METHODOLOGY TO IMPROVE THE NEXRAD RAIN RATE ESTIMATES

by

Xiomara Y. Ortiz de Jesús

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Approved by:

________________________________	__________________
Sandra L. Cruz-Pol, Ph.D President, Graduate Committee	Date
Nazario Ramirez, Ph.D Member, Graduate Committee	Date
José Colom Ustáriz, Ph.D Member, Graduate Committee	Date
Henrick-Mario Ierkic, Ph.D Member, Graduate Committee	Date
Isabel Ríos, MBA Representative of Graduate Studies	Date
Erick E. Aponte, Ph.D Chairperson of the Department	Date

ABSTRACT

There is a limitation of instruments to measure rainfall amounts in Puerto Rico. One of the instruments is the S-band NEXRAD radar located at Cayey. Due to the Earth's curvature, with the information of the radar from only one point in the island, it is difficult to observe the lower part of the troposphere, where the weather events occur. Such uncertainty makes predictions and detections of weather events very difficult. With current *Z-R* relationships, there is an increase in the error due to the distance from the radar and the observation point.

New *Z-R* relations are being developed using rain gauges to validate the data. These relationships are proven to be very effective, depending in the region it is applied to and the type of rain. For tropical region, the most common *Z-R* relationship currently used is Rosenfeld tropical ($Z=250R^{1.2}$).

The development of a reliable *Z-R* relationship applied to different areas in Puerto Rico, is necessary, in order to accurately calculate a more realistic estimation of rain rate from radar data.

The objective of this project is to develop program codes for supporting this goal and will later be applied to the DCAS radars deployed in the student testbed (IP3) for evaluation of the improvements provided by this new technology.

RESUMEN

Existe una limitación de instrumentos para medir la cantidad de lluvia que cae en Puerto Rico. Uno de los instrumentos es el radar banda S NEXRAD localizado en Cayey. Debido a la curvatura de la tierra, con la información del radar desde solo un punto de observación en la isla, es difícil observar la parte baja de la troposfera, donde los eventos meteorológicos ocurren. Esta incertidumbre, hacen difícil la predicción y la detección del estado del tiempo. Con las relaciones *Z-R* actuales, existe un aumento en el error debido a la distancia del radar y el punto de observación.

Nuevas relaciones *Z-R*, están siendo desarrolladas utilizando pluviómetros para validar los datos. Estas relaciones han probado ser muy efectivas, dependiendo en la región a las cuales se les aplica y dependiendo el tipo de lluvia. Para la región tropical, la relación *Z-R* más usada es la de Rosenfeld Tropical ($Z=250R^{1.2}$).

Es necesario el desarrollo de relaciones *Z-R* más confiables, aplicadas a las diferentes áreas en Puerto Rico, con el propósito de calcular de manera más exacta, la estimación de la cantidad de lluvia caída, a través de los datos del radar.

El objetivo de este proyecto, es el desarrollar códigos de programación que sustenten esta meta y que luego pueda ser aplicado a los radares DCAS utilizados por la plataforma de investigación IP3, para evaluación de los avances provistos por esta nueva tecnología.

To my God, my mom, my grandparents, family, and Sally…

ACKNOWLEDGEMENTS

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1 INTRODUCTION

Radars have been generally used to obtain rainfall information in vast areas. During World War II it was discovered that certain frequencies are very sensitive to rain. The power received at the radar reflected from raindrops is proportional to the reflectivity (Z). Due to its ability to detect rain, it has been the goal of several experiments to develop *Z-R* relationships to obtain rain rate from radar reflectivity.

The United States Geological Survey (USGS) has a network of rain gauges distributed along the island [15] to measure rainfall but another method is needed to obtain data in places where there is no rain gauge available. Currently, there is one Doppler WSR-88D radar (NEXRAD)[20], from the National Weather Service, installed at Cayey. Due to the Earth's curvature, with the radar's information from only one point in the island, it is difficult to observe the lower part of the troposphere, where the weather events occur, as you move away from the radar. Such uncertainty makes predictions and detections of weather events very difficult. For tropical regions, the Rosenfeld [10] *Z-R* relationship used has proven to be reasonable when validating data from the rain gauges and radar NEXRAD, but there are still differences between the two measurements. To make corrections for the seasonal climatology, new *Z-R* relationship needs to be developed using in-situ rain measurements together with ancillary data so as to validate the data. In additions, these validations take in consideration such factors as the rainy season or the dry season.

An algorithm is developed to enhance the NEXRAD-rain-rate measurements. 125 rain gauges network was installed in Puerto Rico and collect data every 15 minutes. Radar data is interpolated to location of each rain gauge and rain rate is aggregated to obtain 15 minutes of accumulation rainfall. The four closest radar points to a single rain gauge and the Kriging algorithm [3] were used to perform a rain rate interpolation. PR has been divided in 4 zones according to the distance from radar to rain gauge location for purposes of developing a radar correction factor. Rainfall records (1960-2005) over 40 stations suggested that PR has two seasons, the wet season covering from May to November and the dry season, from December to April. The *Z-R* equations are developed using *Z-R* data with free curvature errors, i.e., the closest rain gauges to the NEXRAD are used. The relationship between *Z-R* may change because of the climatology conditions. Thus, two equations are derived one for dry and one for wet season. Finally, the mean absolute error and mean square error are used to measure the accuracy of estimates and to validate the proposed algorithm. As related work, error due to curvature was modeled as a function of the distance and the elevation of each rain gauge using level III. This work was published on 2010 by Ramirez-Beltran, N.D., Carrasquillo, C. and Cruz-Pol, S. [8]

1.1 Motivation

Puerto Rico is located in a tropical zone. Its climate varies from area to area. For its location, it is prone to be affected by heavy storms and severe weather. It is very important to be able to measure or estimate rainfall rate. One of the instruments used for this purpose, is a radar located at Cayey. Such radar is excellent measuring base reflectivity around its proximity. As the distance from the radar increases, the radar beam altitude increases; it creates a gap that can lead to an underestimation of weather events, leading to devastating effects.

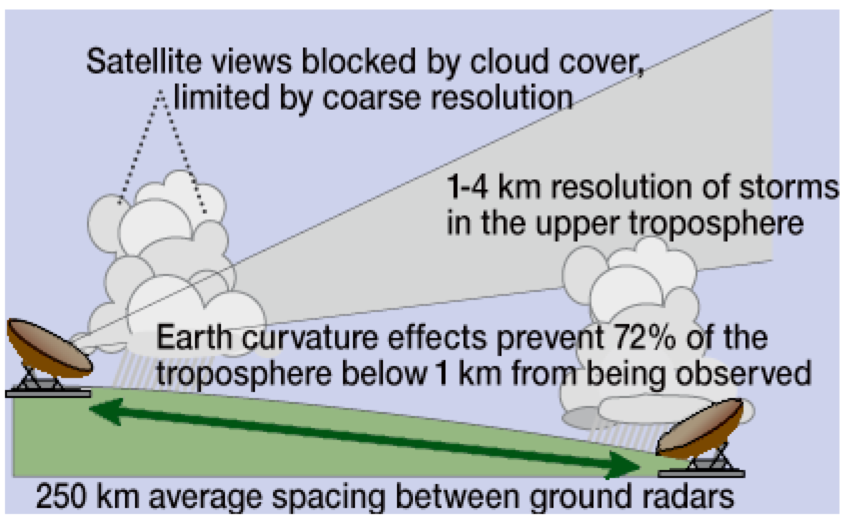

Figure 1-1 Under-sampling of the lower atmosphere due to Earth curvature

Such uncertainty makes predictions and detections of weather events very difficult. With current *Z-R* relationships, there is an increase in the error due to this distance from the radar and the observation point. To make corrections for the distance, new *Z-R* relations are being created using rain gauges to validate the data. Due to a necessity of measurements there has been a need for using other methods to obtain rainfall amounts. Current *Z-R* relationships have been developed in order to use data from radars. Known *Z-R* relationships are: Default WSR-88D [2] ($Z= 300R^{1.4}$), Rosenfeld tropical ($Z=250R^{1.2}$) [10], and Marshall/Palmer ($Z=200R^{1.6}$).

For tropical region, the most common *Z-R* relationship used has proven to be very useful when validating data from the rain gages and radar NEXRAD, but still there are differences between the two measurements. The wrong *Z-R* relationship applied to a location, can lead to overestimation or underestimation of rain amount [4][13].

Therefore there is a need for the development of new *Z-R* relationship in order to estimate rain amount. Such development requires a large amount of computer software and data analyzing in order to be achieved.

1.2 Literature Review

In 1947 J.S. Marshall and W. McK. Palmer made studies trying to create a relationship between a quantity used by the radar which is the reflectivity factor Z (mm^6 m^{-3}) and one used in meteorology which is the rain rate R (mm h^{-1}), in order to obtain the rain rate from radar values. They developed an empirical relationship between Z and R [5][6], $Z=190R^{1.72}$. A Revision from this relationship resulted in $Z=220R^{1.60}$ [9]. Finally, the commonly known Marshall-Palmer *Z-R* relationship is $Z=200R^{1.6}$.

Marshall and Palmer were inspiration for many scientists to keep studying this area. Soon it was discovered that the Marshall-Palmer relationship is very general and does not take into consideration, variations in type of rain, region, and so on [1]. Twomey [12] (1953), while measuring the precipitation intensity by a radar in Australia, noticed that there was a variation in the type of rain from place to place an that the Marshall-Palmer relationship was giving an error in calculations.

The basic *Z-R* relationship formula is $Z=aR^b$ where a and b are adjustable parameters calculated empirically [7]. The Operational Support Facility (OSF) authorized sites to select from five *Z-R* relationships, depending on the season, geographic location, and expected weather type. The Table 1-1 presents different *Z-R* relationship currently available and recommended for different type of precipitation events. If different types of precipitations are present, the *Z-R* relationship must be selected by the predominant type of rain (see http://www.roc.noaa.gov/ops/z2r_osf5.asp) [16][17][18].

Table 1-1 *Z-R* Relationships		
RELATIONSHIP	**Optimum for:**	**Also recommended for:**
Marshall-Palmer ($Z=200R^{1.6}$)	General stratiform precipitation	N/A
East-Cool Stratiform ($Z=130R^{2.0}$)	Winter stratiform precipitation - east of continental divide	Orographic rain - East
West-Cool Stratiform ($Z=75R^{2.0}$)	Winter stratiform precipitation - west of continental divide	Orographic rain - West
WSR-88D Convective ($Z=300R^{1.4}$)	Summer deep convection	Other non-tropical convection
Rosenfeld Tropical ($Z=250R^{1.2}$)	Tropical convective systems	N/A

Table 1-2 Rainfall Rate Comparison					
Reflectivity	**Marshall-Palmer ($Z=200R^{1.6}$)**	**East-Cool Stratiform ($Z=130R^{2.0}$)**	**West-CoolStratiform ($Z=75R^{2.0}$)**	**WSR-88D Convective ($Z=300R^{1.4}$)**	**Rosenfeld Tropical ($Z=250R^{1.2}$)**
15 dBZ	0.01 in/hr	0.02 in/hr	0.03 in/hr	<0.01 in/hr	<0.01 in/hr
20 dBZ	0.03 in/hr	0.04 in/hr	0.05 in/hr	0.02 in/hr	0.02 in/hr
25 dBZ	0.05 in/hr	0.06 in/hr	0.08 in/hr	0.04 in/hr	0.05 in/hr
30 dBZ	0.11 in/hr	0.11 in/hr	0.14 in/hr	0.09 in/hr	0.13 in/hr
35 dBZ	0.22 in/hr	0.19 in/hr	0.26 in/hr	0.21 in/hr	0.33 in/hr
40 dBZ	0.45 in/hr	0.35 in/hr	0.46 in/hr	0.48 in/hr	0.85 in/hr
45 dBZ	0.93 in/hr	0.61 in/hr	0.81 in/hr	1.10 in/hr	2.22 in/hr
50 dBZ	1.91 in/hr	1.09 in/hr	1.44 in/hr	2.50 in/hr	5.80 in/hr
55 dBZ	3.93 in/hr	1.94 in/hr	2.56 in/hr	5.68 in/hr	15.14 in/hr
60 dBZ	8.07 in/hr	3.45 in/hr	4.55 in/hr	12.93 in/hr	39.53 in/hr

The Table 1-2 lists the rainfall rate comparison, in in/hr, for five *Z-R* relationships at various reflectivity levels (see http://www.roc.noaa.gov/ops/z2r_osf5.asp). In order to make corrections to the calculation of current model to estimate rain rate using radars, other factors such as vegetation index [14] and elevation must be taken into consideration.

1.3 Summary of Following Chapters

In Chapter 2, presents the equipment description including the rain gauges, basic components, functionality, and distribution along the island. In addition it also covers the WSR-88D better known as NEXRAD and includes information such as location, functionality, and general information. Chapter 3 deals with data gathering of the rain gauges and the NEXRAD and the software designed to convert data in usable formats and to analyze such information. Analysis and Results are described in Chapter 4 and Conclusions and future work are presented in Chapter 5.

