UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

Enhancing Weather Observations: Bridging The Gap Between Airborne Measurements and ASOS data

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

Degree of

MASTER OF SCIENCE

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Norman, Oklahoma

2025

Enhancing Weather Observations: Bridging The Gap Between Airborne Measurements and ASOS data

A THESIS APPROVED FOR THE

SCHOOL OF METEOROLOGY

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Abstract

Diagnosing the intensity of precipitation during winter is a challenge due to observational uncertainty and representativeness. Automated Surface Observing System (ASOS) stations are widely distributed across the United States, providing on-site current weather conditions to help with go/no-go decisions at airports and other purposes. Despite their many capabilities, previous research highlighted ASOS limitations with regards to precipitation type classification (e.g., ice pellets, drizzle, freezing drizzle and freezing rain) and snow accumulation rates. This study enhances these studies by investigating how well ASOS captures precipitation intensity and spatial variability during winter storms. ASOS reported intensities are compared against those derived from airborne ground-based reflectivity collected during the NASA Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) field campaign. Using radar reflectivity from the Ku and Ka-band High Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) on the NASA ER-2 aircraft, 50 samples from IMPACTS 2020, 2022, and 2023 collocated with ASOS stations were analyzed. Cases were identified when the NASA ER-2 passed within 6.5 km of an ASOS station. Mean reflectivies taken at 0.1 km above the surface were converted to mass fluxes using Z-R and Z-S relationships and compared to ASOS-reported rates for light and moderate intensity cases. For both rain and snow cases, ASOS light intensity reports often missed areas of enhanced reflectivity captured by the HIWRAP. Additionally, statistical analysis revealed an overlap in mean reflectivities between ASOS-reported light and moderate intensities, suggesting ASOS intensity reports may not fully represent precipitation surrounding the site. Further research can explore environmental conditions leading to these discrepancies and expanding cases by using other airborne field campaigns to examine ASOS performance.

1. Introduction

Forecasting winter precipitation remains a challenge as intensity and coverage can vary due to spatial and temporal processes (McMurdie et al. 2022). To better understand how the Automated Surface Observing System (ASOS) captures this variability, this research compares ASOS precipitation intensity reports against airborne data from the NASA Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) field campaign. The National Weather Service (NWS), Federal Aviation Administration (FAA), and Department of Defense (DOD) jointly developed the ASOS network (NOAA 2018). ASOS stations provide real-time weather data from their ground-based instruments, making them useful for detecting rain, snow and freezing rain and their intensities (Vickie 1998). With over 900 active stations located widely across the United States, operating 24 hours a day and 7 days a week, the ASOS data supports aviation operations, local forecasting offices and many meteorological research communities (NOAA 2022 and Vickie 1998). In aviation, ASOS observations are critical for decision making whether it is for go/no-go flight decisions, de-icing, and runway treatments. Making the accuracy of ASOS observations necessary for continuous safety.

Despite the wide distribution and operational usage of ASOS, all stations ultimately rely on point-based, ground level instruments (AOPA 1999). This stationary design limits ASOS ability to capture and generalize precipitation outside the immediate vicinity of its sensor, limiting its view on spatial variability during storms (NOAA 2022). Additionally, it has known limits in reporting precipitation types like drizzle, freezing drizzle and ice pellets (Elmore et al. 2015; Reeves 2016; Landolt et al. 2020). Several studies have further examined ASOS precipitation type classifications by comparing data from ASOS and other surface observation systems. For example, Shrestha et al. (2023) compared microwave radiometer precipitation type retrieved from a microwave radiometer at the New York Mesonet against precipitation types derived from the ASOS and the Meteorological Phenomena Identification Near the ground (mPING). They found that the microwave radiometers identified rain and snow consistent with ASOS and mPING reports, but there was lower accuracy for freezing rain and sleet reports. Limitations of ASOS and mPING were to blame for the drop in accuracy. Elmore et al. (2015) and Reeves (2016) comparison of mPING and ASOS precipitation types also reached a similar conclusion with regards to ASOS limitations. ASOS precipitation types were limited since it could not report ice pellets and often misclassified or missed freezing rain reports unless a human observer was present. Reeves (2016) further highlighted that even if stations were right next to each other, the high spatial variability of ice pellets and freezing rain complicates ASOS observations, resulting in difficulty in classifying these precipitation types. Thus, there is a need for improvement in the ASOS precipitation type algorithm.

Outside of highlighting ASOS precipitation type limitations, Tomkins et al. (2025) conducted an analysis on ASOS snow accumulation rate. This study was focused mostly on heavier snow events and accumulation totals. Through this, they found that only 1 in 4 cases actually resulted in high surface snowfall rates. They concluded that ASOS may face challenges in accurately representing snowfall rate when snowflakes are displaced by the wind.

Although many previous studies explored limitations of ASOS precipitation type identification, far fewer studies investigated ASOS ability to capture precipitation intensity, especially during more complex weather with high variability like winter storms. Tomkins et al. (2025) compared snowfall accumulation against ASOS data, but primarily focused on snowfall totals in heavier events, not addressing the ASOS performance during lighter or more variable precipitation conditions. Thus, there is a need to further evaluate ASOS to understand how representative the data is not only for the type of precipitation but also the intensity.

This research aims to address this gap by evaluating ASOS precipitation intensity reports during winter weather events and comparing them to available airborne reflectivity-based precipitation estimates. Specifically, this research uses reflectivity data from the IMPACTS field campaign. Reflectivity data from the High-Altitude Wind and Rain Airborne Profiler (HIWRAP) instrument on the NASA ER-2 aircraft acquired during this campaign, provides a detailed spatial view of the storm structure from above. By aligning HIWRAP reflectivity with ASOS surface reports in both snow and rain events, this study assesses the representativeness of ASOS intensity classifications and quantifies precipitation estimates from the ASOS.

2. Data

2.1 Data - IMPACTS

Airborne remote sensing retrievals, with typical resolutions of less than 1 s temporally or up to 200 m spatially (Liew 2001), can resolve variability at much smaller temporal and spatial scales than ASOS. In particular, data acquired during the IMPACTS field campaign, with three 6-week deployments in 2020, 2022, and 2023 (McMurdie et al. 2022) offer vertical profiles of remotely sensed cloud and precipitation properties. During this campaign, winter storms were sampled on the United States eastern seaboard and midwest. The NASA ER-2 and NASA P-3 with remote sensing and in-situ data respectively provide detailed information on the systems structure and precipitation type and amount.

In this study, data from the HIWRAP, a down-pointing dual Ku/Ka-band Doppler radar installed on the NASA ER-2 aircraft, are used. HIWRAP measures radar reflectivity, linear depolarization ratio (LDR), spectral width, and retrieves the three-dimensional wind field within clouds and precipitation, providing a vertical profile of the storm structure (Lihua et al. 2020). HIWRAP captures the spatial variability of storm structure at different altitudes, making its use well-suited to assess how well the ASOS ground observations correlate with measurements near the ground and in the area surrounding the ASOS station. Although the flights were not specifically designed to fly over ASOS stations, in several cases the ER-2 flew within 6.5 km of an ASOS station.

2.2 Data - ASOS Data

There are seven critical ASOS instruments that monitor weather conditions: the precipitation gauge, temperature/dew point sensor, precipitation identifier, anemometer/wind tower, ceilometer, freezing rain sensor, and visibility sensor. Data from the ASOS precipitation identifier, also called the Light Emitting Diode Weather Identifier (LEDWI), were used in this study (Figure 1). This sensor can differentiate between rain and snow, and under non-mixed phase conditions, can also estimate precipitation intensity. The LEDWI works using an infrared light beam that shines from a transmitter to a photodiode receiver. When a precipitation particle passes through the beam, it causes fluctuations or scintillations detected at the receiver that are converted into a spectrum of frequencies. These frequency bands are analyzed and help LEDWI differentiate between rain and snow with the result being reported at a 5-minute frequency. If there is both rain and snow present (i.e., mixed precipitation), this leads to a smear signature and is classified as “unknown precipitation / UP” (Vickle 1998).

In addition to rain and snow, the ASOS can also report freezing rain using the Freezing Rain Sensor. This sensor detects changes in the resonant vibration frequency of a probe as ice accumulates. As the ice builds up on the probe, the combined mass increases, and the vibrating frequency decreases, allowing the device to measure accumulations as small as 0.01 of an inch per hour. Once the accumulation is equal to or above 0.08 inches, the sensor goes through a heating cycle to melt and restore its baseline frequency (Vickle 1998). Due to limitations on detection, ASOS is only able to report rain, snow and freezing rain precipitation types.

