 1993; Lund et al., 2009;
Palucci et al., 2011; Geerts et al., 2017). Doppler velocities from two or more radar perspectives are used to estimate the three-dimensional flow in these scenarios to understand a storm’s evolution and structure (Potvin et al., 2012). Similar to supercells and mesoscale convective systems, ground-based mobile Doppler weather radar observations of land-falling tropical cyclones (TCs) have elucidated meso-β scale [O(10—100 km)] and meso-γ scale [O(1—10 km)] features of the TC boundary layer (e.g. Knupp et al., 2006; Hirth et al., 2012), surface rainfall characteristics (e.g. Parrish et al., 1982), surface wind extrema (Alford et al., 2019a), mesovortices (e.g. Wingo and Knupp, 2016; Fernandez-Caban et al., 2019) and boundary layer rolls (e.g. Kosiba et al., 2013). In addition, single-Doppler studies (e.g. Corbosiero et al., 2006) to retrieve rainfall characteristics and the evolution of the low-wavenumber evolution components of the flow have been performed using, for example, the operational United States Weather Surveillance Radar—1998 Doppler (WSR-88D) network (Crum and Alberty, 1993).

The often spatially contiguous precipitation in TCs can severely limit centimetre wavelength radar observations due to the attenuation of the radar signal (Doviak and Zrnić, 1993), particularly at X-band (e.g. Wurman and Kosiba, 2018) and higher frequencies. To document the evolution of landfalling TCs over mesoscale domains, mobile C-band (5-cm wavelength) Doppler radar may be optimal, considering the trade-off between retaining relatively high spatial resolution on a mobile platform while mitigating attenuation concerns.

Herein, data from a mobile, C-band dual-polarimetric Shared Mobile Atmospheric Research and Teaching (SMART) radar (Biggerstaff et al., 2005, 2017) are documented during the landfall of Hurricane Harvey near Rockport, Texas on the United States Gulf Coast. Positioned 42 km to the northeast of the S-band (10-cm wavelength) WSR-88D in Corpus Christi, Texas (KCRP), the SMART radar operated for nearly 18 hr, providing an opportunity for the first ground-based dual-Doppler observations over meso-beta scales of a major hurricane (1-min-averaged, 10-m altitude winds >49.6 m/s). Since the contributing radars operate at C and S-band, attenuation by precipitation did not limit the spatial extent of the wind retrievals. As a result, the kinematic structure of Hurricane Harvey at landfall was well observed. Using seven and one-half hours of these data, Alford et al. (2019a) documented the maximum observed near-surface winds during the time of Hurricane Harvey’s landfall. Their analysis suggests that Harvey was, at most, a Category 3 hurricane as the centre of circulation crossed the outer barrier islands off the Texas coast.

The documented dataset focuses on the retrieval of dual-Doppler winds and the process by which radial Doppler velocity observations from each radar were quality controlled. The dual-polarimetric data collected by each radar are also briefly summarized. This article is structured as follows: Section 1 describes the deployment of the SMART radar and the radar tasks prescribed to collect dual-polarization and radial velocity data. Section 2 summarizes the quality control steps taken to produce research-ready radial velocity observations to use in dual-Doppler synthesis. Section 3 describes processes taken to retrieve dual-Doppler-derived winds from the SMART radar and KCRP. Section 4 documents the location and format of the dataset. Section 5 concludes the work by commenting on the data significance and potential use.

### DATA COLLECTION

The mobile, Doppler, dual-polarimetric C-band SMART radar 2 (see Figure 1a) was positioned approximately 48-km inland of the Gulf of Mexico (28.1480° N, 97.4101° W) and collected approximately 18 hr of dual-Doppler data in conjunction with the WSR-88D in Corpus Christi, TX (KCRP). The area over which dual-Doppler analysis with KCRP is possible, often referred to as the dual-Doppler lobes, is shown in Figure 1b along with the individual radar positions.

![Figure 1](image1.png)
SMART radar 2 has an operating frequency of 5,540 MHz and employs the use of the Vaisala RVP8 signal processor (Vaisala, 2014). The radar typically operates in simultaneous transmission and receive (STaR) mode (Doviak et al., 2000) to collect dual-polarization data but has the option of transmitting horizontal only and receiving both channels if the linear depolarization ratio is needed. The SMART radars have a half-power beamwidth of approximately 1.5°, but data are generally oversampled in azimuth to a recorded resolution of 1°. The radial resolution of the data is described in Table 1.