2 EQUIPMENT DESCRIPTION

In order to create new *Z-R* relationships, the computer software developed during this project needs information from several ancillary sensors which are used as actual rainfall data which are distributed along the island. In addition to the sensors information, the software also needs reflectivity information from radar measurements. These instruments are described in detail in the following sections.

2.1 Rain Gages

Puerto Rico has a large rain gauge network that collects rainfall measurements every 15 minutes. A rain gauge is an instrument used to gather and measure the rain accumulation over a set period of time. It is composed of three parts: a funnel, a measuring tube, and an overflow tube. The funnel at the top directs the precipitation water into the measuring tube. Since the measuring tube is 10 times smaller than the collecting area, the measurement is equivalent to 1/10 of actual rainfall.

Figure 2-1 Typical Tipping Bucket Rain Gauge outside and inside view

The Puerto Rico network of rain gauges was installed and operated by the United States Geological Survey (USGS). For this project, data from 125 rain gauges was used. Figure 3-2 shows the location of each rain gauge.

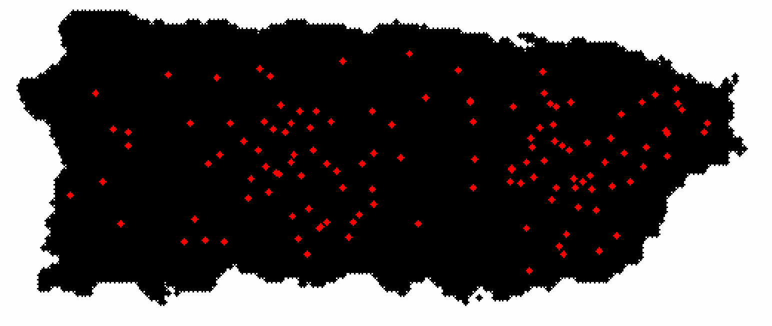

Figure 2-2 Rain gauges location in Puerto Rico

2.2 WSR-88D (Weather Surveillance Radar 88 Doppler)

The WSR-88D is a S-band radar better known as NEXRAD, with a frequency range from 2.7 to 3.0 GHz, maximum range is 250 nautical miles (nm), and tilt angle range from .5° to 19.5°. It completes a full scan every 6-10 minutes. It is located at the eastern-central part of the island in Cayey (Figure 2-3).

Figure 2-3 FAA NEXRAD (Next Generation Weather Radar) at Cayey, PR

The NEXRAD radar provides valuable real time data to create better and more accurate forecast and warnings, and provide input data to weather forecast models. The radar data acquisition is composed of an antenna, a tower, transmitter, receiver, and signal processor to measure reflectivity. Standard data products from the radar are reflectivity, Doppler velocity, and spectrum width. In addition to the products, it can also estimate rainfall, using an algorithm called the Precipitation Processing System (PPS), which transforms the Reflectivity (Z) into rainfall rate (R) using *Z-R* relationships.

Since NEXRAD radar gathers information at different elevation angles, the software ARCGis was used to determine the blind spots of the radar caused by the elevation of the terrain along the island. Based on the results, the optimum tilt angle of .5° was chosen, since this angle avoids beam block and clutter effect [11], and provides the best radar resolution on Level II data reflectivity. Figure 2-4 shows no beam blockage at .5° beam, the radar location, and the distance of the beam from the ground. In the western part of the island, the .5° tilt angle is 2,000m and above from the ground.

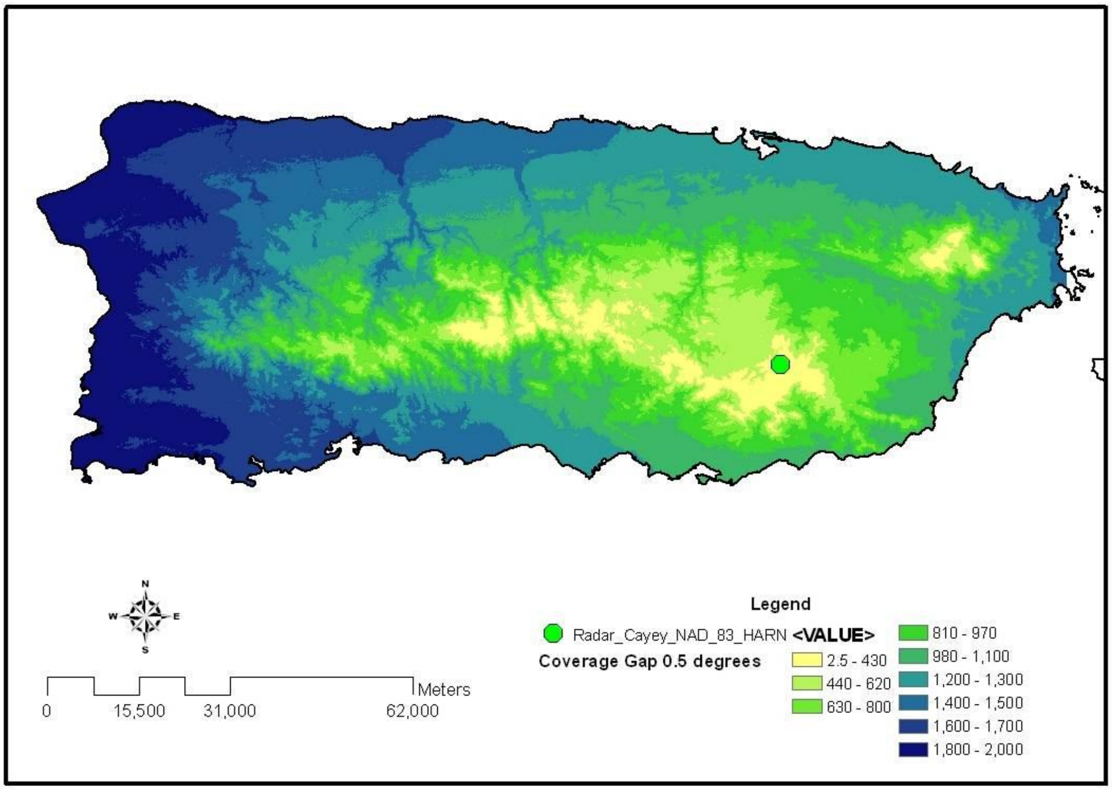

Figure 2-4 WSR-88D location beam blockage at .5° tilt angle

***** ARCGis images generated and provided by Alejandra Rojas for this project.

3 DATA GATHERING AND SOFTWARE DESIGN

3.1 Data Gathering

3.1.1 Rain Gauge Data

Rain Gauge data was supplied by Dr. Nazario Ramirez directly from the USGS and cooperative networks; it is not available in the USGS web page for general public for downloading, instead, it has to be directly requested to USGS personnel. Such data is provided in excel documents, where the name of the file is the rain gauge number and the year of the data taken. The data in the file is organized in a specific format, column A is the rain gauge number; column B is the date in format YYYYMMDD; column C is the time in HHMMSS format, seconds are going to be 00 always because data is being taken each 15 minutes; and column D is the rain rate. Depending on the year, some formats may vary, existing only 3 columns, A with the date, B with the time, and C with rain rate. MATLAB programs named read_xls_to_mat_2_columns.m and read_xls_to_mat_3_columns.m, respectively, were created in order to transform .xls files to a .mat file divided in 8 columns compatible with radar data format. The columns include year, month, day, hour, minutes, seconds, delta (the amount of time in seconds between timeframe, typically 15 minutes ~900s), and rain rate. The new MATLAB file is named as the original excel file.

3.1.2 *Extraction of NEXRAD data*

The NEXRAD data level II can be obtained through a four steps procedure.

1) The data is requested at the web page: http://hurricane.ncdc.noaa.gov/pls/plhas/HAS.FileAppSelect?datasetname=6500. The requested information is received as a webpage sent to a previously specified email, with a link to download the data from a FTP server.

2) The requested data is downloaded and saved in a high capacity hard drive. For instance, Level II data for year 2002 occupy 27 GB in a compressed format, and in an uncompressed format require 227 GB.

3) To process the data, UNIX operating system is used to decompress files .tar and .Z in a fast and time effective way.

4) A computer program written in MATLAB is used to convert the data binary format to MATLAB files. Further analyses are required to derive the *Z-R* relationship.

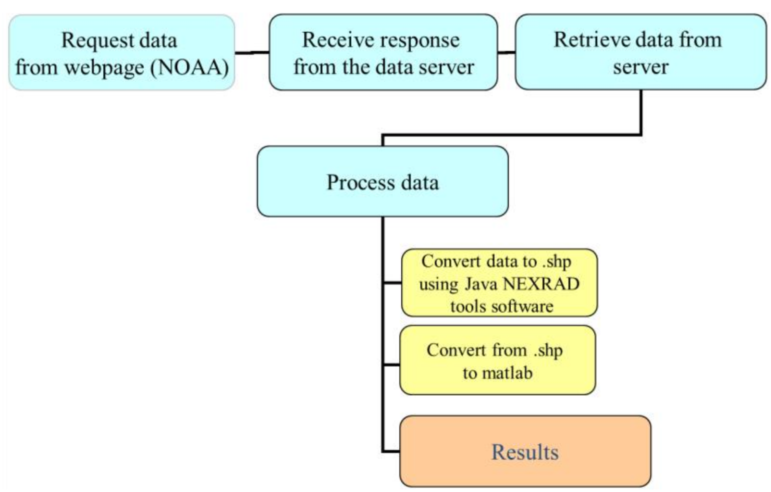

Figure 3-1 Method to process Radar data

*This method is not going to be described but the program is available in the Appendix

An alternative and more effective method may be used to process the NEXRAD data. NOAA provides free software that can be downloaded from the following webpage:

http://lwf.ncdc.noaa.gov/oa/wct/install.php. This software allowed to view the data; choose the product of interest among reflectivity, radial velocity, or spectrum width; choose the angle of elevation; and to export the data into other formats such as: Native NEXRAD, Vector (polygon), Shapefile, text, GML, Raster, Geo Tiff, ESRI ASCII Gris, ESRI Binary Gris, GrADS Binary, and VTK to make it compatible with other software. The data of interest was reflectivity at .5° elevation angle in ASCII format.

In order to analyze the data, first it was converted from ASCII into .mat using a MATLAB program called mvp2007allmonths.m with a function named mvf2007allmonths.m. Such program, open a .asc document, retrieves information from the header needed to create a matrix of latitude, longitude, and Z value which are used by other computer programs.

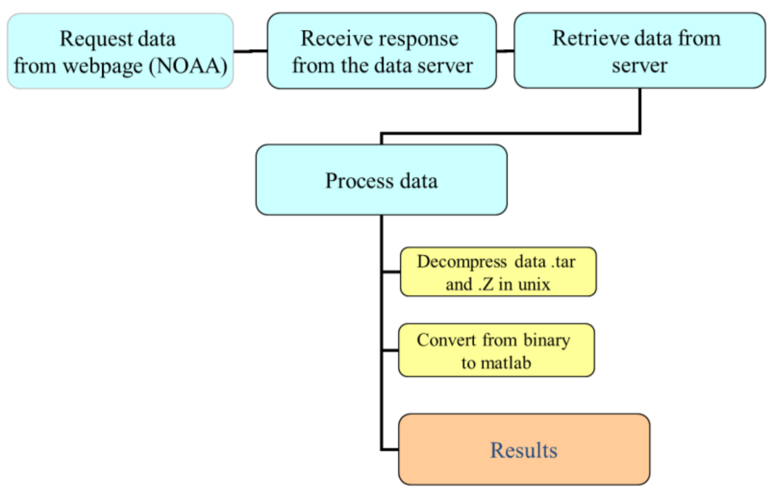

Figure 3-2 Alternate method for processing Radar data

3.2 Software Design

Several computer programs where developed with the purpose of aiding the development of new *Z-R* relationships along the island. One of the first to be developed was the RGmap.m, which creates a map of Puerto Rico showing the location of the NEXRAD radar and the location the rain gauge network along the island, based on the distance from the radar. The first zone is the closest to the radar 15 km or less, the second is between 15 km and 50 km, the third zone is between 50 and 76 km and the forth zone is 76 km or more. These zones were determined in order to develop a radar correction factor to compensate for the Earth's curvature. Bellow there are two pictures, one shows the four zones and the second, only the first zone which is the closest to the radar.