When precipitation is not mixed (e.g., purely rain or snow), the intensity of the precipitation can be estimated based on the strength from the LEDWI frequency. For rain, intensity is defined as the mass flux or rain rate, which is directly dependent on the sizes and fall velocities of drops. Rain rate (R) can be categorized as Light, < 2.54 mm h^{-1}, Moderate, 2.54 - 7.62 mm h^{-1}, and Heavy, > 7.62 mm h^{-1} (Vickle 1998). Snowfall rate (S) also depends on density, which can vary a lot between wet and dry snow, making it harder for the LEDWI to directly estimate the liquid content. Thus, for snow, an algorithm uses visibility sensor data to adjust snow intensity reports. Snow rate can be categorized as follows: Light, Visibility > 0.8km, Moderate, 0.4 km < Visibility < 0.8 km and Heavy, Visibility < 0.4 km (Vickle 1998). Previous research from Rasmussen et al. (1999), demonstrated an inverse relationship between visibility and snowfall rate, suggesting that the following equation can estimate the snowfall rate in mm h^{-} ^{r}:

$$Rate\ (mm\ hr^{-1}) = \frac{1}{Visibility\ (km)}$$

This relationship is used operationally (e.g., Fahey 2008) and helps provide snowfall rate from visibility alone. Applying this equation to ASOS visibility thresholds gives us these approximate intensity categories: Light, < 1.25 mm hr^{-1}, Moderate, 1.25 - 2.5 mm hr^{-1} km and Heavy, > 2.5 mm hr^{-1}.

When it comes to reporting both precipitation type and intensity, ASOS uses an algorithm based on recent observations (Vickle 1998). Precipitation type is determined from the prior 10-minutes of data, requiring at least two matching samples. If there is a tie between types, ASOS applies a hierarchy: Snow > Freezing Rain > Rain. Once precipitation type is selected, precipitation intensity is then determined from the prior 5-minutes of data, now requiring at least 3 matching samples. If this threshold is not met, ASOS defaults to the lightest intensity detected. For example, if in the prior 5-minutes, there is 1 sample of light snow and 2 samples of moderate snow, the report will be Light Snow, because the moderate samples did not meet the 3-sample threshold.

Figure 1: *Light Emitting Diode Weather Identifier (LEDWI) that differentiates rain from snow (Photo Credit: Scott Landolt)*.

3. Methods

To investigate the relationship between the airborne reflectivity and ground-reported precipitation intensity, the HIWRAP Ka/Ku-band data were compared with the ASOS reports. Cases from the 2020, 2022 and 2023 IMPACTS ER-2 flight data were selected to use for the comparison. Figure 2a shows a portion of the ER-2 flight track from 25 January 2020 overlaid over ASOS locations across the northeast United States. A total of 34 case studies (flight tracks) were analyzed to identify time periods when the ER-2 was in the immediate vicinity of an ASOS station. Individual cases of collocation were chosen where the NASA ER-2 was within 6.5 km of an ASOS station for some portion of the flight. This threshold distance was determined based on a sensitivity test comparing 10 km, 8 km, 6.5 km, 4 km and 2 km collocation thresholds. Although the 10 km and 8 km thresholds maximize the number of collocated cases, the larger distance may not be as representative of conditions at the ASOS sites. The 4 km and 2 km thresholds were much closer to the ASOS sites but there were not as many individual cases to analyze. The 6.5 km threshold was chosen as it provided a reasonable number of collocated cases, but had close enough collocation so that there was a relatively consistent storm structure between the location of the plane and the ASOS station. Figure 2b shows the 8 collocated matches between the ER-2 and ASOS for the 25 January 2020 flight based on the 6.5 km threshold. Considering all 34 flights of the ER-2, a total of 123 match cases were identified. Using the time, latitude and longitude of these collocated cases, corresponding ASOS condition reports were retrieved from the University of Utah's MesoWest database (MesoWest 2002). A summary of the ASOS precipitation types reported for these 123 cases is shown in Table 1.

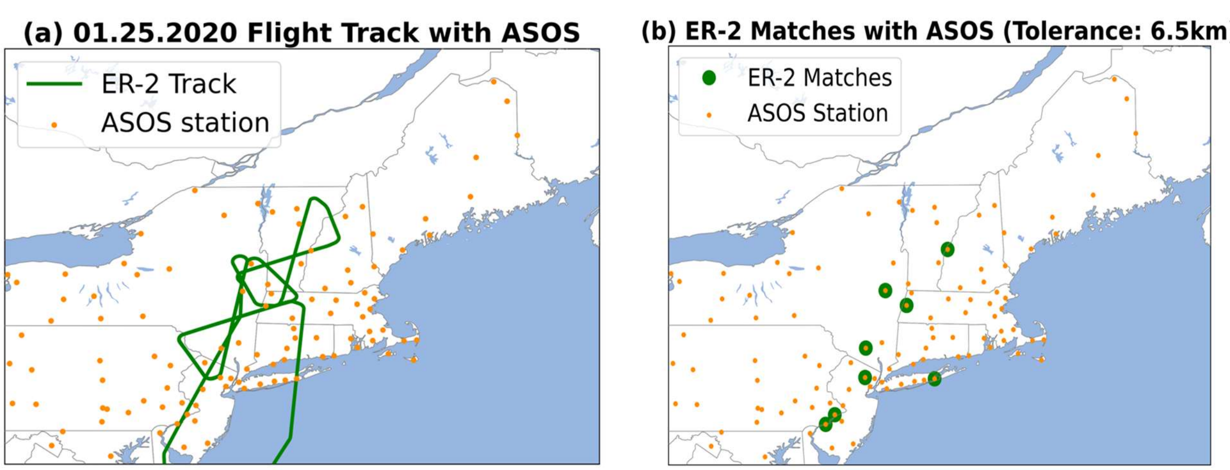


Figure 2: *(a) Reduced ER-2 track (green line) for 01.25.2020 overlaid with ASOS stations (orange dots). (b) Matches found for the same flight track with a tolerance of 6.5km; green dots represent ER-2 Matches/Cases.*

Table 1: *Summary of the precipitation types identified from the ASOS station reports for the 123 cases when the ER-2 flew within 6.5 km of an ASOS station for flights flown during the 2020, 2022, and 2023 IMPACTS campaign.*

Precipitation Type	**Total**
Rain	25
Snow	38
Freezing Rain	2
Fog / Unknown Precipitation	15
None	43
Total	**123**

Only cases that reported rain or snow were analyzed further. Reports classified as "None," "Freezing Rain," or "Fog/Unknown Precipitation" were excluded. These categories either had low frequencies to analyze or presented mixed conditions. Specifically, for the "Unknown Precipitation" reports, these cases are more difficult to compare against radar data and to use retrievals to determine spatial representativeness of data.

After removing cases with freezing rain and no or unknown precipitation, 63 cases remained. Table 2 summarizes the distribution of these cases by precipitation type and intensity reported by the ASOS station. Due to their low count, cases reported as "Heavy Rain", and "Heavy Snow" were removed from further statistical analysis but were used for individual case studies. For the remaining cases, the ASOS condition reports were compared to the ER-2 HIWRAP Ka/Ku-band reflectivity at the time the aircraft passed 6.5 km from the ASOS station. For each case, HIWRAP data over a one-minute window were examined, representing the aircraft's view near the ASOS station. This period was estimated by accounting for storm motion using horizontal wind speed and adjusting for the aircraft speed.

Reflectivity profiles were altered by removing ground clutter and shifting the vertical axis so that the 0 km level corresponded to the surface for each case. Ground clutter was identified by filtering out reflectivity values that abruptly changed by more than 2 dBZ, over the one-minute window or between 0-6 km range. This method was chosen to effectively capture areas with unrealistic fluctuations that come from ground clutter. For the remaining 60 cases, additional filtering was performed based on the reflectivity data quality. Cases with a large amount of missing reflectivity between the surface and aloft during the one-minute window were removed. Figure 3a shows an example of a case with continuous reflectivity throughout the vertical column, especially near and around the surface; this allows for a better comparison with ASOS reports. Figure 3b is the opposite, showing a case that was removed due to insufficient reflectivity near the surface (0 dBZ below 0.1 km height). These inhomogeneous cases were removed because there are not enough data to evaluate spatial representativeness or precipitation classification. After removing cases with the final quality screening, 50 cases were retained for further analysis. These remaining cases are the basis for the statistical analysis, with the aim to understand the relationship between ASOS reports and HIWRAP reflectivity signatures. A listing of the cases retained for analysis is presented in Table 3.

Table 2: *Distribution of intensity measured by ASOS station for cases identified as rain and snow during time of ER-2 flight over ASOS stations.*