Operations in Harvey began at approximately 2050 UTC 25 August 2017 and concluded at 1435 UTC 26 August 2017. Due to antenna drive failures, there were two periods during which the SMART radar was inoperable (2310—2349 UTC 25 August and 0140—0310 UTC 26 August). While the signal processor allows for staggered and dual pulse repetition frequency data collection to mitigate velocity aliasing, the SMART radar was operated using a single pulse repetition frequency (PRF) mode. Unlike in tornadic supercell thunderstorms where horizontal wind shear creates difficulties in dealiasing the data, the horizontal wind shear in most hurricanes is relatively modest and automatic dealiasing procedures are usually sufficient (e.g. Jorgensen et al., 2000; Joe and May, 2003; Altube et al., 2017). The SMART radars operating system provides a framework in which a variety of scanning strategies can be performed sequentially on a fixed schedule. The scheduler greatly aides coordinated data collection. During Harvey, the SMART radar performed a series of scheduled tasks on a 12-min repeat cycle to stay on task with KCRP, which collected volumes approximately every 6 min. Beginning at 2058 UTC 25 August, the 12-min cycle (detailed in Table 1) consisted of three 150° sector volume scans lasting 3 min each, four Range Height Indicator scans (RHIs) lasting a total of 1 min, and full 360° surveillance scans taking approximately 1 min to complete. The focus of this portion of the data collection period was on the eastern dual-Doppler lobe (Figure 1b).

At 0334 UTC 26 August, the 12-min cycle was altered. The three sector volume scans were replaced with two 360° volume scans lasting a total of approximately 10 min and low-level surveillance scans lasting a total of 1.5 min. The resultant change afforded observations of the western dual-Doppler lobe in addition to the eastern lobe (Figure 1b). Moreover, it was determined that the wind gusts were affecting the antenna stability when collecting RHI scans as the stronger winds within the inner core of the hurricane passed the radar site.

### 3 | DATA QUALITY CONTROL

Comprehensive, error-free, automated quality control of research radar data continues to elude the meteorological

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**Table 1** Details of SMART radar tasks during the landfall of Hurricane Harvey

| Task name   | Azimuthal coverage | Time in 12-min cycle | Hours performed | Elevation angles (°) | Gate spacing (m) | Moments |
|-------------|--------------------|----------------------|----------------|---------------------|----------------|---------|
| WINDS, WINDS1, WINDS2 | 50° to 180° | 1.3, 4, 6, 7, 9 | 2050 UTC to 0330 UTC | 0.8, 1.5, 2.3, 3.2, 4.0, 4.7, 5.5 | 75 | ZH, VR, ZDR, ΦDP, ρHV |
| RHI         | 135° (2058 UTC to 0000 UTC) | 10-11 | 0330 UTC to 1435 UTC | 0.8, 1.5, 2.3, 3.2, 4.0, 4.7, 5.5 | 75 | ZH, VR, ZDR, ΦDP, ρHV |
| WINDS, SURV | 360°           | 1.5-6-10 | 0000 UTC to 0330 UTC | 0.8, 1.5 | 150 | ZH, VR, ZDR, ΦDP, ρHV |
community. However, great strides in objective techniques to identify and correct attenuation errors (e.g. Gu et al., 2011), Doppler velocity aliasing (James and Houze, 2001), and Doppler velocity outliers (Altube et al., 2017) have significantly reduced the time needed to quality control a dataset. As such, all 18 hr of SMART radar data collected during Hurricane Harvey have been preliminarily quality controlled.

