Dual-pol Radar Measurements of Hurricane Irma and Comparison of Radar QPE to Rain Gauge Data

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***Abstract*—Hurricane Irma, landed Florida on September 9th, 2017, was the most intense Atlantic hurricane striking the United States since Hurricane Katrina in 2005. The evolution of Irma was well observed on September 9th-11th by an S-band EEC dual-pol radar deployed in Miami, FL. The radar applied a high temporal and spatial resolution (0.5 minute, 62.5~125m range, <1° azimuth) for the observation so that the details of storm feature were well presented. The radar quantitative precipitation estimation (QPE) products have been compared with the rainfall data measured by the national rain-gauge network. Results show a good agreement, implying the potential of dual-pol radar used for QPE. Exceptions and discrepancies are also analyzed and discussed in this study.**

***Keywords*—hurricane, polarimetric weather radar, QPE**

I. INTRODUCTION

Hurricane Irma, landed Florida on September 9th, 2017, was the most intense Atlantic hurricane striking the United States since Hurricane Katrina in 2005 [1]. It has caused significant damages in mainland United States at an estimated minimum of 50 billion dollars. Irma swept Florida from south to north on September 9th-11th and at least 82 people in Florida died in the storm-related incidents. Irma brought about heavy rainfall (more than 300 mm) and strong winds (more than 180 mph), causing significant damages associated with wind gusts, floods, landfalls, power outage, etc.

An S-band (8.5 cm) dual-polarization weather radar (MIR), manufactured by Enterprise Electronics Corporation (EEC) in Enterprise, AL, is deployed in Miami, FL for local TV service. This radar is EEC's Defender series—SK1000H [2], which is equipped with the 1000 kW Klystron transmitter and provides high sensitivity (-20 dBz@30km) radar measurements. It applies the higher frequency portion of S-band (3.55 GHz) and a 20-ft antenna, producing one-degree beamwidth equivalent to the conventional S-band radar (e.g., NEXRAD) equipped with a 28-ft antenna. During hurricane Irma, MIR radar was operated to collect data using a high temporal-spatial resolution (~0.5 minute update interval, 62.5m~250m range gate, <1° azimuth). With the high-resolution setting, the evolution of Irma was well observed by MIR radar with great details. Fig. 1 shows an example of radar reflectivity from MIR radar with the hurricane eye clearly visible in the PPI image.

The dual-pol radar measurements could provide improved quantitative precipitation estimation (QPE) for weather service [3]. The Enterprise Doppler Graphics Environment (EDGE) is an advanced radar analysis tool developed by EEC, integrating various radar algorithms for quality control (QC), weather detection, classification, estimation, and forecasts. The recent dual-pol radar algorithms with promising improvements have been used in EDGE to produce QPE products. The QPE products would be of great interest to meteorologists or hydrologists.

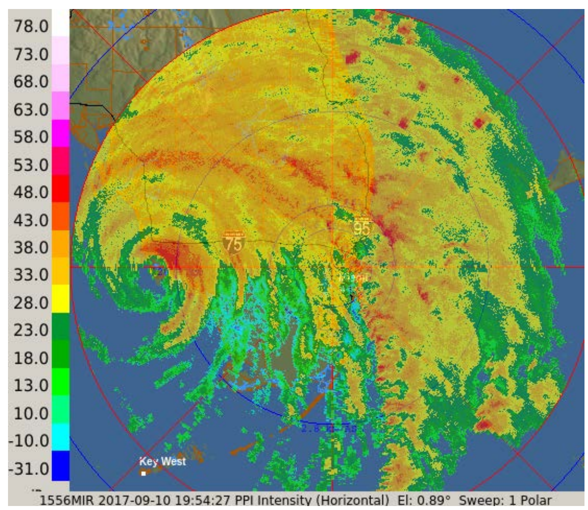


Figure 1. Example of S-band MIR radar reflectivity measurement (El=0.89°, 19:54:27UTC, 09/10/2017)

The ground in-situ measurements (e.g., from rain gauge) can provide reliable reference for the validation of radar QPE. Currently the real-time, quality-controlled (QC'd), hourly precipitation gauge datasets are available in the United States and Canada with nearly 25,000 stations. The QC'd gauge data and statistics have been used for nationwide gauge-adjusted radar estimates, e.g., in multi-radar/multi-sensor (MRMS) system [4]. Fig. 2 shows the sites of national rain gauge network in Florida.