Rain Cases	**Total**
Light Rain	18
Moderate Rain	6
Heavy Rain	1
Total	**25**

Snow Cases	**Total**
Light Snow	27
Moderate Snow	9
Heavy Snow	2
Total	**38**

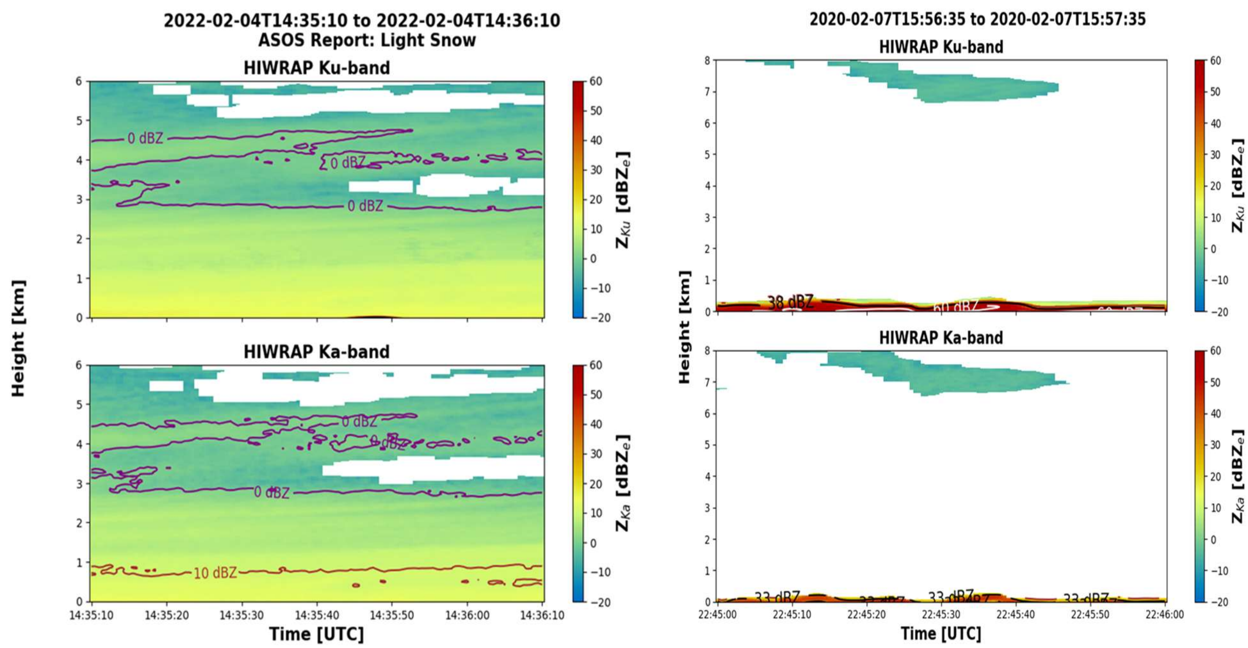


Figure 3*: The reflectivity (dBZ) as a function of time and height for (top panels) Ku-band and (bottom panels) Ka-band radars on 2022.02.04 (left panels) and 2020.02.07 (right panels). The 0 and 10 dBZ contours are overlaid.*

Table 3: *All 50 cases retained and their corresponding date-time and precipitation type. (a) represents all 2020 cases, (b) all 2022 cases and (c) all 2023 cases retained.*

(a) Cases (2020)	Date-Time	ASOS Reported Precipitation
1	*2020.01.25 T20:45:20 - 20:46:20*	*Light Rain*
2	*2020.01.25 T21:50:00 - 20:51:00*	*Light Rain*
3	*2020.01.25 T22:09:30 - 22:10:30*	*Light Rain*
4	*2020.01.25 T23:02:20 - 23:03:20*	*Moderate Rain*
5	*2020.02.05 T21:19:00 - 21:20:00*	*Moderate Snow*
6	*2020.02.05 T21:59:00 - 22:00:00*	*Moderate Snow*
7	*2020.02.07 T14:36:15 - 14:37:15*	*Moderate Snow*
8	*2020.02.07 T15:25:45 - 15:26:45*	*Moderate Rain*
9	*2020.02.07 T16:34:20 - 16:35:20*	*Light Rain*
10	*2020.02.07 T16:49:35 - 16:50:35*	*Light Rain*
11	*2020.02.07 T16:56:00 - 16:57:00*	*Light Rain*

(b) Cases (2022)	Date-Time	ASOS Reported Precipitation
12	*2022.01.29 T23:46:55 - 23:47:55*	*Light Snow*
13	*2022.01.29 T01:01:35 - 01:02:35*	*Moderate Snow*
14	*2022.01.29 T01:10:25 - 01:11:25*	*Moderate Snow*
15	*2022.02.04 T14:35:10 - 14:36:10*	*Light Snow*
16	*2022.02.04 T15:00:45 - 15:01:45*	*Light Snow*
17	*2022.02.04 T15:42:40 - 15:43:40*	*Moderate Rain*
18	*2022.02.08 T15:54:55 - 15:55:55*	*Light Snow*
19	*2022.02.13 T12:28:55 - 12:29:55*	*Light Snow*
20	*2022.02.13 T12:34:05 - 12:35:05*	*Light Snow*
21	*2022.02.13 T12:44:45 - 12:45:45*	*Light Snow*
22	*2022.02.13 T13:51:30 - 13:52:30*	*Light Snow*
23	*2022.02.13 T14:15:50 - 14:16:50*	*Light Snow*
24	*2022.02.13 T14:45:25 - 14:46:25*	*Light Snow*
25	*2022.02.13 T14:56:00 - 14:57:00*	*Light Snow*
26	*2022.02.13 T15:04:10 - 15:05:10*	*Light Snow*
27	*2022.02.13 T15:06:50 - 15:07:50*	*Light Snow*
28	*2022.02.19 T15:20:00 - 15:21:00*	*Moderate Snow*
29	*2022.02.19 T15:38:30 - 15:39:30*	*Light Snow*
30	*2022.02.25 T10:03:15 - 10:04:15*	*Light Snow*
31	*2022.02.25 T13:44:35 - 13:45:35*	*Moderate Rain*

(c) Cases (2023)	Date-Time	ASOS Reported Precipitation
32	*2023.01.19 T23:07:30 - 23:08:30*	*Light Rain*
33	*2023.01.23 T13:07:00 - 13:08:00*	*Light Snow*
34	*2023.01.23 T14:12:55 - 14:13:55*	*Light Snow*
35	*2023.01.23 T17:14:00 - 17:15:00*	*Light Snow*
36	*2023.01.23 T17:30:50 - 17:31:50*	*Moderate Snow*
37	*2023.01.23 T17:37:20 - 17:38:20*	*Light Snow*
38	*2023.01.23 T17:45:10 - 17:46:10*	*Light Rain*
39	*2023.01.23 T17:49:35 - 17:50:35*	*Light Rain*
40	*2023.01.25 T19:13:50 - 19:14:50*	*Light Rain*
41	*2023.01.25 T21:15:30 - 21:16:30*	*Light Snow*
42	*2023.02.12 T19:10:25 - 19:11:25*	*Light Rain*
43	*2023.02.14 T23:25:20 - 23:26:20*	*Light Rain*
44	*2023.02.17 T13:52:55 - 13:53:55*	*Moderate Rain*
45	*2023.02.17 T14:15:20 - 14:16:20*	*Light Rain*
46	*2023.02.28 T11:09:00 - 11:10:00*	*Light Snow*
47	*2023.02.28 T11:13:10 - 11:14:10*	*Light Snow*
48	*2023.02.28 T11:40:10 - 11:41:10*	*Light Snow*
49	*2023.02.28 T13:21:55 - 13:22:55*	*Light Snow*
50	*2023.02.28 T13:55:10 - 13:56:10*	*Light Snow*

3.1 Methods - Z-R Relationships

To directly compare ASOS reported precipitation intensities with HIWRAP reflectivity, various published Z-R and Z-S relationships for Ku- and Ka-band frequencies were tested to convert reflectivity into estimated precipitation rates. These relationships differ by both frequency band (Ku or Ka) and precipitation type (rain or snow). A total of twelve Z-R relationships, 3 per band and precipitation type, were selected based on their relevance to this study. These relationships were gathered from previous studies reflecting a variety of applications, including convective versus stratiform precipitation and differences in snow crystal types, like wet versus dry particles. However, none of these relationships were specifically derived for winter storms in the Midwestern and Northeastern US winter storms, like the ones observed during the IMPACTS field campaign. The precipitation intensity categories for R are based on ASOS classifications (Vickie 1998):

- **Light:** $R < 2.54$ mm h^{-1}
- **Moderate:** $2.54 < R < 7.62$ mm h^{-1}
- **Heavy:** $R > 7.62$ mm h^{-1}

Rasmussen et al.'s (1999) inverse equation converts ASOS visibility classifications into snow rate, yielding the following intensities categories for S:

- **Light:** $S < 1.25$ mm h^{-1}
- **Moderate:** $1.25 < S < 2.5$ mm h^{-1}
- **Heavy:** > 2.5 mm h^{-1}

The resulting reflectivity thresholds obtained by applying these R and S values to each relationship are presented in Table 4 for Ku-band and Table 5 for Ka-band.

Table 4: *(a) Ku-Band Z-R relationships from three different published studies and their reflectivity thresholds. (b) Same as (a) but for Ku-band Z-S relationships.*

(A) Ku-Band For Z-R Relationships

Reference	Z-R Relationship	Light (dBZ)	Moderate (dBZ)	Heavy (dBZ)
X-Band Relationship	$Z = (\frac{R}{0.0306})^{(\frac{1}{0.639})}$	< 30 dBZ	30 - 37.5 dBZ	> 37.5 dBZ
Iguchi et al. (2000)	$Z = 276R^{1.49}$	< 30.4 dBZ	30.4 - 37.6 dBZ	> 37.6 dBZ
Romatschke and Houze (2011)	$Z = 200R^{1.49}$	< 29 dBZ	29 - 36.2 dBZ	> 36.2 dBZ

(B) Ku-Band for Z-S Relationships

Reference	Z-S Relationship	Light (dBZ)	Moderate (dBZ)	Heavy (dBZ)
Gwo-jong Huang (2019)	$Z = 129.27S^{1.64}$	< 22.7 dBZ	22.7 - 27.6 dBZ	> 27.6 dBZ
Gwo-jong Huang (2019)	$Z = 106.25S^{1.58}$	< 21.8 dBZ	21.8 - 26.6 dBZ	> 26.6 dBZ
Gwo-jong Huang (2019)	$Z = 140.52S^{1.48}$	< 22.9 dBZ	22.9 - 27.4 dBZ	> 27.4 dBZ