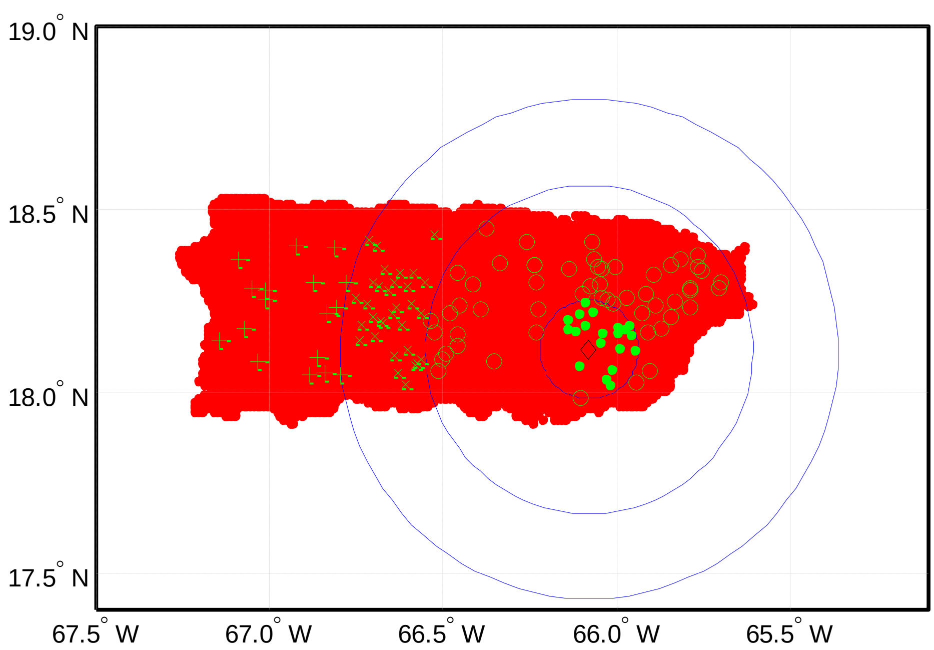

Figure 3-3 RG Distribution by Distance from the NEXRAD Radar

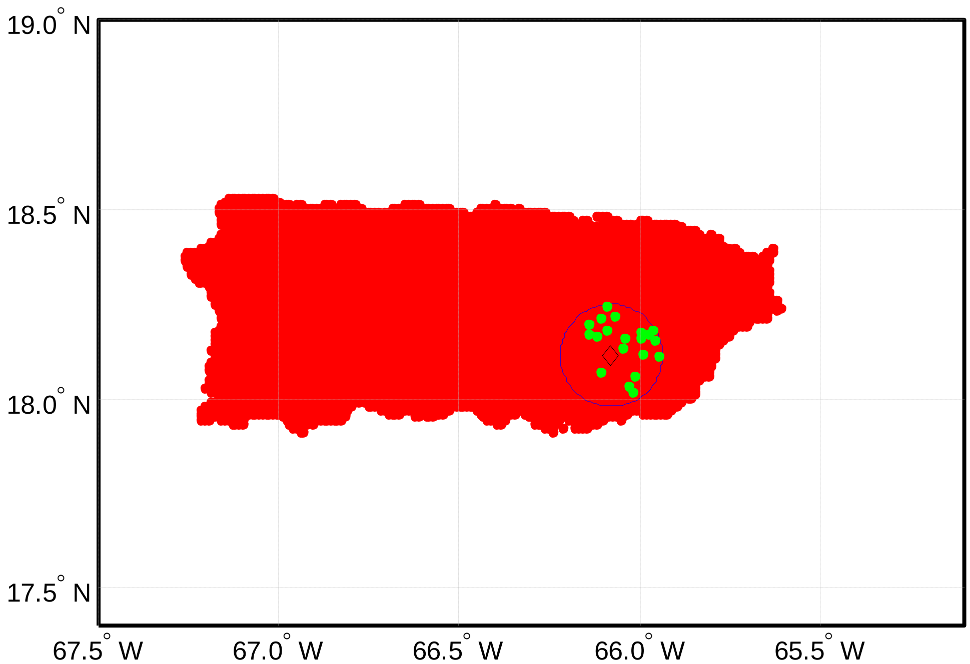

Figure 3-4 RG location within 15 km from the NEXRAD Radar

Rain Gauge Code	Latitude (N)	Longitude (W)	Distance to Radar (km)
50999961	18.136	-66.05	3.7629
50039990	18.073	-66.106	5.8685
50053025	18.16	-66.041	6.2974
50999966	18.183	-66.089	7.3441
50047535	18.17	-66.122	7.4425
50999982	18.062	-66.015	9.4668
50047540	18.174	-66.144	9.5464
50050900	18.119	-65.989	9.942
50999956	18.162	-65.996	10.386
50092000	18.034	-66.033	10.599
50999962	18.215	-66.107	11.175
50999954	18.179	-65.998	11.256
50999965	18.22	-66.067	11.363
50047550	18.199	-66.141	11.363
50047560	18.201	-66.141	11.48
50093045	18.021	-66.022	12.507
50051180	18.173	-65.977	12.859
50051310	18.157	-65.958	14.123
50055100	18.247	-66.094	14.374
50999960	18.114	-65.947	14.665

Table 3-1 Location of the rain gauges and distance from NEXRAD.

3.2.1 For Rain Gauges data:

In order to use the rain gauge data provided by the USGS, it was converted from .xls format to MATLAB data format .mat. Two MATLAB programs, *read_xls_to_mat_2_columns.m* and *read_xls_to_mat_3_columns.m*, were developed depending how the data is organized inside the spreadsheets. Basically, it search all the .xls in a folder for an specific time period, opens each file, and saves the data in a .mat file named identically to the original file.

Once the rain gauge data was in .mat format, it was verified for errors *RGVerification.m*, This program detects values or rain rate (R) higher than normal, *NAN* or negative values. For demonstration purposes, rain gauges for year 2005 where used and 4 in/hr was set as the limit for high normal values of rain. Any value above than 4in/h or negative value will generate a message. For this example, rain gauges for 2005 where used. Alert messages were shown in the command window as shown.

```
Command Window
New to MATLAB? Watch this Video, see Demos, or read Getting Started.
Suspicious elem om month 1 is in data row 84 and it is 8.04
Suspicious elem om month 3 is in data row 21 and it is 21.49
Suspicious elem om month 4 is in data row 21 and it is 21.49
Suspicious elem om month 5 is in data row 91 and it is 4.07
Suspicious elem om month 7 is in data row 2 and it is 26.17
Suspicious elem om month 7 is in data row 91 and it is 19.61
Suspicious elem om month 11 is in data row 72 and it is 24.44
fx >>
```

Figure 3-5 Command window indication abnormal rain rate values.

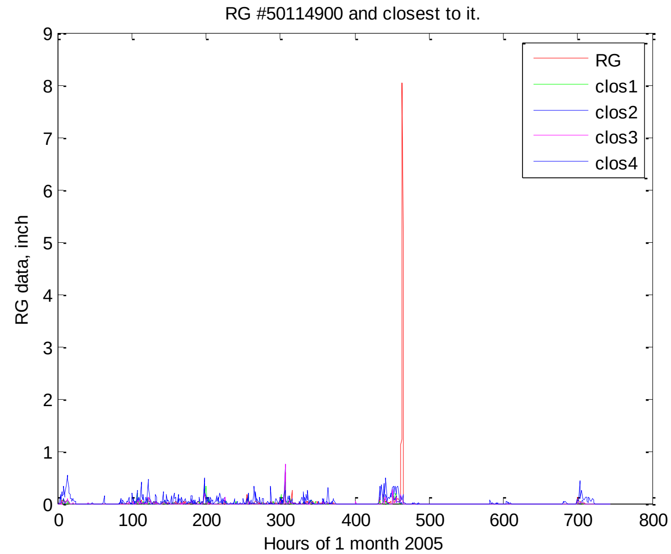

Figure 3-6 Image showing values of rain rate above 4in/hr

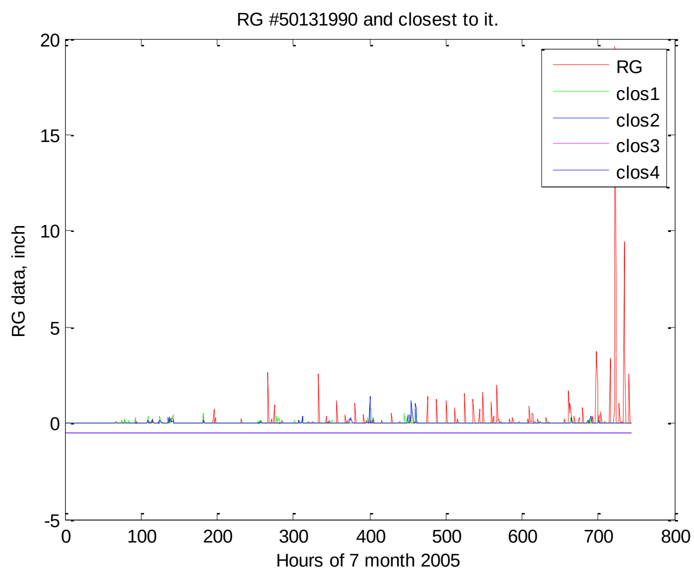

Figure 3-7 Image showing negative values and high values of rain rate

This program also compares the suspicious value with the 4 closest rain gauges in order to determine if it really is an odd value or if actually is occurring and extreme weather event to be recorded. Any pair where the radar or the rain gauge has no data or (-9.99 and -.35) will not be considered and taken out of the dataset.

3.2.2 *For NEXRAD Data:*

NEXRAD data comes in in different forms, depending in the level of processing performed to the data. It comes in three levels but Level I is not considered because it is raw receiver's data. Level II data is radar data initial processing and products consist in Base Reflectivity, Mean Radial Velocity, and Spectrum Width. Level III data, is more processed than Level II, and have more products available, such as, Base Reflectivity, Base Velocity, Storm-Relative Velocity, Echo Tops, Storm Relative Velocity, Vertically Integrated Liquid, One Hour Precipitation Total among others. Level III has more products than level II but at much lower resolution.

Originally, only Level III data was fully available to be downloaded from the Radar, NOAA FTP servers. During the course of this project, Level II data was released and placed available for download. Computer programs were developed for the two types of data.

There are two methods in order to convert radar data into .mat files and make them usable for this project. Level II and Level III data comes in a compress format containing .Z and .tar due to the large size of files. The first method, consisted in removing the compression from the files and then convert the uncompressed file into .mat. A Linux subroutine was created to remove .tar and .Z compression in a fast and time effective way. Computer software and functions *Read_Nexrad_Level_2.m Read_Binary_Level_2.m Graphic_Level_2.m* for conversion of binary files to MATLAB data files, were generated and provided by Joan Manuel Castro.

The second method consisted in downloading Level II or Level III data from the NCDC Archive, commonly known as the Hierarchical Data Storage System (HDSS), and downloading the NOAA Weather and Climate Toolkit. This toolkit provided, for downloading, viewing, manipulating, exporting binary data to other formats, among other functions. In order to use this kit, it was entered, the location were the files were stored and the output directory for the converted file. Desired product, i.e. Reflectivity, elevation angle, and Grid dimension, were selected before the conversion.

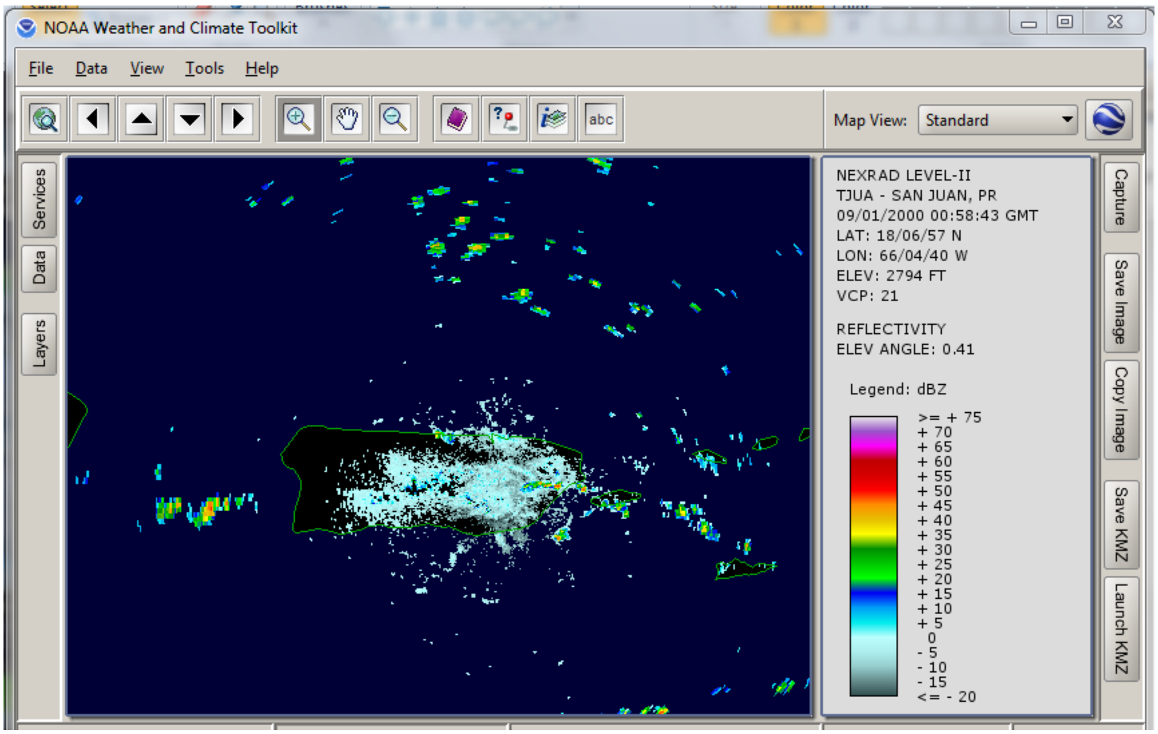

Figure 3-8 Image of the NOAA Weather and Climate Toolkit GUI

4 ANALYSIS AND RESULTS

4.1 Comparison between NOAA Weather and Climate Toolkit and Viewmapfile.m computer program

In order to verify the accuracy of the data conversion from binary format to .mat, a visual comparison of the software codes, was performed for Level II data and Level III data. Figures 4-1 and 4-2 show images obtained from different software for Level II data for August 10, 2002 at an .41° angle. Despite the MATLAB slightly difference in the colorbar, it can be clearly appreciated that they are very similar and that they do not loose accuracy.