The current study presents the high-resolution dual-pol radar measurements (EEC MIR radar) of hurricane Irma and the analysis of storm feature and evolution. The radar QPE products provided by EDGE are also compared to the hourly measurements of rain gauge, which have been QC'd by MRMS system.

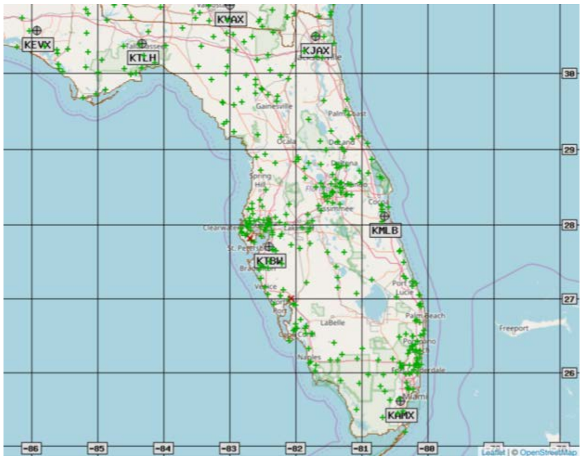


Figure 2. Sites of national rain gauge network in Florida

II. Data Description

The available radar data are from 10:00:27UTC on Sept. 9th to 04:00:23UTC on Sept. 11th. During this period, MIR radar generally applied the following configurations for data collection.

- PRF: 330Hz or 700Hz
- Range: 200 km or 480 km
- Gate width: 62.5 m, 125 m or 250 m
- Sample number: 20, 35, or 50
- Elevation angle: 0.5°, 0.8° or 0.9°
- Scan speed: 12 °/s

All the radar volume scans had one sweep only so that the data were updated fast (0.5-min interval). Although the specific attenuation at S-band is small, the precipitation attenuation might be considerable given the strong intensity and the wide coverage of hurricane Irma. The precipitation attenuation has been corrected for the radar data in EDGE.

The available rain gauge data include the national network hourly observations from 00:00UTC on Sept. 9th to 23:00UTC on Sept. 11th. In addition to hourly-accumulated rainfall (unit in mm), the latitude, longitude, time shift, and QC flag are also provided. In spite of the errors of rain gauge data, the current study assumes gauge measurements as ground truth.

MIR radar is located at (N25.9847°, W80.3460°). The rain gauge sites within 180 km from the radar were sorted out for the comparison with radar QPE products. Considering the radar beam might illuminate the upper portion of precipitating cloud, the rainfall might be under-estimated by radar in the long distance.

III. Description Of EDGE QPE

EEC radar software—EDGE provides a turnkey solution for radar QPE (rain, snow) on single-pol or dual-pol weather radars of S-band, C-band, and X-band. QPE module is usually configured with attenuation correction (AC) module in EDGE processing chain. AC provides the legacy correction approach, which is based on the iterative processing of radar reflectivity. EDGE also has the dual-pol version of correction, which is based on the differential phase as follows.

$$Z^{*}= Z+a\Phi_{dp}, \quad \text{and} \quad Z_{DR}^{*} = Z_{DR}+b\Phi_{dp} \tag{1}$$

where superscript "*" denotes corrected variables. Correction coefficients a and b can be configured for different radar bands. Before applying (1), Φ_{dp} data are smoothed, unwrapped, and corrected for initial offset in a pre-processing module.

There are five different QPE estimators applied in EDGE: R(Z), R(K_{dp}), R(Z,Z_{DR}), R(K_{dp},Z_{DR}), and R(A). The former four estimators use the power-law relations with following forms:

$$Z=aR^{b},\ R=aK_{dp}^{\ b},\ R=aZ^{b}Z_{DR}^{\ c},\ \text{and}\ R=aK_{dp}^{\ b}Z_{DR}^{\ c} \tag{2}$$

where, parameters a, b, and c vary for different estimators and radar bands. R(A) estimator was recently developed by the scientists at National Severe Storm Laboratories (NSSL) [5]. R(A) estimator is based on the specific attenuation (A) and has shown great advantages in mitigating radar partial beam blockage and miscalibration during the QPE.