Table 5: *(a) Ka-Band Z-R relationships from three different published studies and their reflectivity thresholds. (b) Same as (a) but for Ka-band Z-S relationships.*

(A) Ka-Band For Z-R Relationships

Reference	Z-R Relationship	Light (dBZ)	Moderate (dBZ)	Heavy (dBZ)
Meneghini et al. (1989)	$Z = 355R^{1.26}$	< 30.6 dBZ	30.6 - 36.6 dBZ	> 36.6 dBZ
Matrosov et al. (2002b)	$Z = 407R^{1.29}$	< 31.3 dBZ	31.3 - 37.5 dBZ	> 37.5 dBZ
Matrosov et al. (2002b)	$Z = 324R^{1.44}$	< 30.9 dBZ	30.9 - 37.8 dBZ	> 37.8 dBZ

(B) Ka-Band for Z-S Relationships

Reference	Z-S Relationship	Light (dBZ)	Moderate (dBZ)	Heavy (dBZ)
Matrosov 2007	$Z = 56S^{1.2}$	< 18.6 dBZ	18.6 - 22.3 dBZ	> 22.3 dBZ
Gwo-jong Huang (2019)	$Z = 99.85S^{1.25}$	< 21.2 dBZ	21.2 - 25 dBZ	> 25 dBZ
Gwo-jong Huang (2019)	$Z = 60.17S^{1.18}$	< 18.9 dBZ	18.9 - 22.5 dBZ	> 22.5 dBZ

To evaluate how the HIWRAP reflectivity aligned with ASOS intensity as a function of the Z-R and Z-S relationship used, a sensitivity test was conducted. The mean HIWRAP reflectivity at 0.1 km above the surface was used as a representative near-surface value. As an example, Figure 4 and Figure 5, show how the choice of Z-R relationship influences the classification of precipitation intensity for cases classified as light rain by the ASOS.

The results of this test show that the Z-R relationships for Ku and Ka-band and Z-S relationships for Ku-band have less than 1 dBZ difference, making them look almost identical. The Z-S relationships for Ka-band had up to a 3 dBZ difference, where the difference in the intensity thresholds are more obvious. The larger difference in threshold for the Z-S relationships is expected, given there is a greater variability in the size and shape of snow compared to rain droplets.

The final Z-R and Z-S relationship selected for each band was chosen based on relevance to the weather conditions during the IMPACTS campaign and how the relationship was derived. The following relationships were picked, Ku-band rain: $Z = \left(\frac{R}{0.0306}\right)^{\left(\frac{1}{0.639}\right)}$, Ku-band snow: $Z = 106.25S^{1.58}$, Ka-band rain: $Z = 324R^{1.44}$ and Ka-band Snow: $50S^{1.2}$.

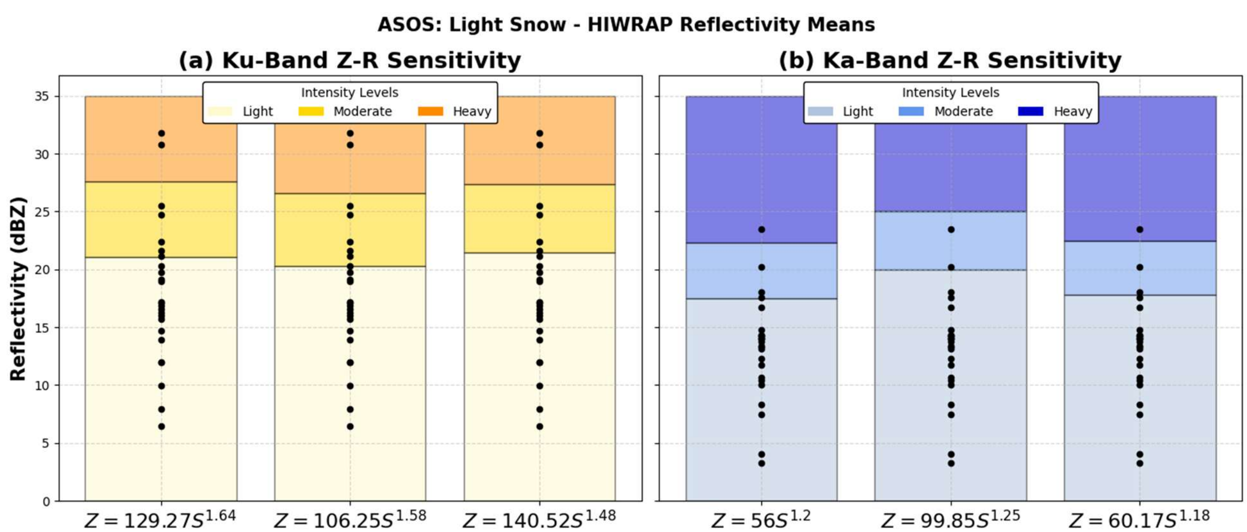


Figure 4: *(a) Sensitivity test of Z-R relationships for (a) Ku-band and (b) Ka-band. Each bar represents a different Z-R relationship, with shaded regions representing reflectivity corresponding to light, moderate and heavy rain as derived from each relationship. Black dots represent the mean HIWRAP reflectivity for ASOS-reported light rain cases.*

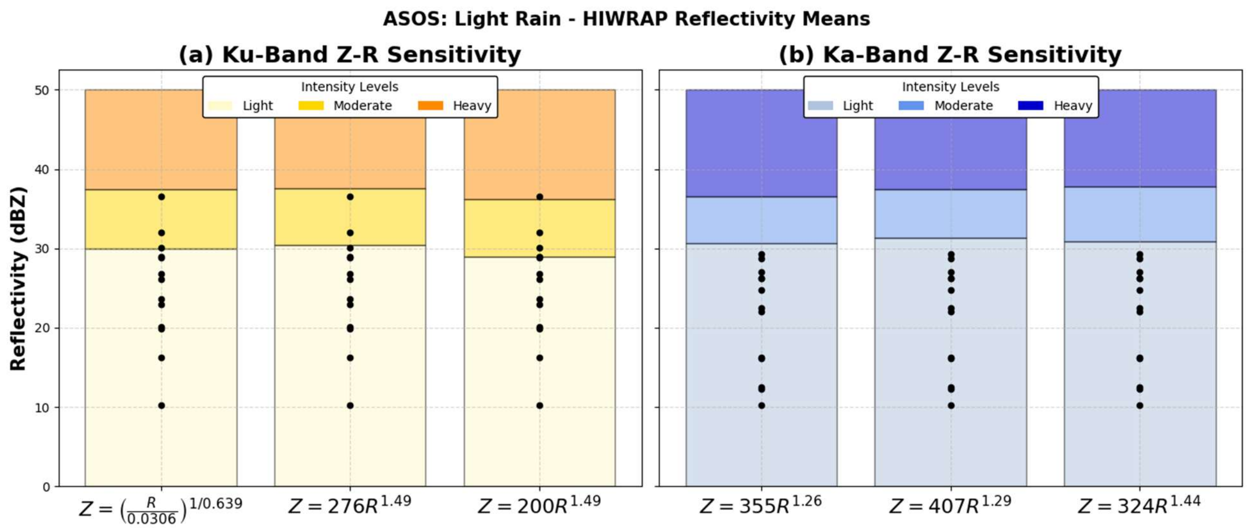


Figure 5: *(a) Sensitivity test of Z-S relationships for (a) Ku-band and (b) Ka-band. Each bar represents a different Z-S relationship, with shaded regions representing reflectivity corresponding to light, moderate and heavy snow as derived from each relationship. Black dots represent the mean HIWRAP reflectivity values for ASOS-reported light snow cases.*

4. Summary Analysis

Figure 6 and Figure 7 show the mean and standard deviation of reflectivity measured 0.1 km above the surface for all ER-2 measurements made within 6.5 km of the ASOS station. The shaded regions in Figures 6 and 7 represent the rain rate and snow rate thresholds determined by applying the selected Z-R and Z-S relationships. The shaded regions in figure 6 marks the reflectivity ranges derived from $Z = (\frac{R}{0.0306})^{(\frac{1}{0.639})}$ for Ku-band and $Z = 324R^{1.44}$ for Ka-band representing light, moderate and heavy rain intensity. In figure 7, the reflectivity thresholds are derived from $Z = 106.25S^{1.58}$ for Ku-band and $50S^{1.2}$ for Ka-band representing light, moderate and heavy snow intensity.

The variability is defined as the spacing between the standard deviation. The larger the size of the error bar (e.g., of 5-10+ dBZ), the more variability exists within that specific case. Smaller error bars (e.g., 0-4 dBZ difference) means that there is more homogeneity in the precipitation for that case.