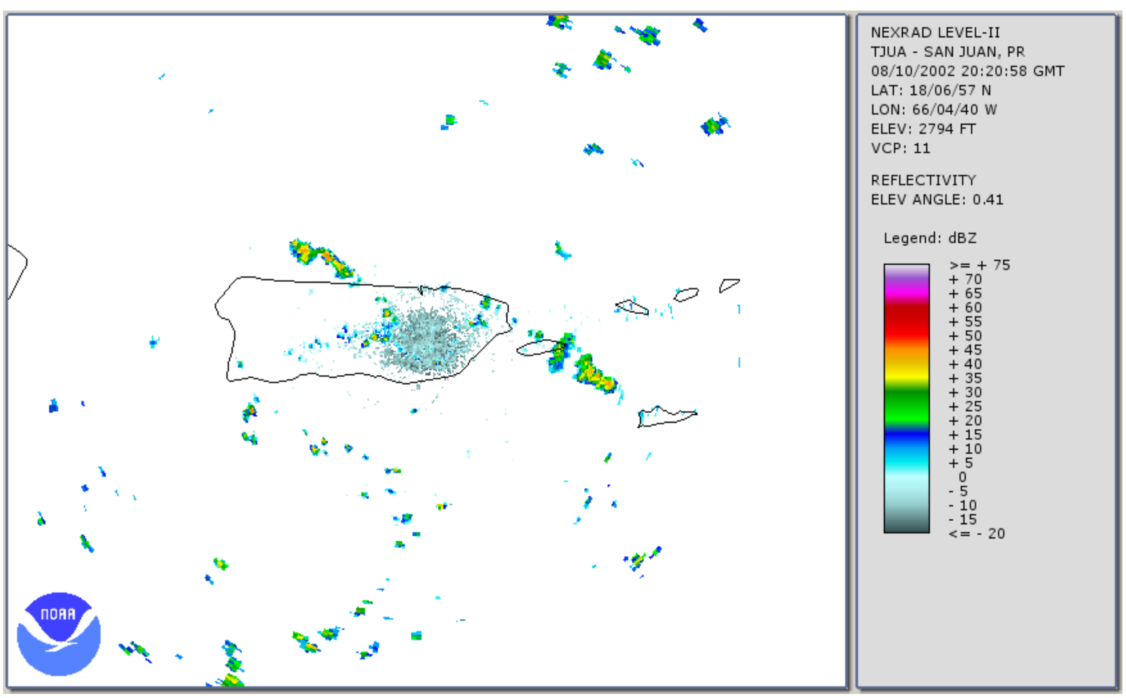

Figure 4-1 Image of the NOAA Weather and Climate Toolkit for TJUA20020810_202058.mat Level II Data

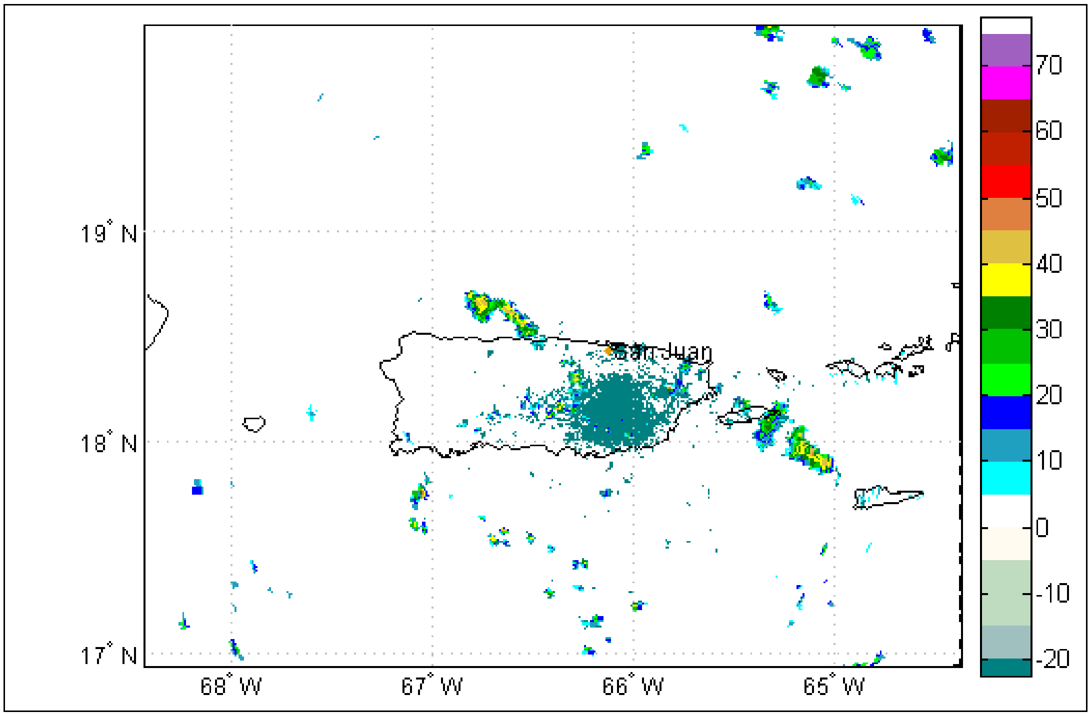

Figure 4-2 Image of Viewmapfile.m forTJUA20020810_202058.mat Level II Data

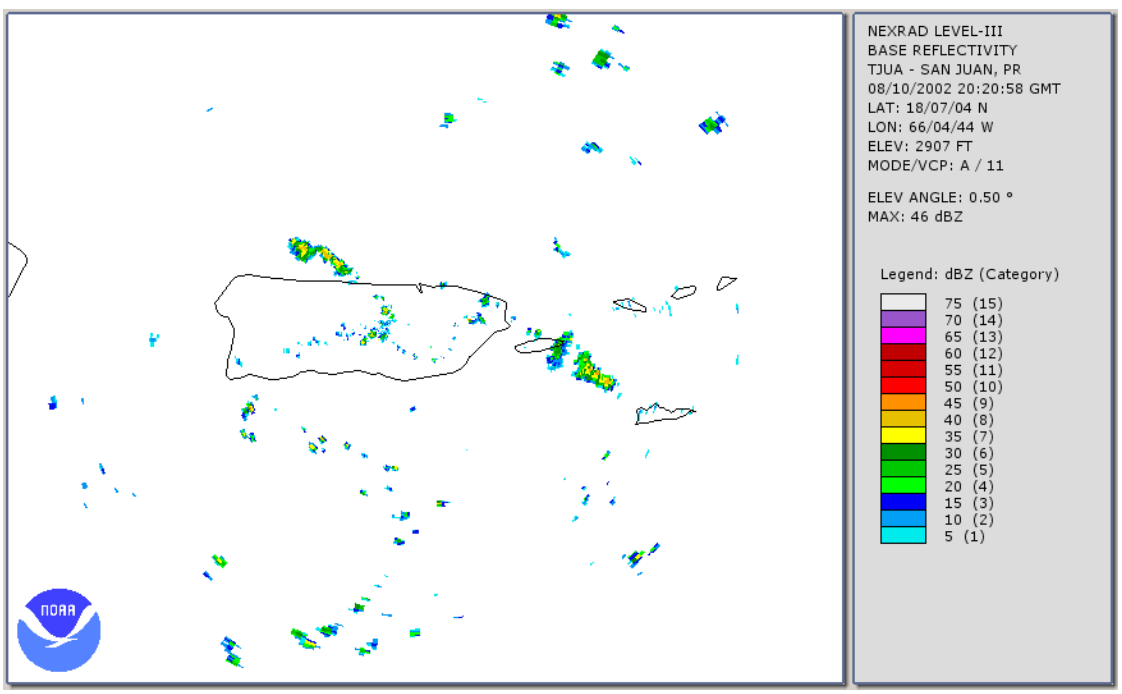

Figure 4-3 Image of the NOAA Weather and Climate Toolkit for TJUAN0R20020810_202000.mat Level III Data

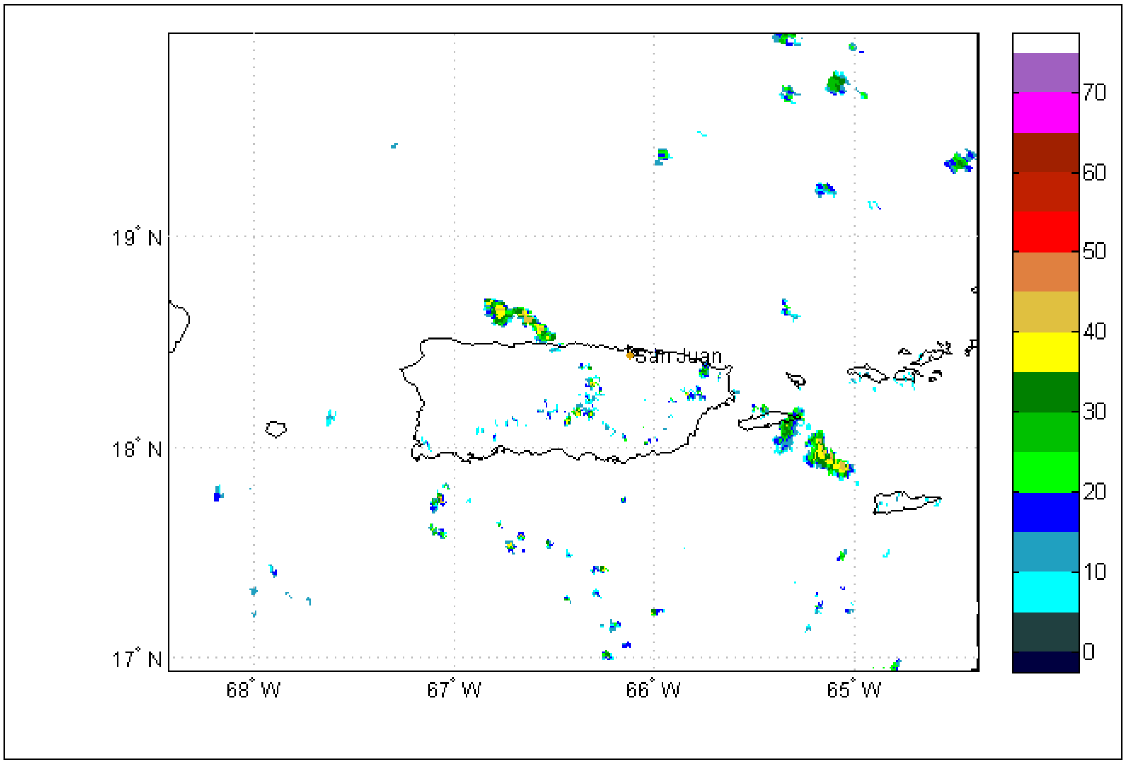

Figure 4-4 Image of Viewmapfile.m forTJUAN0R20020810_202000.mat Level III Data

At level III data, the results were the same, it can be appreciated the similarity of the images. The elevation angle for level III data was .5º.

Considering that the Level II and III data was for the same date and time, the elevation angle and information provided by the image, clearly showed that Level III data has lower resolution and less elevation angles to analyze data. Taking this into consideration, the reflectivity and rain rate modeling was performed using data Level II, and because 0.5º elevation angle does not have interference but is not constant, it varies from .35 º - .5º, it is going to be used the next available angle which is ~1.5º.

4.2 Reflectivity and Rain Rate Modeling

In order to perform the modeling, NEXRAD data was interpolated to the Rain Gauges location. It was only taken in consideration, the first zone which covers the 15km closest to the radar. The time period selected for the project was January 17 to December 17, 2002, in which only 18 out of 20 rain gauges were operating. Time series of 15 minutes intervals were developed for reflectivity and rain rate. Only data pairs considered were radar and rain gauge data were available at the same time.