The Doppler velocity data were passed to an automated dealiasing algorithm after several pre-processing steps were taken. First, a threshold based on the dual-polarimetric correlation coefficient was applied to the Doppler velocity to remove regions of noise. Velocities associated with correlation coefficient values <0.01 were removed. While the 0.01 threshold value seems extremely low, the purpose of this step was to conservatively remove regions of non-meteorological echo before proceeding. Next, a local neighbourhood standard deviation of Doppler velocity at each gate was calculated using a rolling, centred, 20-gate sample. Standard deviations in both the radial and azimuthal directions were computed and the minimum of the two estimates was retained. The minimum was used to assure both radial and azimuthal standard deviations were representative of noise. If the radar reflectivity of a gate was below 5 dBZ and the local neighbourhood standard deviation exceeded 16 m/s, the gate of data was removed. Effectively, this removed most of the remaining noise in the Doppler velocity field in regions of low signal-to-noise (SNR) ratio. Solely using a threshold on correlation coefficient (e.g. < 0.9) often resulted in edges of echoes being removed. A despeckling function over a width of five gates removed any remaining isolated velocity-outlier gates in low SNR regions.

After pre-processing, the Python Atmospheric Radiation Measurement (ARM) Radar Toolkit (Py-ART; Helmus and Collis, 2016) software package was used to objectively dealias the Doppler velocity data for all sector and 360° volumes, excluding RHI and surveillance volumes. Within Py-ART, the four-dimensional Doppler dealiasing scheme (James and Houze, 2001) objectively processed all data collected between 2058 UTC 25 August and 0600 UTC 26 August. After 0600 UTC through the end of data collection, the ‘region-based’ scheme was chosen in Py-ART. For the former portion of the dataset, the shear of the horizontal wind was large, which resulted in the sweep-wide aliasing of the Doppler velocities into the incorrect Nyquist interval. The 4DD scheme affords the ability to use a previous radar volume to constrain the current volume being dealiased. As a result, the 4DD method resulted in significantly less dealiasing errors than the region-based scheme during the 2058 to 0600 UTC time period. The dealiased Doppler velocity data between 2058 and 0600 UTC were further quality controlled subjectively using the National Center for Atmospheric Research Solo3 software package (Oye et al., 1995) to produce a final

![Figure 2](https://example.com/figure2.png)

**Figure 2** (a) Aliased Doppler velocity $V_R$ from SMART radar 2. The black lines indicate the 20° dual-Doppler lobe. (b) Dealiased Doppler velocity after processing described in Section 2. Note that there is a region near $x = 20, y = -100$ that is well outside of the dual-Doppler lobe that was ignored.
quality controlled version of the data (Figure 2) within the dual-Doppler domain. Subjective dealiasing was required to correct regions that were aliased into the incorrect Doppler velocity interval. These errors were particularly apparent in regions of strong shear in Harvey’s eyewall. In addition, gates in low signal-to-noise regions were sometimes not captured by the above-described standard deviation and despeckling functions and had to be removed manually using Solo3. Only radar volumes included in dual-Doppler analyses were quality controlled to produce the final version via Solo3. Since the focus of the research project was dual-Doppler wind retrievals, erroneous gates outside of the dual-Doppler lobes were not manually edited. In addition to Doppler velocity, dual-polarimetric moments were also recorded. Radar reflectivity $Z_H$, differential reflectivity $Z_{DR}$, differential phase $\phi_{DP}$ and correlation coefficient $\rho_{HV}$ are included in the dataset, but were not post-processed. Users should be aware that the SMART radar 2 has a high bias in differential radar reflectivity, which has been noted across multiple field deployments of the radar. No $Z_{DR}$ calibration scans were performed during the event. However, utilizing the volumes collected between 1400 and 1435 UTC, the 29° elevation scan was extracted from each volume. A mean $Z_{DR}$ value using all gates above the melting level (ranges $>5.5$ km from the radar) characterized by reflectivity values $>15$ dBZ was computed for each sweep. The mean of the sweep-mean $Z_{DR}$ value was taken to find an approximate high bias of 1.4 dB, consistent with historical biases for SMART radar 2. Users of the $Z_{DR}$ field should remove the bias from the data.

KCRP data in Level II format were retrieved from the National Centers for Environmental Information (NCEI, Available online at: https://www.ncdc.noaa.gov/data-access/radar-data) and were processed in a similar fashion. Using Py-ART, radial velocity data were excluded if the gate's reflectivity was $<0$ dBZ. The data were also passed through the same standard deviation filter as above, but almost no data were removed as a result of pre-processing performed on the Level II data. The data were passed into Py-ART’s region-based dealiasing scheme in order to correct the aliasing of Doppler velocities for the entire dataset. The data are also included for reference in the Zenodo archive. While the data during the 2058—0600 UTC period were processed in Solo3 as well, very few subjective edits were needed. Thus, we anticipate the data after 0600 UTC would also require minimal manual dealiasing.