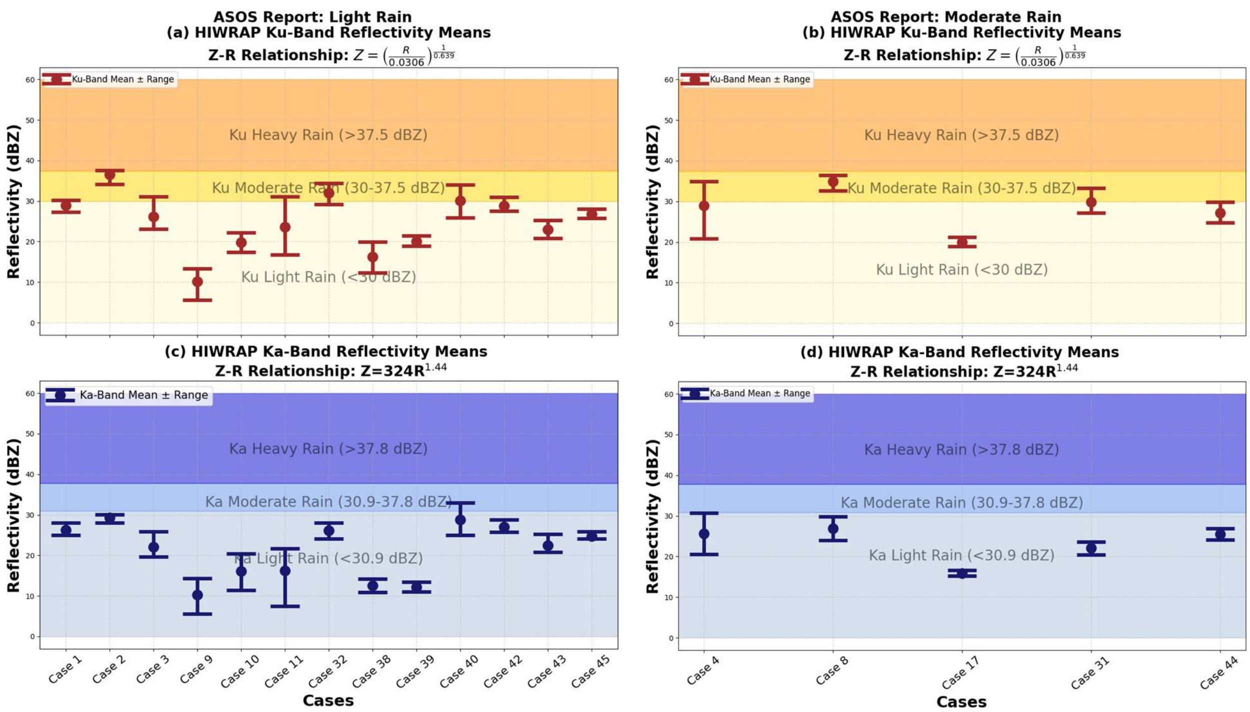


Figure 6: *Summary plots for light rain (a and c) and moderate rain (b and d) as classified by ASOS report. Mean reflectivity and standard deviation displayed for each case. Shading indicates the rain rate range for light, moderate and heavy based on the selected Z-R relationship. Ka-band distribution is shown in (a) and (b), Ku-band distribution is shown in (c) and (d).*

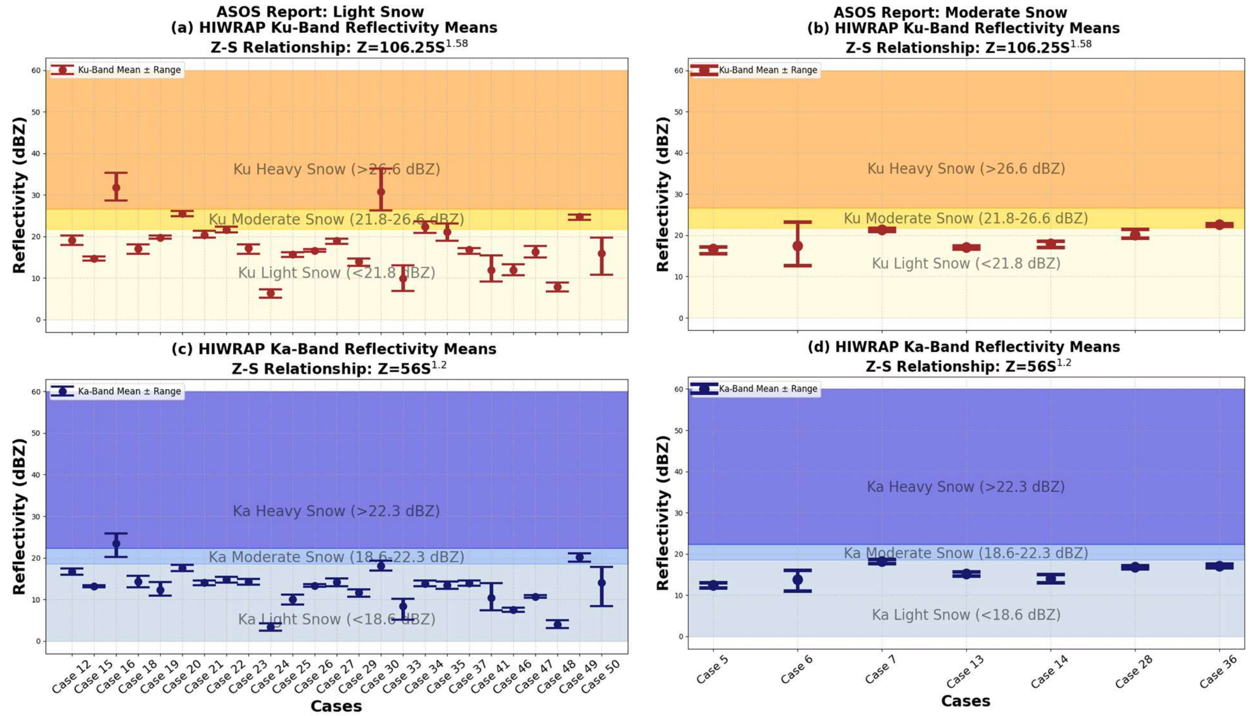


Figure 7: *Summary plots for light snow (a and c) and moderate snow (b and d) as classified by ASOS report. Mean reflectivity and standard deviation displayed for each case. Shading indicates the rain rate range for light, moderate and heavy based on the selected Z-S relationship. Ka-band distribution is shown in (a) and (b), Ku-band distribution is shown in (c) and (d).*

4.1 Rain Cases

For ASOS cases identified as light rain by the ASOS station Figure 6a shows that 10 of the 13 Ku-band reflectivity values fall below the light rain threshold (<30 dBZ) and 3 cases within the moderate category. Figure 6c shows that all 13 Ka-band reflectivity values fall below the threshold for light rain (< 30.9 dBZ), showing strong agreement with the ASOS report. For the ASOS reported moderate rain cases shown in Figure 6b, 2 of the 5 cases had Ku-band reflectivity within the Ku moderate rain range, while the other 3 cases underestimated the ASOS intensity. On the other hand, all 5 mean reflectivities in the Ka-band from HIWRAP underestimated the ASOS intensity, falling below the moderate rain Ka-band threshold. Overall, the Ka-band reflectivities were slightly more consistent with the ASOS classifications for the light rain threshold and Z-R relation used, while the Ku-band reflectivities show a bit more agreement for cases identified as moderate rain by the ASOS reports.

To better examine the variability and agreement of the HIWRAP data with the ASOS reports, Cases 45, 4 and 11 were examined in more detail. In Figure 6, Case 45 shows strong agreement between HIWRAP and the ASOS report as they both fell within the light rain threshold and had minimal variability (±1.5 dBZ difference). Based on the reflectivity threshold and ASOS report, this case represents a consistent light rain event. Case 4 and Case 11 represent the opposite with the greatest spatial variability in reflectivity. For Case 4, ASOS reported moderate rain, however both the Ka and Ku-band underestimated rain, falling below the moderate threshold derived from the Z-R relationships. Additionally, both bands showed larger standard deviation (±5-8 dBZ difference), calculated over a 1-minute interval at the 0.1 km near-surface height during the aircraft passing, indicating at increased horizontal variability (Figure 6). In Case 11, the Ka- and Ku-band matched the ASOS report of light rain. However, the HIWRAP exhibits a 10 dBZ range of variability, with the Ka-band standard deviation extending into the moderate threshold, suggesting the presence of more intense precipitation (Figure 6).

Looking further into the HIWRAP reflectivity of these three cases helps visualize why these differences happen and what they reveal about the ASOS reported intensity and HIWRAP comparisons.

Case 45 (Light Rain): The narrow spread and the homogeneity observed at 0.1 km in Figure 8, suggest that there is not large variability in the precipitation. This sets up a good baseline for comparison against more complex structures where discrepancies between ASOS reports and HIWRAP may be more noticeable.