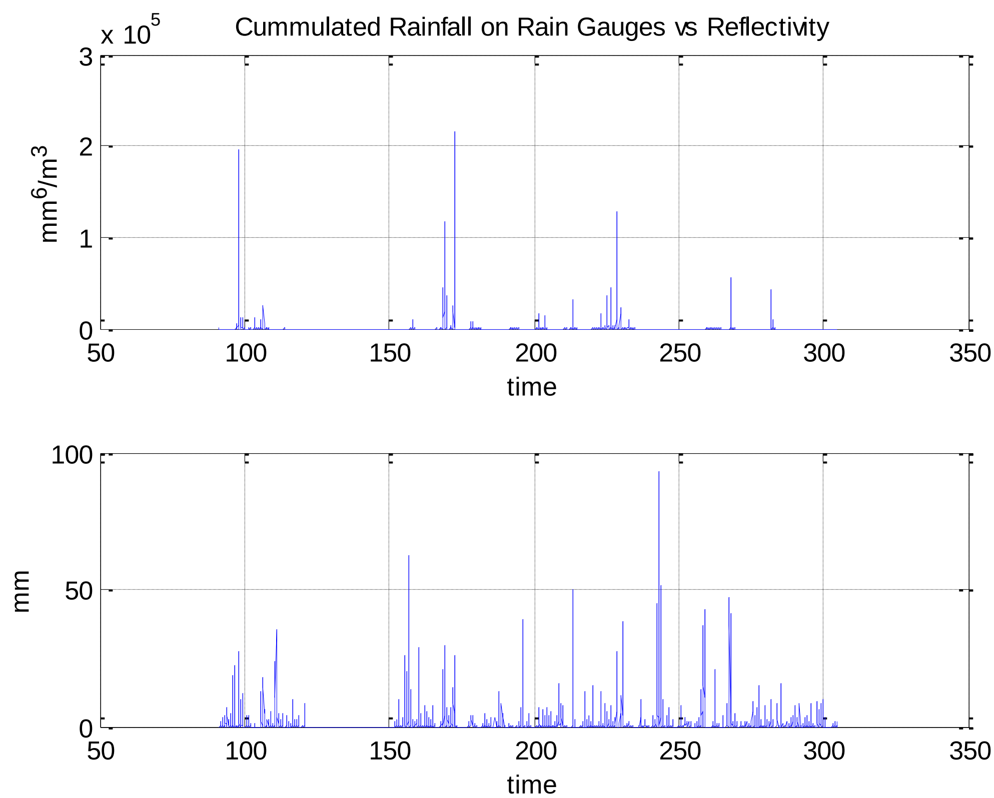

Figure 4-5 Image of the Reflectivity and Rain Rate for 2002

A total of 32,129 rain gauge and 21,005 reflectivity values were observed, only 1310 rainfall events, provide both rain rate and reflectivity information.

4.2.1 Dry Season:

Dry period: comprehend from January to March, May, November and December 2002. Typically, May is considered a rainy month, it is considered dry for analysis purposes, because for 2002 this was not the case.

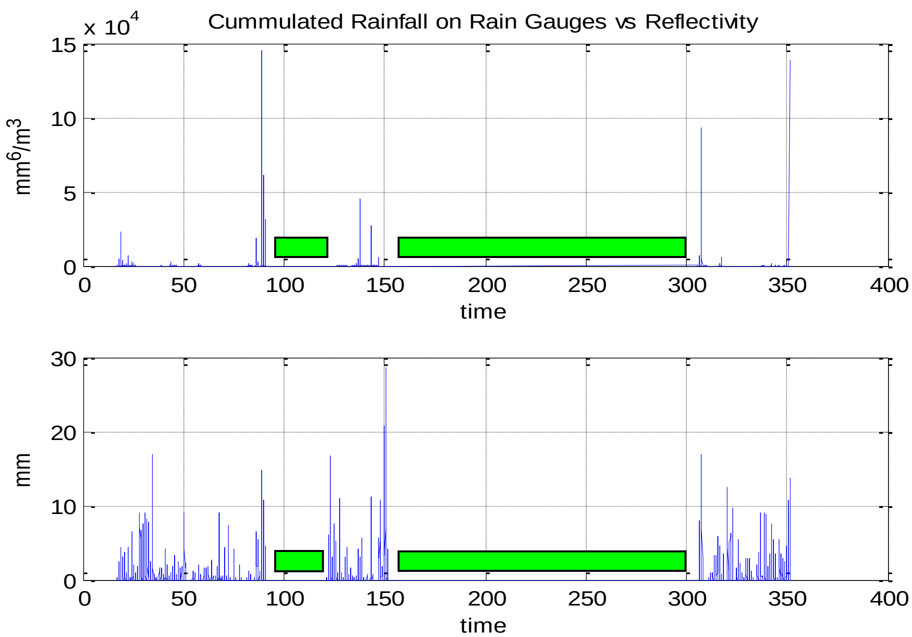

Figure 4-6 Comparison between rain rate and reflectivity during Dry season

The dry season included only 484 data *Z-R* pairs that registered rainfall and reflectivity data on the same time and space. Green bars are placed to denoted lack of data for being part of the wet season. The largest accumulated rainfall for the 15 minutes interval was 28.67mm recorded on May 31.

Z-R Function	a	b	SSE	R^2
Linearization Function	208.11	1.1531	44915	0.19
Unconstrained Optimization	208.11	2.8532	1791.4	0.19

Table 4-1 Estimated parameter for Dry season

Figure 4-7 shows the comparison between the observed and the estimated rainfall using equation $Z = a_i R^{b_i}\ i = 1,2$ with the estimated coefficients, which are shown in Table 4-1.

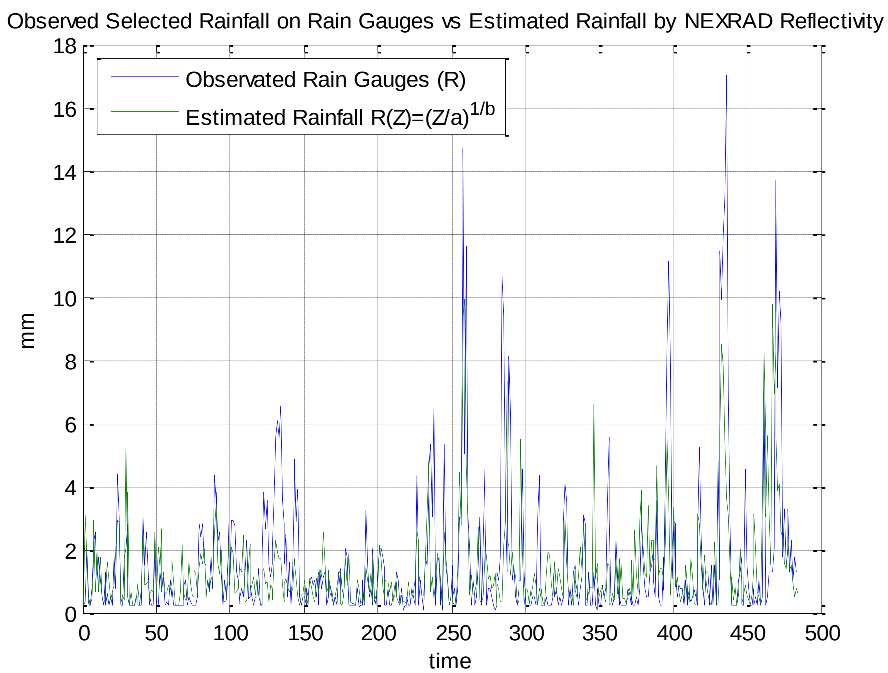

Figure 4-7 Observed and estimated accumulated rainfall for Dry Season

4.2.2 Wet Season:

Wet period: comprehend April and June to October, 2002.

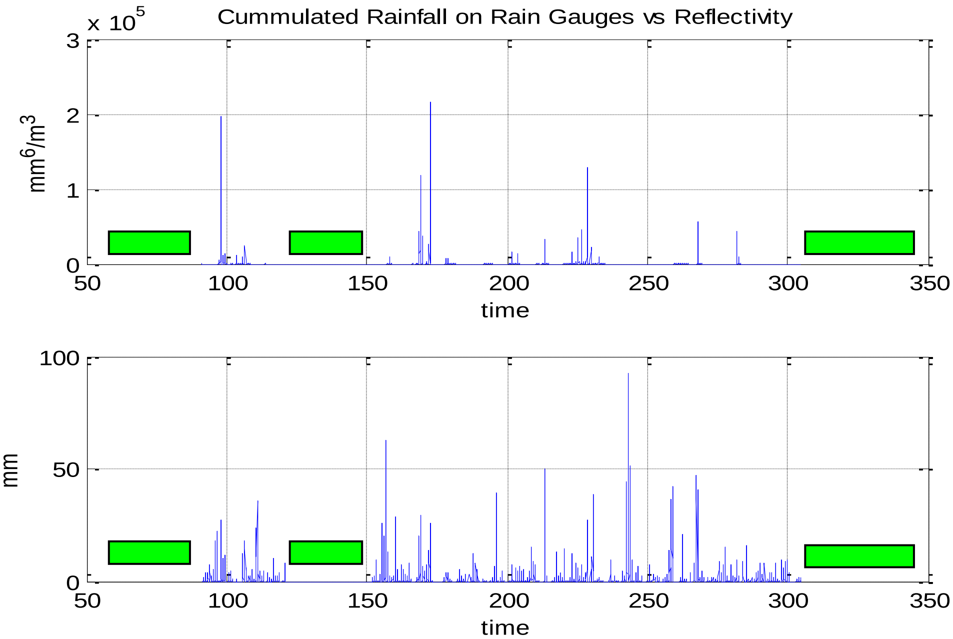

Figure 4-8 Comparison between rain rate and reflectivity during Wet season

The wet season included only 826 data *Z-R* pairs that registered rainfall and reflectivity data on the same time and space. Green bars are placed to denoted lack of data for being part of the dry season.

Z-R Function	a	b	SSE	R^2
Linearization Function	194.07	1.2885	36963	0.26
Unconstrained Optimization	27.365	3.046	12338	0.14

Table 4-2 Estimated parameter for Wet season

Figure 4-8 shows the comparison between the observed and the estimated rainfall using equation $Z = a_i R^{b_i}\ i = 1,2$ with the estimated coefficients, which are shown in Table 4-2.

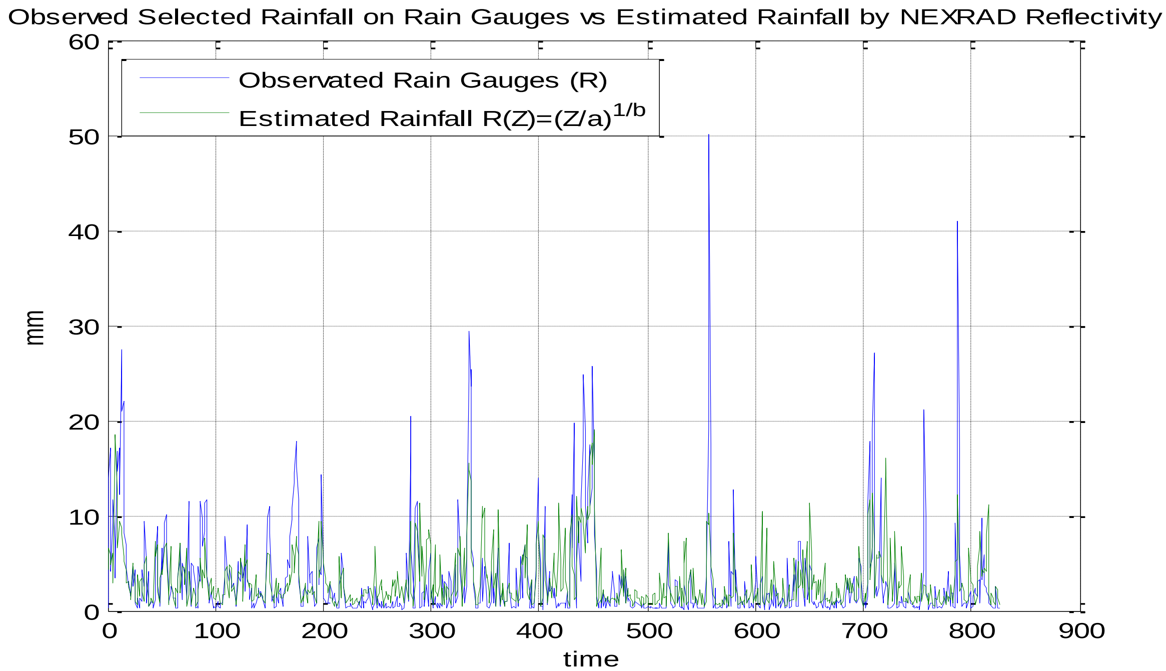

Figure 4-9 Observed and estimated accumulated rainfall for Wet Season

*Methods for *a*, *b*, *SSE* and R^2 calculations, were proposed by Ph.D Nazario Ramirez. Joan Manuel Castro aided in the development and troubleshooting of the software for these calculations.

4.3 Drawbacks:

4.3.1 Data Availability:

At the beginning of this Project, data intended for the calculations of the different *Z-R* relationships where XMRG. During the research process, it was discovered that such data was already process and that it could compromise the research for the *Z-R* relationships. The second form of data to be analyzed was the *Rmosaic* which was another level III data product that would produce the same results.

Data Level II was available, for use and analysis but it was very limited and time consuming to obtain and only Level III data was available for research. During the Level III data analysis, FTP servers were updated, making data Level II fully available and easy to download, providing software for the ease of the user. For the period under test there were 393 files downloaded from the FTP server, 27 GB of compress format, 227GB once uncompressed.