4 | DUAL-DOPPLER ANALYSIS

Dual- and multiple-Doppler analysis has long been utilized by the meteorological community to retrieve the three-dimensional flow within storms. The errors associated with dual-Doppler analysis are well known (Chong et al., 1983; Dowell and Shapiro, 2003; Shapiro et al., 2010; Potvin et al., 2012), often related to the temporal and spatial offset of radar observations, the underlying assumptions of mass continuity, and the under-sampling of the boundary layer or storm top divergence.

The SMART radar and KCRP were operated in a quasi-time synchronous task cycle in order to reduce the spatial offset of observations. Discussion with the National Weather Service in Corpus Christi at the start of the radar deployment resulted in the task cycle described in Section 1 being chosen to sync the SMART radar data collection as close as possible to the KCRP data collection. For each dual-Doppler analysis, the central (mean) KCRP volume time was used to select the SMART radar volume whose central volume time was the nearest to KCRPs. The processed volumes were passed into a natural neighbour (Sibson, 1981) scheme described in Betten et al. (2018) to interpolate each radar volume to a common Cartesian grid of 1-km horizontal and vertical spacing. The origin of the grid is located at KCRP at 0 km above mean sea level. For the eastern dual-Doppler lobe, the minimum x, y and z locations of the grid were set to 0, −60 and 0.5 km, respectively. The eastern dual-Doppler grid spans 130, 130 and 10 grid points in the x, y and z directions.

Additional dual-Doppler analyses were performed over a larger domain between 0400 UTC and 0600 UTC to include both the eastern and western lobes again centred at KCRP. The dual-Doppler times were established as described for those in the eastern lobe, and all interpolation schemes were kept the same. However, the minimum x, y and z locations were changed to −70 km, −60 km and 0.5 km. The larger grid spans 200, 200 and 10 grid points in the x, y and z directions. These analyses are also included in the Zenodo archive.

The maximum temporal offset between radar volumes from KCRP and the SMART radar was limited to 2—3 min to mitigate concerns related to proper advection of the data. At times, the majority of the inner core of Harvey was contained within the eastern dual-Doppler lobe. Hence, the wind field exhibited strong curvature. As the current version of the wind retrieval programme only allows for advection of data using a single linear velocity (e.g. Shapiro et al., 2010), no advection correction was applied to the wind retrievals documented here. Given that our research focus was on meso-beta (10-100 km) features, the errors induced by the lack of advecting the data to a single point in time were deemed acceptable. Users who desire to examine convective scale processes may need to perform their own retrievals.

The Cartesian radar volumes were passed into a three-dimensional variational dual-Doppler wind retrieval algorithm documented in Potvin et al. (2012). The procedure works by minimizing a total cost function comprised of three separate constraints associated with the radial velocity observations, mass continuity and smoothness of the solution. The
The variational technique is advantageous over traditional techniques, particularly at lower and upper levels since the explicit integration (and associated boundary condition errors) of the mass continuity equation is not employed. The cost function was minimized as described in Potvin et al. (2012) with one addition. The smoothness of the solution in the vertical was found to be an insufficient constraint. To compensate, a 2-step Leise filter (Leise, 1981) was applied every 50 iterations of the cost function, which resulted in an average estimated vertical velocity error near 1 m/s.

To demonstrate the result of the dual-Doppler analysis, Figure 3 displays an example at 0314 UTC. The maximum reflectivity between the two contributing radars and the horizontal wind vectors is shown in Figure 3a. Vertical vorticity derived from the horizontal wind components and the magnitude of the horizontal wind are shown in Figure 3b. For further discussion of this particular analysis, the reader is referred to Fernandez-Caban et al. (2018).