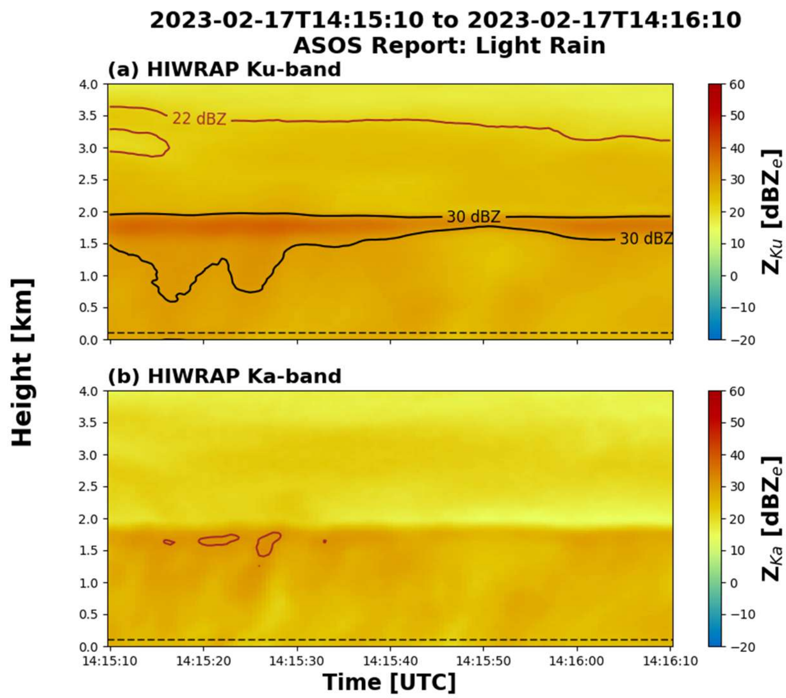


Figure 8: *Radar reflectivity of both HIWRAP Ku (a) and Ka-band (b) on 2023-02-17 (Case 45). Dashed black line represents the 0.1km height that the mean reflectivity in Figure 6 was calculated for.*

Case 4 (Moderate Rain): Figure 9 displays high variability where HIWRAP reflectivity at 0.1 km decreased between 23:02:50 - 23:03:20 UTC. Around 23:03:00 UTC, this reflectivity drop corresponds with a reduction in the melting layer height (1.3 km). As the melting layer dissipates, reflectivity values under 1.0 km decrease, introducing inhomogeneity. While the ASOS reported moderate rain for this case, the horizontal variability indicates that a range of intensities occurred, something that is not fully captured by the ASOS report.

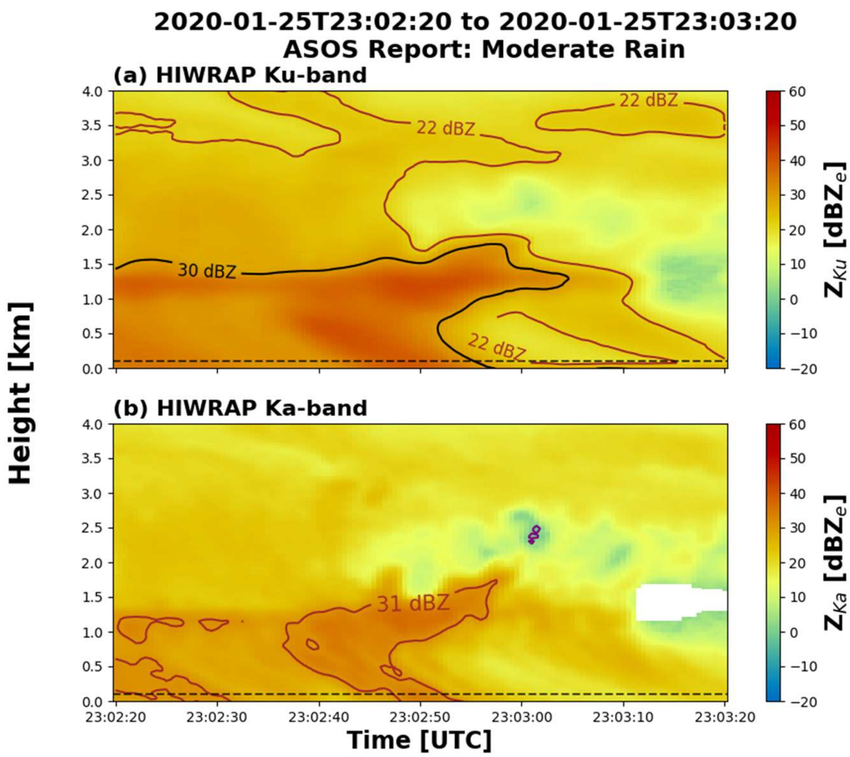


Figure 9: *Radar reflectivity of both HIWRAP Ku (a) and Ka-band (b) on 2020-01-25 (Case 4). Dashed black line represents the 0.1km height that the mean reflectivity in Figure 6 was calculated for.*

Case 11 (Light Rain): In Figure 10, around the 0.1 km line, horizontal variability is clearly visible, especially between 16:56:10 - 16:56:30 UTC, when reflectivity decreases by 5-10 dBZ. Following this region of reduced reflectivity, there is a localized region of increased reflectivity between 16:56:20 - 16:56:50 UTC. This storm structure is different from the stratiform type structure in Case 4 and 39, as it is more vertically developed, which is indicative of convective clouds. The ASOS does not capture this brief enhanced localized reflectivity in the overall reporting.

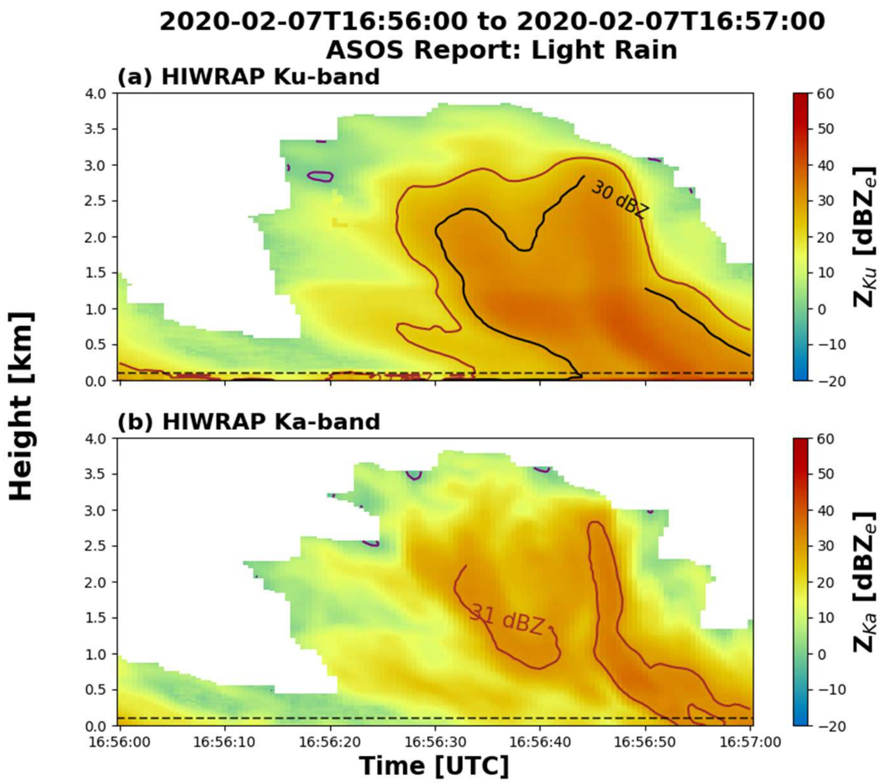


Figure 10: *Radar reflectivity of both HIWRAP Ku (a) and Ka-band (b) on 2020-02-07 (Case 11). Dashed black line represents the 0.1km height that the mean reflectivity in Figure 6 was calculated for.*

Overall, the Ka-band rain estimate tends to align a bit more closely with ASOS light rain reports, while the Ku-band rain estimate had more cases agreeing with ASOS moderate rain reports. The better Ka-band agreement in the light precipitation cases aligns with its sensitivity to smaller particles. Meanwhile, the Ku-band is more responsive to larger particles, which may explain why more cases agreed with ASOS moderate reports, where larger particles are likely present. However, structural differences evident in HIWRAP reflectivity, such as localized enhanced reflectivity regions and variations in melting layer position, as shown in Case 4 and 11, can introduce spatial variability that is not reflected in the ASOS reports. Given these are rain reports, the ASOS misclassifications may not appear as impactful; however similar discrepancies were found in snow events, which pose a greater hazard for aviation.

4.2 Snow Cases

Figure 7 visualizes the comparison of HIWRAP reflectivity versus the ASOS reports for snow cases identified to have low or moderate intensity snow.

For cases identified as light snow by the ASOS, the measured Ka-band reflectivity corresponds to light snow for the thresholds used for 23 of the 25 cases, with the HIWRAP mean reflectivities falling below the light snow threshold of < 17 dBZ. Only 1 case is classified as moderate and 1 as heavy. For the Ku-band, 19 cases had mean reflectivity below the light snow threshold (< 21.8 dBZ), with 4 cases having reflectivities corresponding to moderate snow and 2 to heavy snow.

For cases where the ASOS identified as moderate snow, the agreement is not as good. The mean Ka-band reflectivity is consistent with that of light snow for all 7 cases. In 6 of the 7 cases, Ku-band reflectivity is consistent with that of light snow while only 1 matched with the ASOS moderate snow report. Overall, the Ka-band reflectivities were slightly more consistent with the ASOS classifications for the light snow threshold and Z-R relation used, while both bands showed little to no agreement for cases identified as moderate snow by the ASOS reports.