Data Level II is more complete and has higher resolution than Level III, but it also occupy more space and the processing is more time consuming. The files being so numerous and big in size, requires a big capacity storage server and powerful computer in order to process and make calculations. There are still problem with data updates where Level II data is incomplete or unavailable for the subsequent years. Proper follow up to the web site is needed to check for updates in the data.

5 CONCLUSIONS AND FUTURE WORK

The main objectives of this project were met successfully. These were, to develop the computer programs to aid in the process of calculation of *Z-R* relationship along the island defining different zones based on distance from the NEXRAD radar.

Several programs were develop for converting rain gauge and NEXRAD data into a format native to the computer software more commonly used in the research, MATLAB. The development of such software, required to be very accurate because a small error, in programming for analyzing and converting a large amount of data can be crucial, due to the sensitivity of such data.

This project was performed only in the 15 km closest to the NEXRAD radar and included all the rain gauges within that range. Future work must comprehend a period longer than one year, covering all wet and dry months, to obtain more accurate results. In addition, it is considered to expand these equations, in order to cover the entire island, taking in consideration the Earth curvature, elevation, distance from the radar, orographic correction, and neural networks. Future work can also include the use of other instruments, such as a disdrometer to measure drop size distribution. Once these new *Z-R* relationships are developed, might be used to validate the network of X-band radars that CASA project is working to install in the west part of the island with the intention of improving the sampling of precipitation of rain.

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[17] http://www.usbr.gov/pmts/rivers/publ/amsABQ01qpe.pdf -last verified 05-23-2011

[18]http://www.ou.edu/radar/z_r_relationships.pdf -last verified 05-23-2011

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APPENDIX A. MATLAB CODES

RGmap.m

```
%%%%%%%%%%%Generates the distribution of the RG in PR by zone%%%%%%%%%%%%
%Test file. Read geo.txt, which includes 886 coordinates of the points 5x5
%km, and plot it on the map. We can calculate - for each RG - dist to the
%radar, and find closest point on the "radar data" grid to compare data with
%2 May - add PR map (dots for now) from  allprpixels.mat var geo
% Also use usgs_stns_geo.mat , not a data0905_1h.mat RG coordinates

close all;
clear all;
clc

figure; worldmap([17.4 19],[-67.5 -65.1])%,'patch');%generates PR map
load allprpixels.mat geo;
geoshow(geo(:,2), geo(:,1),'DisplayType','point','Marker','.');

NEX_lat=18.118;      %Radar coord, to calculate distance for each
NEX_lon=-66.079;
hold on; plotm(NEX_lat,NEX_lon,'kd');
[latc,lonc] = scircle1(NEX_lat,NEX_lon,km2deg(15)); %plot circle at 15 km dist
plotm(latc, lonc,'b');
[latc,lonc] = scircle1(NEX_lat,NEX_lon,km2deg(50));
plotm(latc, lonc,'b');
[latc,lonc] = scircle1(NEX_lat,NEX_lon,km2deg(76));
plotm(latc, lonc,'b');
hold on

load usgs_stns_geo_125.mat; %coordinates of RG, stgeo 125x3
  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Now read coordinates of the RG stations FROM usgs_stns_geo.mat !

lat_rg=stgeo(:,3);      %lat for RG network - FROM usgs_stns_geo.mat !
long_rg=stgeo(:,2);
table(:,1)=stgeo(:,1);table(:,2)=stgeo(:,3);table(:,3)=stgeo(:,2); %creates table of RG lat long and distance from radar
s2=size(stgeo,1);        %125x3 , 125 RGs
```

```
d_NEX=zeros(1,s2);      %dist to NexRad for each RG, meters

zone_rg=ones(s2,1)*4;
clos=ones(s2,4);   %here will be index of the closest 4 rad pix

for i=1:s2  %for each RG
   [dist,az] = distance(NEX_lat,NEX_lon,lat_rg(i),long_rg(i))
   table(i,5)=deg2km(dist);
   d_NEX(i)=deg2km(dist);
   table(i,4)= d_NEX(i);
         if d_NEX(i)<=15; zone_rg(i)=1        %15 km
         elseif d_NEX(i)<=50                  %50 km
         elseif d_NEX(i)<=76;                 %76 km
         end
end %end of s2 loop

[c(:,1),c(:,2)] = sort(table(:,4));%sort RG by distance from the radar
A=max(find(c(:,1)<15));           %Number of RG closer than 15km from radar
for h=1:A  %for each RG closer than 15km
   RG15kmlist(h,1)=table(c(h,2),1)
   RG15kmlist(h,2)=table(c(h,2),2)
   RG15kmlist(h,3)=table(c(h,2),3)
   RG15kmlist(h,4)=table(c(h,2),4)
end

z1=0;z2=0;z3=0;z4=0;
for i=1:s2  %for each RG
   if zone_rg(i) == 1
      plotm(lat_rg(i), long_rg(i),'g.');z1=z1+1;
    elseif zone_rg(i) == 2
       plotm(lat_rg(i), long_rg(i),'go');z2=z2+1;
    elseif zone_rg(i) == 3
       plotm(lat_rg(i), long_rg(i),'gx');z3=z3+1;
    else plotm(lat_rg(i), long_rg(i),'g+');z4=z4+1;
   end
end

hold on
```

Read_Xls_to_Mat_2_Columns.m

```
clear all
close all
clc

d=dir('*2002*.xls');
for l=1:1:size(d);
   archivo=d(l).name;
   archivo
   [data,fecha]=xlsread(archivo);
   s=size(data);
   t1=[str2num(fecha{1,2}(1:4)) str2num(fecha{1,2}(5:6)) str2num(fecha{1,2}(7:8))
   str2num(fecha{1,3}(1:2)) str2num(fecha{1,3}(3:4)) str2num(fecha{1,3}(5:6))];
   dato=[t1 0 data(1,1)];

   for i=2:s(1)
      t2=[str2num(fecha{i,2}(1:4)) str2num(fecha{i,2}(5:6)) str2num(fecha{i,2}(7:8))
      str2num(fecha{i,3}(1:2)) str2num(fecha{i,3}(3:4)) str2num(fecha{i,3}(5:6))];
      delta=etime(t2,t1);
      dato=[dato;t2 delta data(i,1)];
      t1=[str2num(fecha{i,2}(1:4)) str2num(fecha{i,2}(5:6)) str2num(fecha{i,2}(7:8))
      str2num(fecha{i,3}(1:2)) str2num(fecha{i,3}(3:4)) str2num(fecha{1,3}(5:6))];
   end

   savefile = [archivo(1:(length(archivo)-4))];          %Obtien la raiz del nombre
   save([savefile],'dato')   %Indica las variables a guardar
end
```

read_xls_to_mat_3_columns.m

```
clear all
close all
clc
d=dir('*2006*.xls');
for l=1:1:size(d);
   archivo=d(l).name
   archivo
   [data,fecha]=xlsread(archivo);
   s=size(data);
   t1=[str2num(fecha{1,1}(1:4)) str2num(fecha{1,1}(5:6)) str2num(fecha{1,1}(7:8))
   str2num(fecha{1,2}(1:2)) str2num(fecha{1,2}(3:4)) str2num(fecha{1,2}(5:6))];
   dato=[t1 0 data(1,1)];
   for i=2:1:s
      t2=[str2num(fecha{i,1}(1:4)) str2num(fecha{i,1}(5:6)) str2num(fecha{i,1}(7:8))
      str2num(fecha{i,2}(1:2)) str2num(fecha{i,2}(3:4)) str2num(fecha{i,2}(5:6))];
      delta=etime(t2,t1);
      dato=[dato;t2 delta data(i,1)];
      t1=[str2num(fecha{i,1}(1:4)) str2num(fecha{i,1}(5:6)) str2num(fecha{i,1}(7:8))
      str2num(fecha{i,2}(1:2)) str2num(fecha{i,2}(3:4)) str2num(fecha{i,2}(5:6))];
   end
    savefile = [archivo(1:(length(archivo)-13))];          %Obtien la raiz del nombre
   save([savefile],'dato')   %Indica las variables a guardar
end
```

RGVerification.m

```
%This program is for verification of RG data, month by month
%uses usgs_stns_geo_127.mat for Rg coordinates,
%RG_closest_5.mat for clos (closest 4 RG for each RG)
close all;
clear all;

ans= 2005; %input('Ano que se desea trabajar:  ');
%mes= input('Mes que se desea trabajar:  ');
in= 4; %input('Numero de pulgadas maximo:  ');
load usgs_stns_geo_127.mat; %coordinates of RG, stgeo 125x3
%Now read coordinates of the RG stations FROM usgs_stns_geo.mat !
load RG_closest_5.mat   % clos , 127x5 (4 closest RG
lat_rg=stgeo(:,3);      %lat for RG network - FROM usgs_stns_geo.mat !
long_rg=stgeo(:,2);
s1=885; %885 x 696
s2=length(stgeo);         %127x3 , 127 RGs
load zone_rg.mat;   % zone_rg - array of zone for each RG

name=num2str(ans);
nam=name(3:4);
%nam=str2num(name,1:3);
month_rg=['data01',nam,'_1h.mat';'data02',nam,'_1h.mat';'data03',nam,'_1h.mat';'data03',nam,'_1h.mat';'data05',nam,'_1h.mat';...
     'data06',nam,'_1h.mat';'data07',nam,'_1h.mat';'data08',nam,'_1h.mat';'data09',nam,'_1h.mat';'data10',nam,'_1h.mat';...
     'data11',nam,'_1h.mat';'data12',nam,'_1h.mat';];    %9x15
%estim_month=[1,2,3,4,5,6,7,8,9,10,11,12];  %available monthes for reading right coefficients of Z_R relation
dry_months=[1,2,3,4];
wet_months=[5,6,7,8,9,10,11,12];
a2=stgeo(:,1);  %% names of all RG, full list 127
[c1,c2]=size(month_rg);

for m=1:12; %for each dry month Jan, Feb, March, and December
   load(['H:\Maxtor backup\XIOMY-LAPTOP\C\Users\Xiomyx\Documents\Thesis\Sandra\Data',num2str(ans),'\',month_rg(m,:)]);
%load RG data, rainate in inches, 102x747
   %look for existing in this month RG (107 from 125)
   a1=data(:,1);   % names of existing RG, like 50010500. 107 elems
   k1=length(a1);   %k1=107
   id_nan=find(isnan(data));   %look for NaN elements in RG data, they could destroy all the calculations
   if isempty(id_nan)~=1
      data(id_nan)=0;       %put 0s there
```

```
  end
  for i=1:k1   %1:107 , for each rg from current month
     mm=max(max(data(i,4:end)));
     if mm>in %we look for suspicious data, where rain is> 3 inches (76.2 mm/hr)
        disp(['Suspicious elem om month ',num2str(m),' is in data row ',num2str(i),' and it is ',num2str(mm)]);
        id=find(stgeo(:,1)==data(i,1)); %we look for the index of current RG(from data) in stgeo full list.
        idd1=find(a1==stgeo(clos(id,2)));%we need back indexing too -because clos(id,2)is closest RG in full list a2, but we need in
current list (a1)
        idd2=find(a1==stgeo(clos(id,3)));%so idd is index of closest RG in current data (line actually)
        idd3=find(a1==stgeo(clos(id,4)));
        idd4=find(a1==stgeo(clos(id,5)));
        if isempty(idd1)~=1
        d1=data(idd1,4:end);    %we select from the data line where first closest RG, and plot it too;
        else d1=ones(1,length(data)-3)*-0.5; % mark unexisting rg as -1
        end
        if isempty(idd2)~=1
        d2=data(idd2,4:end);    %start with 2nd, because 1st is the same (distance=0)
        else d2=ones(1,length(data)-3)*-0.5; % mark unexisting rg as -1
        end
        if isempty(idd3)~=1
        d3=data(idd3,4:end);    %start with 2nd, because 1st is the same (distance=0)
        else d3=ones(1,length(data)-3)*-0.5; % mark unexisting rg as -1
        end
        if isempty(idd4)~=1
        d4=data(idd4,4:end);    %start with 2nd, because 1st is the same (distance=0)
        else d4=ones(1,length(data)-3)*-0.5; % mark unexisting rg as -1
        end
        lnt=length(data)-3;
    figure;plot(1:lnt,data(i,4:end),'r');hold on;
    plot(1:lnt,d1,'g');
    plot(1:lnt,d2,'b');
    plot(1:lnt,d3,'m');
    plot(1:lnt,d4,'b'); hold off;legend('RG','clos1','clos2','clos3','clos4',5);
    xlabel(['Hours of ',num2str(m),' month ',num2str(ans)]);ylabel('RG data, inch');title(['RG #',num2str(a2(i)),' and closest to it.']);

    end %end if
  end
end
```

Linux subroutine created to remove .tar and .Z compression

```
for j in {2000..2003}
do      echo $j
        for i in 01 02 03 04 05 06 07 08 09 10 11 12;
        do      mkdir $j-$i;
                echo $j-$i;
                        for archivo in 6500TJUA$j$i*;
                        do      echo $archivo;
                                tar xvf $archivo;
                                gunzip *.Z;
                                find . -name "TJUA$j$i*"  -exec mv {} /home/xortiz/xortiz/Prueba\ 4/prueba/$j-$i \;
                        done
        done
done
```