5 | ARCHIVE INFORMATION AND DATA FORMAT

5.1 | PPI and RHI data

All SMART radar and KCRP data are stored at Zenodo Archive https://doi.org/10.5281/zenodo.3371710 (Alford et al., 2019b). The data are separated by radar and further delineated into three subsets: wind retrieval volumes, range height indicators and surveillance sweeps. The SMART radar and KCRP wind retrieval volumes are further separated into final QC (2058 UTC—0600 UTC) and preliminary QC data (2058 UTC—1435 UTC). The former refers to data processed as described in Section 2 both objectively by Py-ART and subjectively by Solo3. The latter subset of data refers to the volumes only objectively processed by Py-ART, but not checked for final quality assurance in the dual-Doppler domain by manual inspection. Again, only volumes (from 2058—0600 UTC) flagged for dual-Doppler analysis were further processed in Solo3. Both the preliminary and final QC versions of the files are included in the archive.

KCRP did not collect surveillance or RHI data. SMART radar RHI data taken prior to 0330 UTC 26 August are designated by an azimuth along which the RHI was taken. No quality control was performed on the RHI data. Similarly, surveillance data are archived without quality control. Surveillance sweep data can be used to place RHI data in spatial storm structure context due to their close temporal proximity.

All radar data are presented in cfradial netCDF format (Dixon, 2010). This data format is accessible to common software packages used in radar processing (e.g. Py-ART or RadxConvert). In sub-directories (wind retrieval, RHI, and surveillance), a file is included detailing the header information present in the netCDF files. It should be noted that both raw (aliased) Doppler velocities and processed (dealiased) Doppler velocities are indeed included in all files. The
detailed field names for all raw and processed fields are included in the dataset archive.

5.2 | Dual-Doppler data

The dual-Doppler portion of the dataset is also contained in the Zenodo archive. Only dual-Doppler analyses using the final quality controlled radar data (2058—0600 UTC) are included. The dual-Doppler portion of the dataset is partitioned into sub-directories containing the smaller and larger dual-Doppler domains as described in Section 3. The files are archived in netCDF format (Rew et al., 2018). Each dual-Doppler analysis is denoted by the average times of the two contributing radar volumes. Within each file, a maximum reflectivity field is included which is simply the maximum of the 1-km interpolated reflectivity values at each grid point between the two contributing radar volumes. Kinematic fields include u (east-west), v (north-south) and w (vertical) wind components. In addition, a coverage variable is also included. The coverage value of 1 indicates that a grid point within the dual-Doppler lobe contains data. A value of 0 indicates that the point is either outside of the dual-Doppler lobe or contains no data. Similarly to the raw and dealiased radar data, a file detailing the netCDF file header information is included in the archive.

6 | SIGNIFICANCE AND USE OF DATA

The dataset presented herein affords the opportunity for extensive analysis of Hurricane Harvey’s wind field prior to, during and after landfall. Using the dual-polarization observations, single-Doppler perspectives and the dual-Doppler volumes, we anticipate widespread, diverse use of the data. For example, surface rainfall validation (Tokay et al., 2008), rainband process studies (Didlake and Houze, 2013a, 2013b) and data assimilation/numerical modelling (Gall et al., 2013) are active areas in which research is being pursued heavily through airborne instrumentation (Allen et al., 2010; Braun et al., 2013; Gall et al., 2013; Shen et al., 2016), but may strongly benefit from the surface-based observations documented here. Particularly during landfall of TCs, airborne platforms are often unavailable as the aircraft missions are frequently focused on open-ocean observations. Observations from the coastal WSR-88Ds in the United States can sometimes be used in a single-Doppler capacity. However, the addition of the SMART radar data and associated wind retrievals offers the opportunity to examine the three-dimensional airflow in Hurricane Harvey in great detail, perform validation of numerical simulations and to examine processes that affect coastal communities in high temporal and spatial resolution. The small-scale circulations in the surface winds, for example, can cause immense devastation in regional and local capacities (Klotzbach et al., 2018; Alford et al., 2019a). The ability to delineate wind damage that leads to water intrusions versus other water damage is paramount to the wind engineering and insurance communities (Baradaranshoraka et al., 2017). Therefore, we anticipate uses of this dataset and similar future datasets beyond the meteorological community to achieve a more comprehensive, interdisciplinary assessment of TCs at landfall.

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OPEN PRACTICES

This article has earned an Open Data badge for making publicly available the digitally-shareable data necessary to reproduce the reported results. The data is available at http://catal https://doi.org/10.5281/zenodo.3371710 Learn more about the Open Practices badges from the Center for Open Science: https://osf.io/tvyxz/wiki.

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