EDGE provides default configures for all the parameters used in AC module and QPE estimators for S-, C-, or X-band radar applications. These parameters are flexible for the custom tuning by users in order to get optimal results in different locations and events. Besides all these embedded AC and QPE modules, EDGE also provides the application programming interface (API) capability for users to develop new algorithms of attenuation correction and radar QPE.

IV. Data Analysis

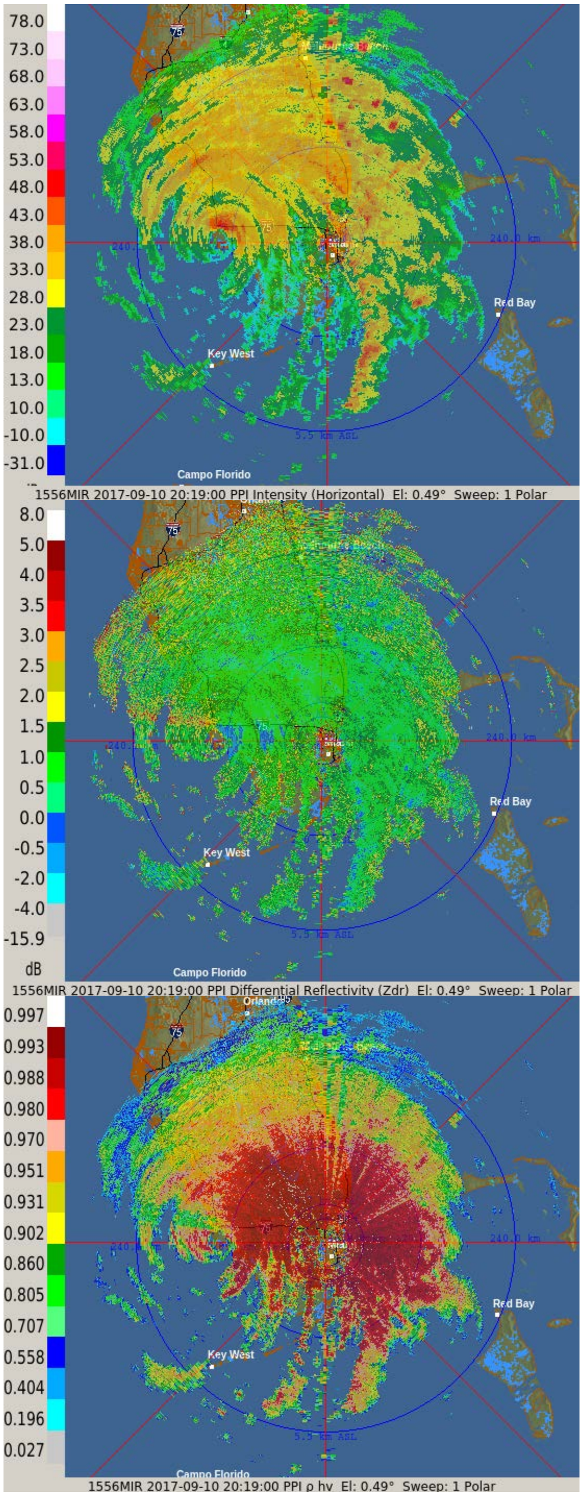
Fig. 3 shows an example of dual-pol radar measurements of Irma: Z_H, Z_{DR}, ρ_{hv}, and Φ_{dp}. For this case, the radar was operating in the long-range mode with a low PRF (=330Hz). The measurements cover more than 300km radius but the radar beam apparently overshot the cloud at far range. The hurricane eye with ~30 km in diameter is visible at ~135 km away from the radar in the west. The most intense radar echoes appear in the north portion of eyewall with the highest reflectivity more than 55 dB. The whole cyclone system was moving northward and several incomplete/rings of cloud cells were visible with a counter-clockwise rotation.