MATLAB program and functions to convert NEXRAD data Files to .mat

Read_Nexrad_Level_2.m

Created by: Joan Manuel Castro

```
clear all;
clc;
close all;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
year='2000'; %Ano para buscar los archivos de reflectividad
latitud=18.118; %Latitud del radar  La > 0 North ~~ La < 0  South  para  -90 <= La <= 90
longitud=-66.079; %Longitud de radar Lo < 0 W ~~ Lo > 0 East para -180 <= Lo <= 180
directorio=[cd 'Z']
mkdir(directorio)
c=dir(['*TJUA*']);  %Busca los archivos de Reflectividad dentro del folder
angulo=2; %(1.3-1.5)
for i=1:length(c) %Evaluar todo el banco de datos relacionados con la reflectividad
   i
   c(i,1).name
   [product]=read_binary_level_2([c(i,1).name],latitud,longitud,str2num(year));
   [XI,YI,ZI]=graphic_level_2(product,angulo); %Mostrar la figura
   save([ cd 'Z\' c(i,1).name],'ZI','XI','YI');
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Read_Binary_Level_2.m

Created by: Joan Manuel Castro

```
function [product]=read_binary_level_2(archivo,latitud,longitud,yearf)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fid=fopen(archivo)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cod=fread(fid);
nbytes=2432;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
nbhead=24;
head=cod(1:nbhead);
%head=fread(fid,[1 nbhead])';
%fclose(fid);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
year=1970:yearf-1;
bisieto=length(find(mod(year,4)==0));
totaljulian=365*length(year)+bisieto;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Head data
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
name=char(head(1:12)');
juliano=bin2dec([dec2bin(head(13),8) dec2bin(head(14),8) dec2bin(head(15),8) dec2bin(head(16),8)])-totaljulian; %julian day
tiempo=0.001*bin2dec([dec2bin(head(17),8) dec2bin(head(18),8) dec2bin(head(19),8) dec2bin(head(20),8)]); %seconds
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Message Header
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
levels1=13;
ldata1=nbhead+levels1*nbytes;
data1=cod(nbhead+1:ldata1);
%fid=fopen(archivo)
%data1=fread(fid,[nbhead+1 ldata1])';
seedato1=reshape(data1,nbytes,[]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% sizehalf=bin2dec([dec2bin(seedato1(13,:),8) dec2bin(seedato1(14,:),8)]); %halfword = 2 btyes
% canal=seedato1(15,:)'; %ID Channel (0 - Non Redundant Size, 1 - Redundant Channel 1, ...)
% mensaje=seedato1(16,:)'; %Message for 1 - 14
% idseq=dec2hex(bin2dec([dec2bin(seedato1(17,:),8) dec2bin(seedato1(18,:),8)]));
% julian=bin2dec([dec2bin(seedato1(19,:),8) dec2bin(seedato1(20,:),8)]); %julian day
% tiemp=0.001*bin2dec([dec2bin(seedato1(21,:),8) dec2bin(seedato1(22,:),8) dec2bin(seedato1(23,:),8) dec2bin(seedato1(24,:),8)]);
%seconds
% nummeng=bin2dec([dec2bin(seedato1(25,:),8) dec2bin(seedato1(26,:),8)]); %Number of messages
% segnumber=bin2dec([dec2bin(seedato1(27,:),8) dec2bin(seedato1(28,:),8)]); %segment number
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
levels2=24;
ldata2=ldata1+levels2*nbytes;
data2=cod(ldata1+1:ldata2);
seedato2=reshape(data2,nbytes,[]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% sizehalf2=bin2dec([dec2bin(seedato2(13,:),8) dec2bin(seedato2(14,:),8)]); %halfword = 2 btyes
% canal2=seedato2(15,:)'; %ID Channel (0 - Non Redundant Size, 1 - Redundant Channel 1, ...)
% mensaje2=seedato2(16,:)'; %Message for 1 - 14
% idseq2=dec2hex(bin2dec([dec2bin(seedato2(17,:),8) dec2bin(seedato2(18,:),8)]));
% julian2=bin2dec([dec2bin(seedato2(19,:),8) dec2bin(seedato2(20,:),8)]); %julian day
% tiemp2=0.001*bin2dec([dec2bin(seedato2(21,:),8) dec2bin(seedato2(22,:),8) dec2bin(seedato2(23,:),8) dec2bin(seedato2(24,:),8)]);
%seconds
% nummeng2=bin2dec([dec2bin(seedato2(25,:),8) dec2bin(seedato2(26,:),8)]); %Number of messages
% segnumber2=bin2dec([dec2bin(seedato2(27,:),8) dec2bin(seedato2(28,:),8)]); %segment number
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
data3=cod(ldata2+1:end);
if mod(length(data3),nbytes)==0
seedato3=reshape(data3,nbytes,[]);
sizehalf3=bin2dec([dec2bin(seedato3(13,:),8) dec2bin(seedato3(14,:),8)]); %halfword = 2 btyes
canal3=seedato3(15,:)'; %ID Channel (0 - Non Redundant Size, 1 - Redundant Channel 1, ...)
mensaje3=seedato3(16,:)'; %Message for 1 - 14
idseq3=dec2hex(bin2dec([dec2bin(seedato3(17,:),8) dec2bin(seedato3(18,:),8)]));
julian3=bin2dec([dec2bin(seedato3(19,:),8) dec2bin(seedato3(20,:),8)])-totaljulian; %julian day
tiemp3=0.001*bin2dec([dec2bin(seedato3(21,:),8) dec2bin(seedato3(22,:),8) dec2bin(seedato3(23,:),8) dec2bin(seedato3(24,:),8)]);
%seconds
nummeng3=bin2dec([dec2bin(seedato3(25,:),8) dec2bin(seedato3(26,:),8)]); %Number of messages
segnumber3=bin2dec([dec2bin(seedato3(27,:),8) dec2bin(seedato3(28,:),8)]); %segment number
clear cod
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
colectiempo=0.001*bin2dec([dec2bin(seedato3(29,:),8) dec2bin(seedato3(30,:),8) dec2bin(seedato3(31,:),8)
dec2bin(seedato3(32,:),8)]); %seconds
juliano3=bin2dec([dec2bin(seedato3(33,:),8) dec2bin(seedato3(34,:),8)])-totaljulian; %julian day
rango=0.1*bin2dec([dec2bin(seedato3(35,:),8) dec2bin(seedato3(36,:),8)]); %rango (km)
azimuth=(180/4096)*(bin2dec([dec2bin(seedato3(37,:),8) dec2bin(seedato3(38,:),8)])/8); %azimuth angle
radial_num_scan=bin2dec([dec2bin(seedato3(39,:),8) dec2bin(seedato3(40,:),8)]); %Radial number withnthe elevation scan.
radial_status=bin2dec([dec2bin(seedato3(41,:),8) dec2bin(seedato3(42,:),8)]); %Status - Start o new elevaton, intermediate radial,
%end of elevation, beginning of volumen scan, end of volumen scan
elevation_angle=(180/4096)*(bin2dec([dec2bin(seedato3(43,:),8) dec2bin(seedato3(44,:),8)])/8); %Elevation angle 22
rda_ele_num=bin2dec([dec2bin(seedato3(45,:),8) dec2bin(seedato3(46,:),8)]); %RDA elevation number 23
range_reflec=bin2dec([dec2bin(seedato3(47,:),8) dec2bin(seedato3(48,:),8)]); %Range of reflectivity data (meters) 24
range_doppler=bin2dec([dec2bin(seedato3(49,:),8) dec2bin(seedato3(50,:),8)]); %Doppler data gate size (meters) 25
reflec_gates=bin2dec([dec2bin(seedato3(51,:),8) dec2bin(seedato3(52,:),8)]); %Reflectivity gates 26
```

```
doppler_gates=bin2dec([dec2bin(seedato3(53,:),8) dec2bin(seedato3(54,:),8)]); %Doppler gates 27
num_reflec_gates=bin2dec([dec2bin(seedato3(55,:),8) dec2bin(seedato3(56,:),8)]); %Number of reflectivity gates 28
spectrum_velocity=bin2dec([dec2bin(seedato3(57,:),8) dec2bin(seedato3(58,:),8)]); %Spectrum width data o number of velocity
sector_num=bin2dec([dec2bin(seedato3(59,:),8) dec2bin(seedato3(60,:),8)]); %Sector number 30
base=bin2dec([dec2bin(seedato3(61,:),8) dec2bin(seedato3(62,:),8)]); %31
expo=bin2dec([dec2bin(seedato3(63,:),8) dec2bin(seedato3(64,:),8)]); %32
% signo=find(expo>=2^15); % expo(sg=expo-2^16;
gain_cali_cons=base.*expo; %system gain calibration constant (dB)
reflec_pointer=bin2dec([dec2bin(seedato3(65,:),8) dec2bin(seedato3(66,:),8)]); %byte # from start of digital radar header 33
velo_pointer=bin2dec([dec2bin(seedato3(67,:),8) dec2bin(seedato3(68,:),8)]); %byte # from start of digital radar header 34
spectrum_pointer=bin2dec([dec2bin(seedato3(69,:),8) dec2bin(seedato3(70,:),8)]); %byte # from start of digital radar header 35
dopp_velo_res=bin2dec([dec2bin(seedato3(71,:),8) dec2bin(seedato3(72,:),8)]); %Doppler velocity resolution 2 =0.5 m/s 4 = 1.0 m/s
36
vol_cov_patt=bin2dec([dec2bin(seedato3(73,:),8) dec2bin(seedato3(74,:),8)]); %Volume coverage pattern 11 = 16 elev. scans/ 5 mins
%21 = 11 elev. scans/6 mins. 31 = elev. scans/ 10 mins. 32 = 7 elev. scans/ 10 mins 37
reflec_pointer_rda=bin2dec([dec2bin(seedato3(83,:),8) dec2bin(seedato3(84,:),8)]); %reflectivity data pointer RDA 42
velo_pointer_rda=bin2dec([dec2bin(seedato3(85,:),8) dec2bin(seedato3(86,:),8)]); %velocity data pointer RDA 43
spectrum_pointer_rda=bin2dec([dec2bin(seedato3(87,:),8) dec2bin(seedato3(88,:),8)]); %spectrum data pointer RDA 44
nyquist=0.01*bin2dec([dec2bin(seedato3(89,:),8) dec2bin(seedato3(90,:),8)]); %Nyquist velocity m/s 45
att_factor=0.001*bin2dec([dec2bin(seedato3(91,:),8) dec2bin(seedato3(92,:),8)]); %Atmospheric attenuation factor 46
threshold=0.1*bin2dec([dec2bin(seedato3(93,:),8) dec2bin(seedato3(94,:),8)]); %Threshold parameter for min diff in echo power
(watts)
reflectividad=((seedato3(125:end,:)-2)/2)-32;
% espectro=((seedato3(125:end,:)-2)/2)-63.5; % velocidad=((seedato3(125:end,:)-2))-127;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
pointers=[rda_ele_num elevation_angle reflec_pointer velo_pointer spectrum_pointer azimuth];
pointers=pointers';
vueltas=1;
clear data2 data3 seedato2 seedato3
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for rda_pases=1:max(rda_ele_num)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  pases=find(rda_ele_num==rda_pases);
  reflect_inicial=min(reflec_pointer(pases));
  reflect_final=min(velo_pointer(pases));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  if reflect_final==0 && reflect_inicial>0 && rda_pases==1
    reflect_final=460;
  elseif reflect_final==0 && reflect_inicial>0
    reflect_final=460-reflect_inicial;
  elseif reflect_inicial>0
```

```
        reflect_final=reflect_final-reflect_inicial;
    end
    if reflect_inicial>0
        [orden,orpases]=sort(azimuth(pases));
        product(vueltas).radial_scans=max(radial_num_scan(pases(orpases)));
        product(vueltas).reflect_inicial=min(reflec_pointer(pases(orpases)));
        product(vueltas).reflect_final=min(velo_pointer(pases(orpases)));
        product(vueltas).threshold=max(threshold(pases(orpases)));
        product(vueltas).elevacion=elevation_angle(pases(orpases));
        product(vueltas).azimuto=azimuth(pases(orpases));
        product(vueltas).nyquist=nyquist(pases(orpases));
        product(vueltas).att_factor=att_factor(pases(orpases));
        product(vueltas).vol_cov_patt=vol_cov_patt(pases(orpases));
        product(vueltas).year=yearf;
        product(vueltas).julian=julian3(pases(orpases));
        product(vueltas).time=tiemp3(pases(orpases));
        product(vueltas).time=timedim(product(vueltas).time,'sec','hms');
        product(vueltas).time=time2str(product(vueltas).time,'24','hms','hms');
        grid_pases=nm2deg(0.54*repmat([1:reflect_final]',1,length(pases)));
        altura_radar=0.001*(2907/3.2808);

        distancia=altura_radar + deg2km(grid_pases)*(inv(cos(0.3*pi/180))-1);
        la_angulo=cos((360-repmat(product(vueltas).azimuto',reflect_final,1))*pi/180);
        lo_angulo=sin(repmat(product(vueltas).azimuto',reflect_final,1)*pi/180);
        product(vueltas).La=latitud+grid_pases.*la_angulo;
        product(vueltas).Lo=longitud+grid_pases.*lo_angulo;
        product(vueltas).datapase=reflectividad(1:reflect_final,pases(orpases));
%       datapasen=reshape(product(vueltas).datapase,(reflect_final)*length(pases),1);
%       miss=find(datapasen<0);
%       datapasen(miss)=min(datapasen);
%       product(vueltas).datapasen=reshape(datapasen,(reflect_final),length(pases));
        vueltas=vueltas+1;
    end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
end
product=product';
else
    product=[];
end
fclose(fid);
```

Graphic_Level_2.m

Created by: Joan Manuel Castro