To better examine the variability and agreement of the HIWRAP data with the ASOS reports, snow Cases 15, 6 and 50 were examined in more detail. In Figure 7, both Ka- and Ku-band reflectivity values for Case 15 fell within the light snow threshold, with minimal variability (±0.5 dBZ difference). Based on the reflectivity threshold and ASOS report, this case represents a consistent light snow event. In Case 6, Figure 7 showed that there was more variability compared to Case 15 with ± 5 dBZ variation in reflectivity for the period when ER-2 was within

6.5 km of the ASOS station. For this case, both the Ka- and Ku-band reflectivity suggest light snow, inconsistent with the ASOS report. Lastly, in Figure 7, the HIWRAP mean reflectivity in Case 50 suggests light snow for this case, consistent with the ASOS reports. However, the variability of reflectivity 0.1 km above the surface layer suggests HIWRAP is not always measuring light snow. For the Ka-band, the upper range of the observed reflectivity is consistent with the reflectivity of moderate snow, implying areas and times of higher intensity. Similar to the rain cases, the HIWRAP reflectivity of these three cases were further examined.

Case 15 (Light Snow): In Figure 11, homogeneity can be seen horizontally across the 0.1 km height. This along with the narrow spread suggests there is not much variability in this case. Cases 6 and 50 are examples of more spatially variable cases.

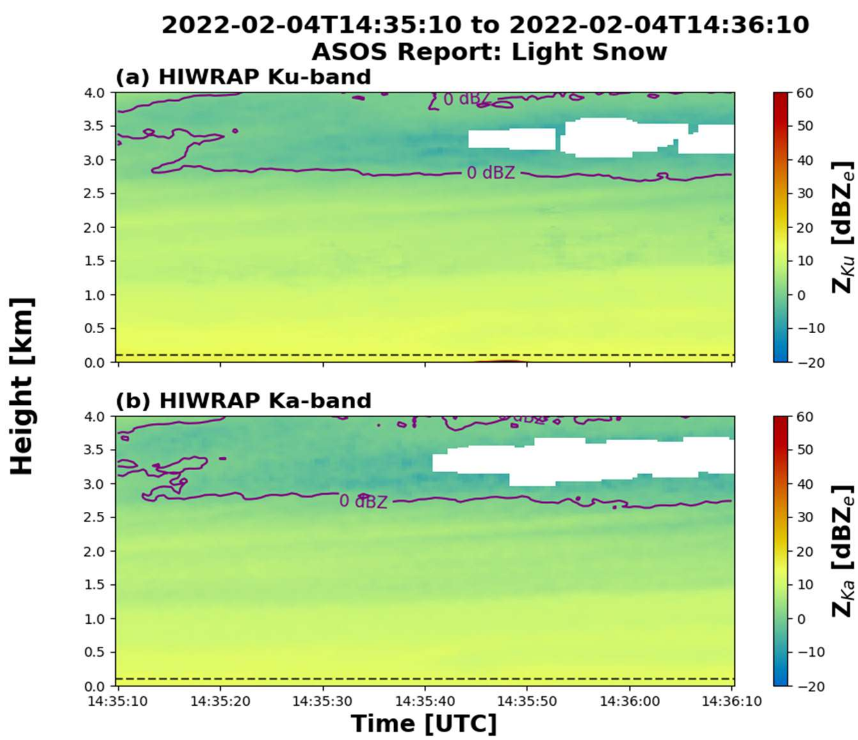


Figure 11: *Radar reflectivity of both HIWRAP Ku (a) and Ka-band (b) on 2022-02-04 (Case 15). Dashed black line represents the 0.1km height that the mean reflectivity in Figure 7 was calculated for.*

Case 6 (Moderate Snow): Figure 12 shows that at the 0.1 km height, reflectivity decreases by ~5 dBZ in the Ku-band reflectivity and ~3 dBZ in the Ka-band reflectivity between 21:59:00 - 21:59:40 UTC. This reduction of reflectivity occurs right below 0.4 km, an enhanced reflectivity region. While this region did not extend to the 0.1 km height, the decreasing reflectivity is potentially the contributing factor to the discrepancy between HIWRAP and the ASOS report.

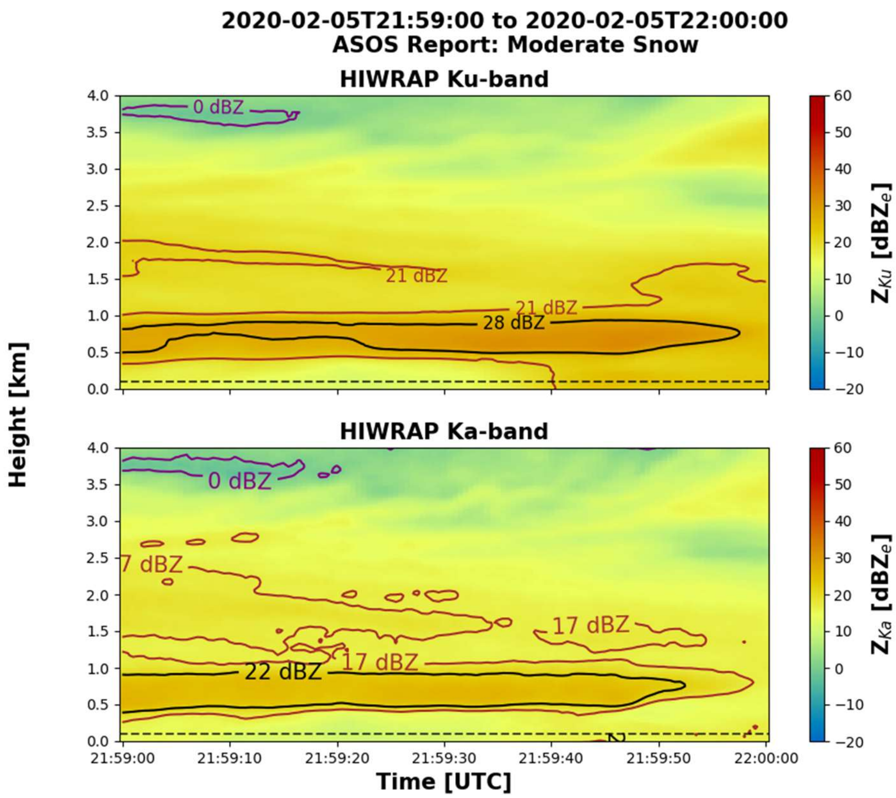


Figure 12: *Radar reflectivity of both HIWRAP Ku (a) and Ka-band (b) on 2020-02-05 (Case 6). Dashed black line represents the 0.1km height that the mean reflectivity in Figure 7 was calculated for.*

Case 50 (Light Snow): Figure 13 shows a visible increase in reflectivity between 13:55:10 - 13:56:00 UTC. These higher values emerge below the 0.5 km height and continue to extend downward to the surface. This structure leads to enhanced reflectivity near the 0.1 km height, where the mean is calculated. These pockets of enhanced reflectivity are not reflected in the ASOS report, remaining consistent with light snow.

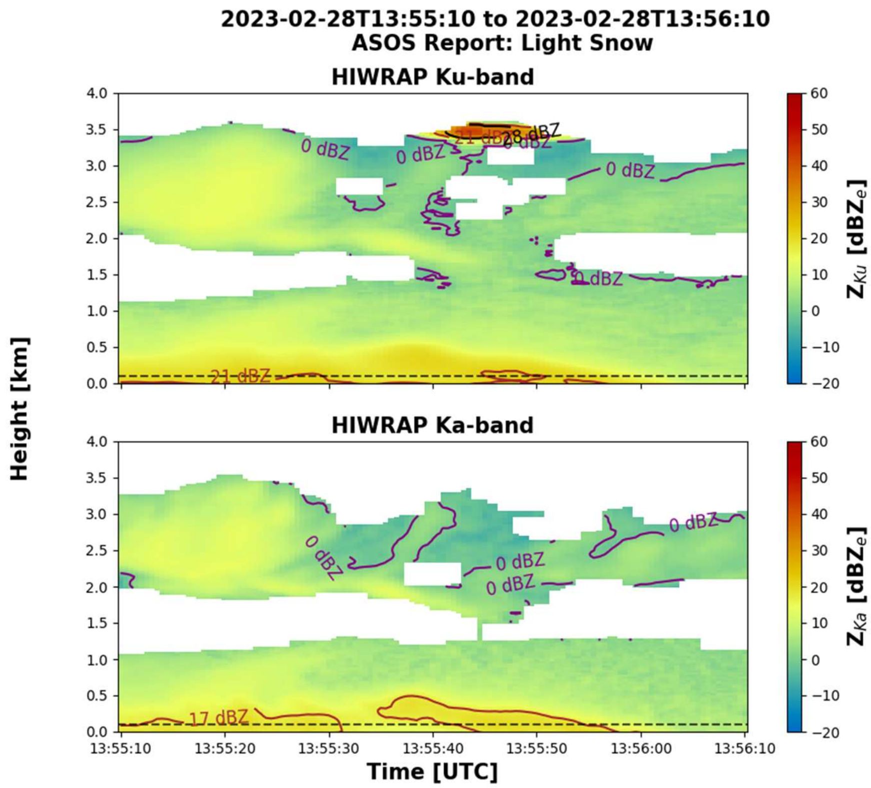
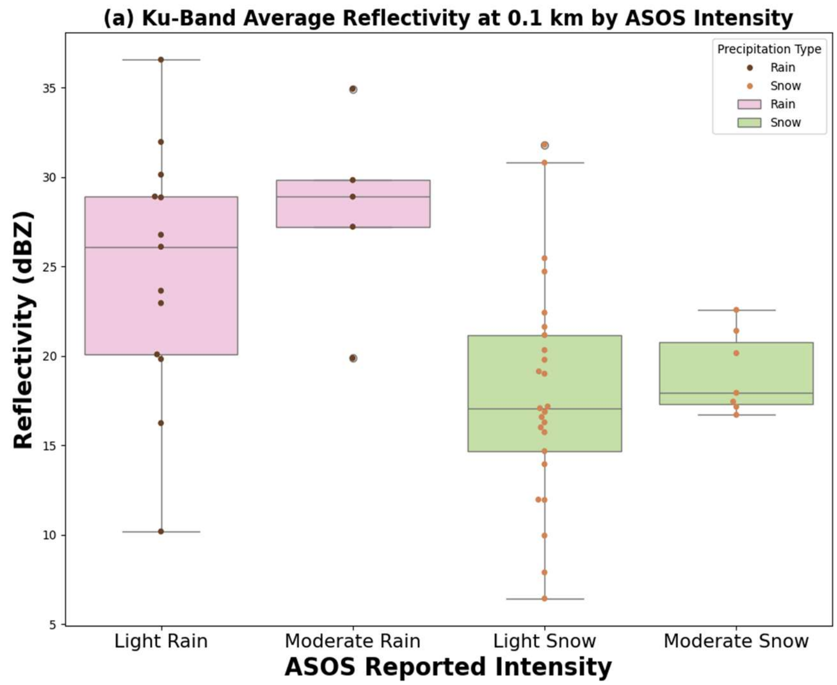