As Fig. 3 shows, the radar echoes are relatively higher in the rings than elsewhere. The precipitating cloud is less visible in the southwest of eye. Most of precipitation occurred in north/northeast/east region of eye. Most outer layer areas (away from the eye) have the moderate precipitation with 30-45 dBZ reflectivity. Both Z_H and Z_{DR} images clearly show the storm feature of several (incomplete) rings.

The Z_{DR} is relatively higher in the rings while it is generally small (e.g., ~1 dB or less) in other regions. A few Z_{DR} pixels show slightly negative values. It is likely due to the attenuation or the bias, which was not well corrected. The negative Z_{DR}

shown beyond 240km is attributed to low SNR signals (noise effect). The noise contamination is likely seen in the northern edge as well with a reduction of Z_H but an increase of Z_{DR}.

The ρ_{hv} data have high values (>0.98) in the rain region within the range of 140 km. Beyond 140 km, ρ_{hv} values are slightly reduced due to the likely mixing phase of hydrometeors. At the edge of rain cell, noise effect also contributes to the reduction of ρ_{hv}.



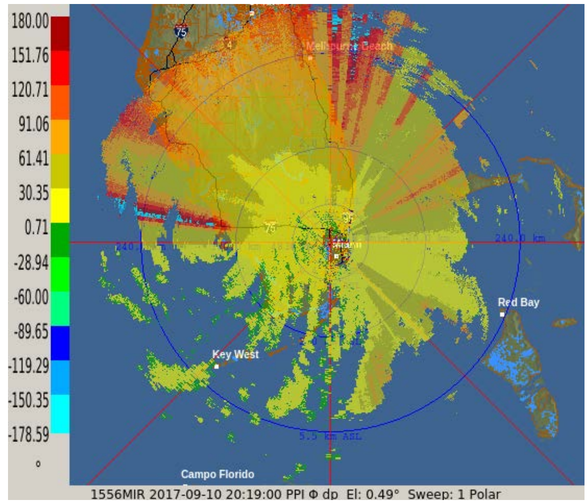


Figure 3. Dual-pol radar measurements of MIR radar: (from top to bottom) Z_H, Z_{DR}, ρ_{hv}, and Φ_{dp} (El=0.5°, 20:19UTC, 09/10/2017).

Because of the large coverage of precipitation region, Φ_{dp} shows an increase of several tens of degrees and up to more than 170 degrees. The largest gradient appears in the area of eyewall, implying the heavy precipitation there. The folded Φ_{dp} data will be unwrapped in the pre-processing module used for attenuation correction.

Fig. 4 and Fig. 5 show the storm evolution of Irma with PPI images of reflectivity (Z_H) and radial velocity (V_H). The whole Irma system was spinning counterclockwise with the wide coverage of more than 500 km in radius. Several enhanced storm chains are visible in the huge circulation.

The first image of Fig. 4 shows the furthest enhanced storm chain (more than 400km away from the eye of Irma) was sweeping over southern Florida peninsula at 00:25UTC on 09/10/17. The Irma core was approaching Key West in the southeast direction from Cuba. During this period, the warm sea surface temperatures and low wind shear helped to sustain and strengthen hurricane intensity. The motion of Irma core was slowing down and it was strengthened from category 3 to category 4 before it hit the Keys.

The second image shows the north portion of Irma when the strengthened Irma brought about abundant precipitation in southern Florida peninsula. The eye of Irma was visible near Key West in radar images around 10:00UTC (not shown). The strengthened hurricane began to move northwards until the hurricane core landed on mainland Florida about 10 hours later. The cooler and drier air on the land helped to weaken the storm intensity. Irma began to degrade to category 2 after its core landed.

The third and fourth images show the intense process of Irma before its core landed Florida. The storm chains are not evident because there are wide coverage of intense precipitating clouds around the eye of Irma, mainly in the north and south directions. The sustained intense precipitation in the vast circulation region caused hazardous flooding and landfall in Southern Florida.