```
function [XI,YI,ZI]=graphic_level_2(product,angulo)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Genera una figura en coordenadas rectangulares de la reflectividad dentro
%de rango del radar NEXDAR (hasta 250 nm)
%product: archivo donde se almacena la informacion recopilada en NEXDAR
%Nivel 2 en funcion del angulo de elevacion
%angulo (entre 1 y max(product)): valor que se asigna al angulo de elevacion
% ajustado por el radar en el momento del pase circular
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
n=size(product(angulo).La); %Determina la resolucion rectangular de la imagen
Lai=reshape(product(angulo).La,n(1)*n(2),1); %Reacomoda el matriz de latitud en un vector de n(1)*n(2) filas x 1 columna
Loi=reshape(product(angulo).Lo,n(1)*n(2),1); %Reacomoda el matriz de longitud en un vector de n(1)*n(2) filas x 1 columna
D=reshape(product(angulo).datapase,n(1)*n(2),1); %Reacomoda el matriz de los datos de reflectividad en un vector de n(1)*n(2)
filas x 1 columna
miss=find(D==min(D)); %Busca los valores minimos en el vector
D(miss)=NaN;%Inf; %Los convierte en NaN, como efecto de manipular la grafica y la figura.
miss=[];
miss=find(D<5); %Tambien busca los valores menores al umbral D<5
D(miss)=NaN; %Los convierte en NaN, como efecto de manipular la grafica y la figura.
alldata=[Loi Lai D]; %Los almancena en un nuevo vector de tres columnas y n(1)*n(2) filas.
limites=minmax(alldata(:,1:2)'); %Busca los limites superiores e inferiores de latitud y longitud


limites =[
  -68.1474  -64.0106
   16.0496   20.1864];
[XI,YI] = meshgrid(limites(1,1):1/110.7:limites(1,2),limites(2,1):1/110.7:limites(2,2)); %Define un nuevo rango de valores de
l%atitud y longitud reduciendo la resolucion espacial a 0.01 grados
ZI=griddata(alldata(:,1),alldata(:,2),alldata(:,3),XI,YI); %Interpola la reflectividad observada en funcion del nuevo conjunto de
cuadros (pixels)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Accum_Rain_Reflect_Station.m

```
clear all;
clc;
close all;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
load data_2002_15min_b %Contiene la cantidad de lluvia caida cada 15 minutos en las 18 estaciones mas cercanas al radar (comdata)
%y la reflectividad (dB) de los 20 cuadros mas cercanos a cada estacion (data). Tambien incluye una variable que indica que los 18
%cuadros mas cercanos a cada estacion de lluvia (rain gauge)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
comdata=comdata(17:end,:);  %Las series de tiempo para cada estacion en funcion de la lluvia acumulada cada 15 minutos
data=data(17:end,:); %Un estimado de la reflectividad detectada por el radar en los cuadros mas cercanos cada estación cada
%15 minutos.
timestep=timestep(17:end); %Periodo de analisis para R y Z

% comdata=comdata(17:size(comdata,1)-1,:);  %Las series de tiempo para cada estacion en funcion de la lluvia acumulada cada 15
minutos
% data=data(18:size(data,1),:); %Un estimado de la reflectividad detectada por el radar en los cuadros mas cercanos cada estación
dentro
% 15 minutos.
% timestep=timestep(18:length(timestep)); %Periodo de analisis para R y Z

% low=[17 91;121 152;305 366];
% alltime=[];
% timeselec=find(timestep>=low(1,1) & timestep<low(1,2));
% alltime=[alltime;timeselec'];
% timeselec=[];timeselec=find(timestep>=low(2,1) & timestep<low(2,2));
% alltime=[alltime;timeselec'];
% timeselec=[];timeselec=find(timestep>=low(3,1) & timestep<low(3,2));
% alltime=[alltime;timeselec'];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
high=[91 121;152 305];
alltime=[];
timeselec=find(timestep>=high(1,1) & timestep<high(1,2));
alltime=[alltime;timeselec'];
timeselec=[];timeselec=find(timestep>=high(2,1) & timestep<high(2,2));
alltime=[alltime;timeselec'];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
R=sum(comdata')'; %Lluvia acumulada en la estaciones mas cercanas al radar.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Conversion de reflectividad (dB) a reflectividad (mm^6/m^3) en los cuadros
```

```
%donde tenemos constancia que hay información en las estaciones
Zf=10.^(0.1*(data(:,compare))); %Z(dB)=10*log10(Z(mm^/m^3)) -> Despejar para Z( Z(mm^6/m^3)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Busca aquellos puntos donde Z(dB)<5 y se sustitye la reflectividad (mm^6/m3) = 0
Z=zeros(size(Zf));
for i=1:size(Zf,2)
  pos=find(Zf(:,i)>1);
  Z(pos,i)=Zf(pos,i);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Z=sum(Z')'; %Reflectividad acumulada en las estaciones donde tengamos informacion en las estaciones
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Rf=R(alltime);
Zf=Z(alltime);
%Se encontró que aparentemente hay una diferencia de 15 minutos entre las
%observaciones de lluvia y las observaciones de radar aun cuando se
%consideró previamente que las observaciones de radar estan sincronizadas
%en el horario (UTC), mientras las estaciones en tierra están sicronizadas
%en el horario local (- 4 h UTC) .
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Rf=R(1:length(R)-1); %Lluvia acumulada en Puerto Rico
sel=find(Rf<=1e-4); %Aquellas interpolaciones menor de 1e-4 se consideraran como cero
Rf(sel)=0;
%Zf=Z(2:end); %Reflectividad acumulada considerando los 15 minutos de diferencia.
%timestep=timestep(2:end);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1)
subplot(2,1,1)
plot(timestep(alltime),Zf);grid
title('Cummulated Rainfall on Rain Gauges vs Reflectivity')
xlabel('time')
ylabel('mm^6/m^3')
subplot(2,1,2)
plot(timestep(alltime),Rf);grid
xlabel('time')
ylabel('mm')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Buscar solamente las estaciones donde haya caido lluvia y el radar haya
%dectectado reflectividad en la atmosfera
sel=find(Zf>0); %Si la reflectividad es mayor a 0 mm^6/m^3
timestep=timestep(sel);
Zc=Zf(sel); %Seleccionamos los valores de reflectividad mayores a 0 unidades
```

```
Rc=Rf(sel); %Igualmente seleccionamos la lluvia acumulada en 15 minutos
sel=find(Rc>0); %Buscamos si hubo lluvia acumulada en cada instante
timestep=timestep(sel);
Rc=Rc(sel); %Seleccionamos solamente en aquellos intervalos donde se registró lluvia acumulada en el radar
Zc=Zc(sel);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Regresion lognormal en funcion de la lluvia de las estaciones R
X=[ones(length(Zc),1) log(Rc)];  %constante y log natural
a=(X'*X)^-1*X'*log(Zc); %Estimados iniciales de (a, b)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
logZe=X*a; %Estimado de la funcion lognormal
logZo=log(Zc); %Observado de la reflectividad
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
e=logZo-logZe;
SSE=e'*e;
SST=sum(logZo.^2)-length(logZo)*mean(logZo).^2;
R2=1-SSE/SST;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(2)
plot([logZo logZe]);grid
title('Observed and Estimate lognormal Reflectivity during 2002')
xlabel('samples')
ylabel('log(Z)')
legend('log(Z)','log(a)+b*log(R)')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(3);
subplot(2,1,1)
plot(Zc);grid
title('Observed Selected Reflectivity on NEXRAD')
xlabel('time')
ylabel('mm^6/m^3')
subplot(2,1,2)
Ze=250*Rc.^1.2;
plot([Ze]);grid
title('Estimated Reflectivity Z(R)=250*R^1^.^2')
xlabel('time')
ylabel('mm^6/m^3')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% ez1=Zc-Ze;
% SSEz1=ez1'*ez1;
% SSTz1=sum(Zc.^2)-length(Zc)*mean(Zc).^2;
% R2z1=1-SSEz1/SSTz1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
figure(4)
subplot(2,1,1)
Ree=(Zc/250).^(1/1.2);
plot([Rc]);grid
title('Observed Selected Rainfall on Rain Gauges')
xlabel('time')
ylabel('mm')
subplot(2,1,2)
plot([Ree]);grid
title('Estimated Rainfall R(Z)=(Z/250)^1^/^1^.^2')
xlabel('time')
ylabel('mm')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% er1=Rc-Ree;
% SSEr1=er1'*er1;
% SSTr1=sum(Rc.^2)-length(Rc)*mean(Rc).^2;
% R2r1=1-SSEr1/SSTr1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
xi=[exp(a(1)) a(2)]; %Valores iniciales de a, b
x=fminunc(@(x) reflectivity(x,Zc,Rc),xi); %Optimizacion para buscar los a, b optimos para estimar la cantidad de lluvia caida
% %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Observado vs Estimado de Z
figure(5)
subplot(2,1,1)
plot(Zc);grid
title('Observed Selected Reflectivity on NEXRAD')
xlabel('time')
ylabel('mm^6/m^3')
subplot(2,1,2)
Zee=x(1)*Rc.^x(2);
plot([Zee]);grid
title('Estimated Reflectivity Z(R)=aR^b')
xlabel('time')
ylabel('mm^6/m^3')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% ez=Zc-Zee;
% SSEz=ez'*ez;
% SSTz=sum(Zc.^2)-length(Zc)*mean(Zc).^2;
% R2z=1-SSEz/SSTz;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Observado vs Estimado de R
figure(6)
```

```
%subplot(2,1,1)
Re=(Zc/x(1)).^(1/x(2));
plot([Rc Re]);grid
title('Observed Selected Rainfall on Rain Gauges vs Estimated Rainfall by NEXRAD Reflectivity ')
xlabel('time')
ylabel('mm')
legend('Observated Rain Gauges (R)','Estimated Rainfall R(Z)=(Z/a)^1^/^b ')

figure(7)
subplot(2,1,1)
plot(Rc,Re,'*',sort(Rc),sort(Rc),'--r');grid
title('Dispersion relation between R and Re')
xlabel('R(mm)')
ylabel('Re(mm)')
legend('R vs Re','y = x')
subplot(2,1,2)
plot(Zc,Zee,'*',sort(Zc),sort(Zc),'--r');grid
title('Dispersion relation between Z and Ze')
xlabel('Z(mm)')
ylabel('Ze(mm)')
legend('Z vs Ze','y = x')
% %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% er=Rc-Re;
% SSEr=er'*er;
% SSTr=sum(Rc.^2)-length(Rc)*mean(Rc).^2;
% R2r=1-SSEr/SSTr;
% R2=[R2 R2z1 R2r1 R2z R2r];
% SSE=[SSE SSEz1 SSEr1 SSEz SSEr];
x=[xi;x];
%x=(x(1,1), x(1,2)) = (ai,bi) Estimados a,b Funcion lognormal
%(x(2,1), x(2,2)) = (af,bf) Estimados a,b Optimizacion no lineal sin
%retricciones minimizando el SSE

Rlog=(Zc/x(1,1)).^(1/x(1,2)); %Estimado R-Z Funcion lognormal
Ronl=(Zc/x(2,1)).^(1/x(2,2)); %Estimado R-Z Optimizacion No lineal
elog=Rc-Rlog; %errores (ai, bi)
eonl=Rc-Ronl; %errores (af, bf)
SSElog=elog'*elog; %SSE Estimado R-Z Funcion lognormal
SSEonl=eonl'*eonl; %SSE Estimado R-Z Optimizacion No lineal
SSE=[SSElog SSEonl]; %Almacena ambos resultados de errores.
```

APPENDIX B. GLOSSARY

CASA: Collaborative Adaptive Sensing of the Atmosphere

CLiMMATE: Cloud Microwave Measurements of Atmospheric Phenomena

DCAS: Distributed Collaborative Adaptive Sensing

FTP: File Transfer Protocol

IP3: PR Technology Testbed

NEXRAD: Next generation radar

NOAA:

NSF: National Science Foundation

NWS: National Weather service

OSF: Operational Support Facility

PPS: Precipitation processing system

R: rain rate

TCESS: Tropical Center for Earth and Space Studies

USGS: United States Geological Survey

WSR-88D: Weather Surveillance radar 88 Doppler

Z: Reflectivity