Figure 13: *Radar reflectivity of both HIWRAP Ku (a) and Ka-band (b) on 2023-02-28 (Case 50). Dashed black line represents the 0.1km height that the mean reflectivity in Figure 7 was calculated for.*

Overall, the Ka-band reflectivity derived intensity has more cases consistent with the ASOS for light snow, while there was little consistency of the HIWRAP radar for both the Ka and Ku-bands with the ASOS reports of moderate snow; except for one Ku-band case. The Ka-band dominating in the light precipitation cases is expected, however Ku-band is not as consistent with the ASOS moderate rain reports. Consistent with conclusions drawn from rain cases, structural differences in HIWRAP reflectivity introduce spatial variability that is not reflected in the ASOS reports. Cases 11 and 50 revealed that this can result in missed regions of enhanced intensity precipitation.

4.3 Statistical Analysis

Box Plots in Figure 14a and 14b summarize observations of reflectivity at 0.1 km above the surface as a function of ASOS reported precipitation type and intensity. This helps visualize whether there is distinct separation between the HIWRAP reflectivities for the different ASOS intensities. Figure 14a for the Ku-band and Figure 14b for the Ka-band reveal substantial overlap in reflectivity values across ASOS precipitation intensities. Statistical tests indicate no strong evidence of a difference in reflectivity between ASOS-reported light and moderate precipitation. For rain cases, the t-test determined a p-value of 0.308 for the Ku-band and 0.459 for the Ka-band, suggesting no statistically significant difference. For snow cases, the p-value is 0.475 for the Ku-band and 0.068 for the Ka-band, suggesting that at least the Ka-band has a marginal, but not statistically significant difference. The mean and interquartile ranges are aligned, showing that several ASOS-reported moderate cases have similar reflectivities to those reported as light. From a reflectivity standpoint, some cases classified as moderate by ASOS could also be considered light, and vice versa. This shows that reflectivity at 0.1 km may not be enough to put a distinction between light and moderate intensities, at least as they are calculated by ASOS.



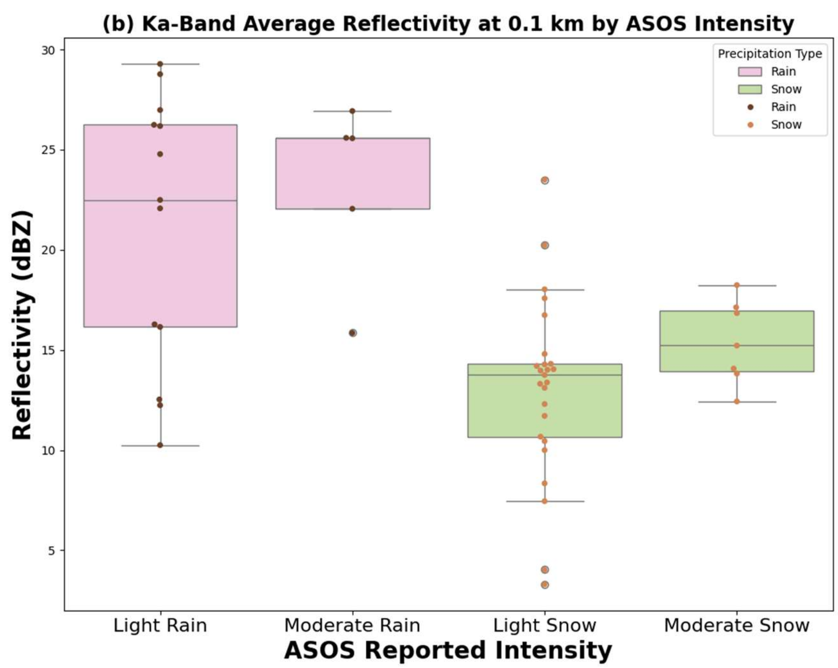


Figure 12: *Boxplots for Ku-band average reflectivity at 0.1km by ASOS intensity (a) and Ka-band (b).*

5. Summary and Discussion

This study assessed the degree of consistency between ASOS precipitation reports and precipitation intensity derived from airborne HIWRAP radar observations. These observations were obtained in the vicinity of ASOS stations during flights over these stations by the NASA ER-2 during the IMPACTS project sampling the structure of winter storms. The availability of these collocated data offers an opportunity to assess the precipitation intensities detected by the ASOS station.

To identify collocated cases, NASA ER-2 flight tracks from 2020, 2022 and 2023 were overlaid over all ASOS locations across the United States. Individual cases of collocation were defined when the NASA ER-2 passed within 6.5 km of an ASOS station. Through this, 123 collocations were identified between the NASA ER-2 and ASOS station. After filtering cases when the ASOS reported “None,” “Freezing Rain,” or “Fog/Unknown Precipitation,” and removing cases with insufficient HIWRAP reflectivity 0.1 km above the surface, 50 collocated cases were identified for analysis. For each of the 50 collocated cases, the mean and standard deviation of the HIWRAP reflectivity at 0.1 km was plotted against thresholds corresponding to light, moderate and heavy precipitation derived from the Ku and Ka-band Z-R and Z-S relationships. The consistency between the HIWRAP and ASOS reported precipitation intensity was evaluated. After further investigation of 6 cases (3 rain and 3 snow cases), 4 of the 6 cases showed a 5-10 dBZ variability in the HIWRAP horizontal reflectivity profile. These cases showed that variability in the reflectivity 0.1 km above the surface, impacted the agreement between the reported ASOS intensities and the HIWRAP reflectivity. Additionally, the analysis revealed that the Ku-band agreed more with ASOS reports in moderate intensity and the Ka-band agreed more with ASOS reports in light intensity based on the Z-R and Z-S relationship used.

This is consistent with expectations, where the Ka-band is more sensitive to smaller particles while the Ku-band is suited better in larger precipitation.

Changes in the Z-R relationships had less than 1 dBZ difference on rain thresholds while the snow thresholds shifted up to 3 dBZ more across the Z-S relationships, corresponding to greater microphysical variability in snow. The final relationships used for this study were selected based on relevance to weather conditions and how the relationship was derived. Comparing the final derived threshold against ASOS-reported intensities offered valuable analysis on how they align.

Beyond the expected difference found between ASOS station and HIWRAP reflectivity, this study also highlights the impact of these differences. The analysis of the individual collocated cases reveals that these differences reflect missed regions of enhanced precipitation that ASOS fails to capture. In both case 11 and case 50, ASOS reported light intensity, yet HIWRAP reflectivity showed enhanced regions of reflectivity, including in snow, where missing pockets of intense precipitation can pose greater hazards for aviation.

ASOS categorical distinctions also come into question after the statistical analysis of all 50 cases. The overlap in mean reflectivity between the ASOS reported light and moderate cases, and confirmed by p-values, suggests that ASOS classifications may not fully reflect variability in precipitation rates. Given that ASOS intensity method relies on photodiode detection, using a more advanced laser-based detector or updating the intensity classification algorithm could capture the variability changes more reliably.

Some limitations of this study include the use of Z-R and Z-S relationships that were not specifically developed for this dataset, presenting possible uncertainty in the derived intensity thresholds. Additionally, due to quality control issues, ASOS 1-minute data is not obtainable for most of the cases, limiting the ability to see if ASOS is smoothing over the periods of enhanced precipitation. Finally, with the limitation of collocated cases, ASOS heavy precipitation reports could not be analyzed and limits our scope in statistical analyzing the light and moderate ASOS reports. For future work, many directions can be taken to enhance this analysis. Applying additional environmental variables like vertical velocity and dual-frequency ratio (DFR) can help explain some of the discrepancies found and provide further details about the microphysical processes. Also, increasing the number of cases, especially if taken from other airborne campaigns, would further strengthen conclusions drawn and provide better statistical analysis.

6. Acknowledgements

This research was funded by the NASA Earth Venture Suborbital-3 (EVS-3) program under grant 80NSSC19K0399 and by a graduate fellowship from the Cooperative Institute for Severe and High Impact Weather Research and Operations (CIWRO)

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