The fifth and sixth images show the degradation process of Irma after the landing. Apparently, the land interaction gradually weakened the favorable conditions of hurricane and reduced Irma intensity. The reflectivity near eye region began to decrease and the coverage of precipitating clouds was also reduced. As a result, the storm chains included in the circulation were more visible. The outer layer of circulation existed a long chain of convective storm with enhanced radar reflectivity. This long chain is the band feature of the cyclone. With further moving northward into inland, Irma weakened to a tropical depression over the Georgia-Alabama border one day later on 09/12/17.

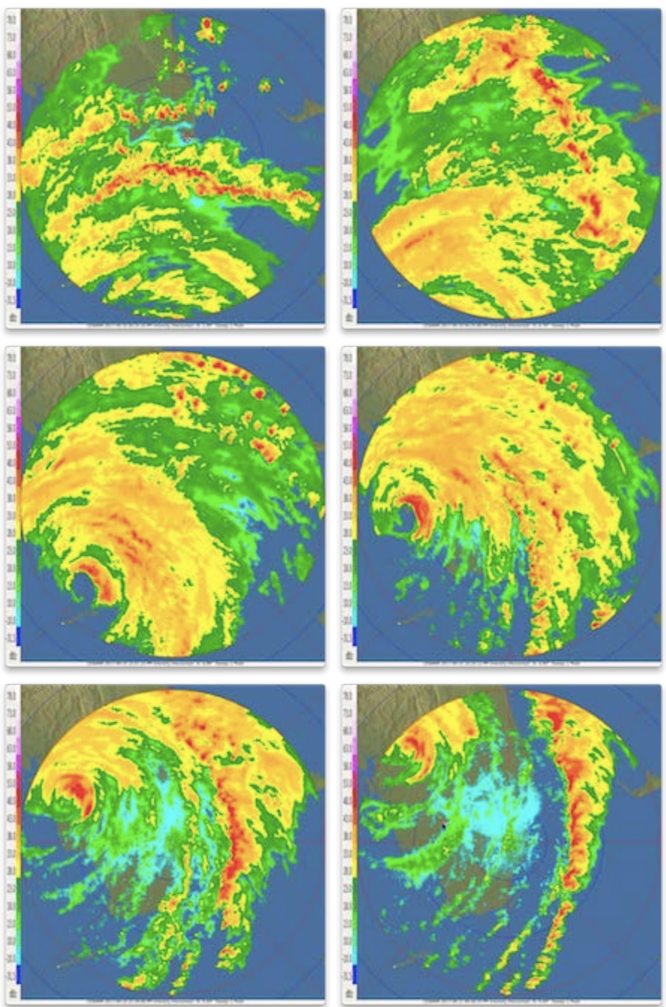


Figure 4. Evolution of Irma: Z_H, measurements at 00:25:10 UTC (09/10/2017), 06:35:00 UTC, 15:01:15 UTC, 19:29:12 UTC, 22:39:00 UTC, and 00:58:33 UTC (09/11/2017).

The Nyquist velocity of radar was 59.5 m/s (133 mph) given the PRF was set to 700Hz. Therefore, the radar could resolve the radial velocity without ambiguity in most of storm region. The small circle of folding velocity is visible near the eye of Irma, indicating the strong winds in the eyewall there. The symmetry of negative/positive velocity regions with respect to the zero velocity curves indicates the circulation of whole system. The orientation of zero velocity curves also gives the direction of storm motion. As shown in the first image of Fig. 5, Irma was moving towards west. It was moving towards northwest and north as shown in the third and fourth images, respectively. Fig. 5 shows that the maximum radial velocity is generally found in the region close to the eye area and parallel to the storm motion. Overall, the velocity images of MIR radar look quite smooth with few noisy pixels, implying the high quality of velocity data generated by the radar.

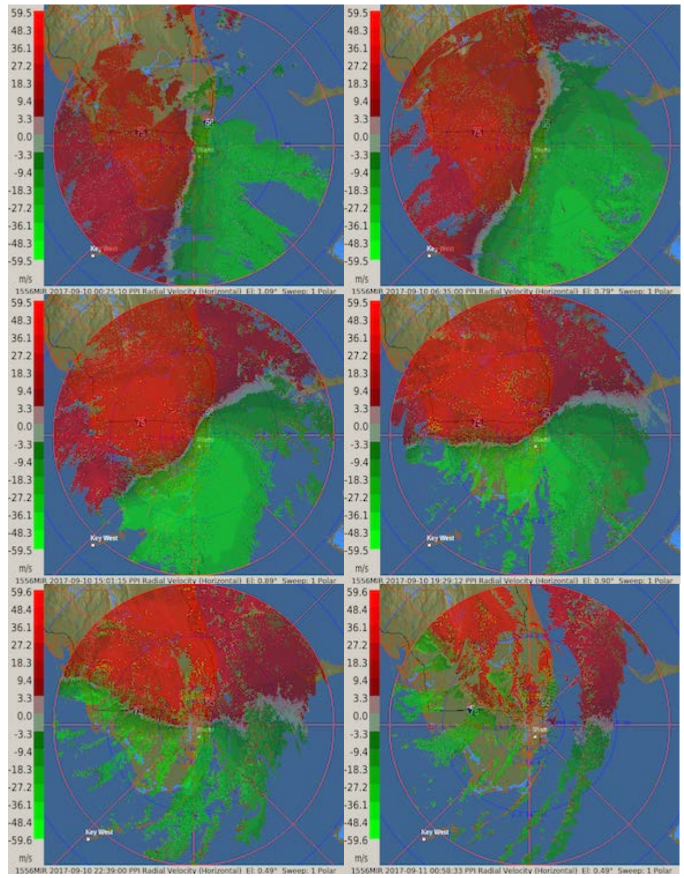


Figure 5. The same as Fig. 4 except for V_H measurements

V. Rainfall Estimation

The raw radar measurements were processed with EDGE processing chain for rainfall estimation, which also includes data quality control and attenuation correction. Fig. 6 gives an example of rainfall rate output from EDGE QPE module. The default AC and QPE configurations without optimal tuning are used in this figure, given as follows:

$$Z^{*} = Z + 0.017 \times \Phi_{\mathrm{dp}}, \text{ and } Z_{DR}^{*} = Z_{DR} + 0.003 \times \Phi_{\mathrm{dp}} \quad (3)$$

$$R = 0.0067 \times Z^{0.93} Z_{DR}^{-3.43} \quad (4)$$

It is noted that the instantaneous rainfall rate is more than 150 mm/h near the eye area. The rainfall in the region away from eye area is not as intense as there but relatively heavier precipitation has occurred in several evident storm chains (i.e., incomplete rings).

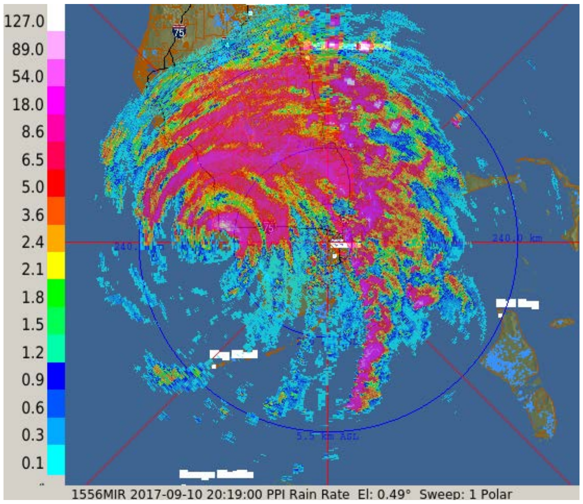


Figure 6. Rainfall estimation using the data shown in Fig. 3

Fig. 7 shows two examples of time series of hourly rainfall measurements by radar and rain gauges. To pair the radar-gauge measurements, the radar data from 3 rays × 5 gates grids centered at the gauge location were sorted out and their median value was calculated to represent the radar observation at the gauge site. The instantaneous QPE results are hourly rainfall (equivalent to rainfall rate) estimated from the radar data with 0.5-min update interval. The hourly accumulation is the 60-min averaged instantaneous results.

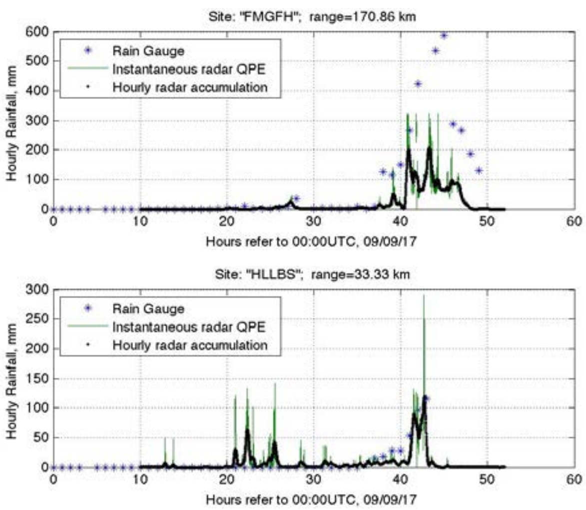


Figure 7. Examples of hourly rainfall (mm) measured by radar and rain gauges at sites: "FMGFH" and "HLLBS".

Site "FMGFH" has measured the heaviest rainfall among all the sites within the 180km from radar. According to rain gauge measurements, the maximum hourly rain accumulation was close to 600 mm. Such an extreme precipitation should occur in the central area of hurricane though the hourly rainfall amount was surprisingly high. The radar QPE has a great underestimation for the precipitation there. The mismatched sampling volumes of radar and gauge might be the primary reason for large discrepancy in the rainfall estimation in hurricane core. It is noted that "FMGFH" site is located at 170km away from radar. The radar sampling volume there, especially for considering the data averaging within the 3 rays × 5 gates grids, is much larger than gauge's. Another reason is that the EDGE QPE algorithm might not be suitable for the extreme rainfall estimation. Furthermore, EDGE sets a default reflectivity threshold (<55 dB) for rainfall estimation and the maximum rainfall could be limited. The sampling volume discrepancy is much reduced for near range sites and the QPE results can be improved. Site "HLLBS" is located at 33.3 km from radar and measured maximum ~120 mm hourly rainfall. As Fig. 7 shows, the radar estimated hourly accumulations well match the gauge measurements at "HLLBS".

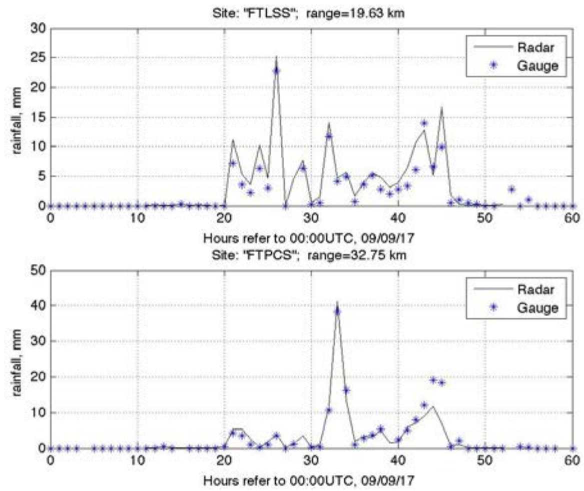


Figure 8. Examples of hourly rainfall (mm) measured by radar and rain gauges at sites: "FTLSS" and "FTPCS".

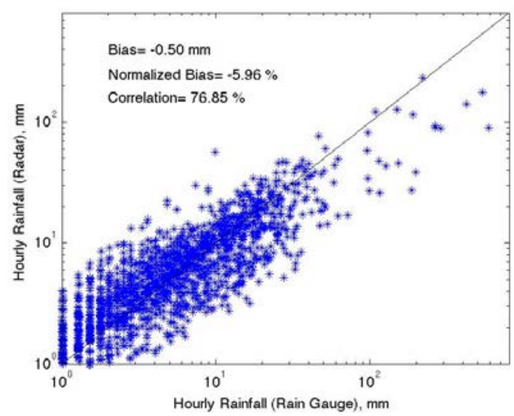


Figure 9. Scatter plot of radar estimated hourly rainfall versus gauge measured hourly rainfall.

Fig. 8 shows the examples from two near range sites "FTLSS" and "FTPCS", which generally measured the moderate or moderate to heavy rain. Their estimated hourly rainfall accumulations also match gauge measurements well.

Fig. 9 shows the scatter plot of hourly rainfall accumulation in terms of radar estimation versus rain gauge measurement. This plot includes data points from all the available radar-gauge pairs at 182 sites (within 180km away from radar) and at hours from 11:00UTC (Sept. 9th) to 04:00UTC (Sept. 11th). The underestimation is evident for data points of extreme rainfall (>100 mm/h). If we exclude the extreme rainfall data (>100 mm) and only consider the range of 1-100 mm, the QPE bias is only -5.96% and the correlation is 76.85%. Considering the effect of sampling volume discrepancy at different sites, the comparison results shown in Fig. 9 look fairly reasonable.

Table: Statistics of radar hourly rainfall estimation

Type	**Light Rain**	**Moderate**	**Heavy**	**Very heavy or Extreme**
Hourly Rainfall (mm)	$1<R\le2.5$	$2.5<R\le20$	$20<R\le50$	$50<R<600$
	Rain-gauge site < 180km			
Bias (mm)	0.6935	0.0949	-6.3193	-79.5412
Bias (%)	42.69%	1.24%	-22.15%	-49.83%
STD (%)	66.91%	50.03%	38.47%	62.38%
	Rain-gauge site < 50km			
Bias (mm)	0.4460	0.6212	-1.5645	-21.6232
Bias (%)	27.68%	7.91%	-5.34%	-25.47%
STD (%)	45.34%	38.69%	34.98%	33.23%

Assuming rain gauges have measured the ground truth, the bias and standard deviation (STD) of radar QPE are listed in the Table with four categories in terms of hourly rainfall (mm): light rain-LR ($1<R<2.5$), moderate rain-MR ($2.5<R<20$), heavy rain-HR ($20<R<50$ mm), and very heavy/extreme rain-ER ($50<R<600$). For rain gauge site within 180km, the categories of LR and ER have considerably large bias and STD. One of major reasons should be the mismatched sampling volumes between the radar and rain gauges. The measurements aloft and on the ground tend to have large discrepancy in this extreme event, especially for the comparison at the sites in the far range. This effect also exists for the radar QPE results in other categories, causing the increased STD of rainfall estimation. The sampling volume discrepancy can be reduced for the radar-gauge comparison at the sites in the near range. For rain gauge site within 50km, the bias and STD of rainfall estimation considerably decrease for all the categories, regardless of a minor exception for the bias of MR. The estimation of MR and HR rainfall is more accurate than QPE of LR and ER rainfall and generally has a bias less than 8%. Radar QPE tends to have a positive bias for LR and MR rainfall but a negative bias for HR and ER rainfall.

Another reason for QPE uncertainty might be attributed to the imperfect attenuation correction and rainfall estimator used for the analysis of Irma. Apparently, the default configurations in AC/QPE modules are not optimized for hurricane rainfall. The improvement of QPE in extreme events would be worthy of further research. Nevertheless, it is worth to note that EDGE is flexible for setting custom parameters in AC/QPE modules. More importantly, its API allows convenient implementation of new algorithms. As a supportive software platform, EDGE has great capability in improving the radar QPE, depending on the needs of customers.

VI. Conclusions

The current study presents the high quality dual-pol radar measurements of hurricane Irma observed by EEC S-band radar (MIR, mode SK1000H) and shows the comparison of radar QPE results to the hourly rainfall data of rain gauges.

The high spatial-temporal resolution radar measurements provide good details of storm feature and evolution, implying the great potential of dual-pol radar data in weather analysis and forecast.

EDGE software provides reasonable data processing of quality control, attenuation correction, and radar QPE. The QPE results are generally consistent with the ground truth measured by rain gauges. The mismatched sampling volume is likely a reason for the discrepancy and variation in the radar-gauge comparison. The extreme event (e.g., hurricane) might enlarge this effect. The QPE results show a much better consistence with gauge measurements at near range sites. Better QPE results are seen for moderate and heavy rains. In addition, the imperfect QPE model used in this study might be another reason for the QPE uncertainty of hurricane Irma. Optimal module configurations for extreme events will be further investigated in future studies.

In all, the case study of hurricane Irma well demonstrates the capability of EEC's high-S band (3.5GHz) dual-pol radar for weather applications.

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