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Development of Composite Algorithms to Create Rainfall Mosaics Using 3-D Weather Radar during a Typhoon Event

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Synopsis

Radar reflectivity mosaics were created to estimate rainfall distribution for South Korean region during the Typhoon RUSA which hit the Korean peninsular on August 31 and September 1, 2002. Recorded data was geographically corrected and transformed into 30” x 30” x 500m three-dimensional databases. Beam blockage is computed from terrain files, and data from radars with a clear view is used to replace blunder values. Three-dimensional quality controlled radar reflectivity data recorded from seven ground radar stations were used to improve the accuracy of radar reflectivity mosaics to estimate rainfall rates over large areas.

Keywords: radar reflectivity, mosaics, Typhoon RUSA

1. Introduction

The use of weather radars in the field of hydrology has made a considerable progress over the last decade due to advantages associated with high temporal and spatial resolution observations and advances in distributed hydrological models. In addition, real time radar observations can be used to forecast short-term rainfall. Combined use of forecasted rainfall and distributed hydrological models creates a powerful numerical tool for forecasting floods and related natural disasters.

Early work on single Doppler radar analysis mainly focused on rainfall analysis using reflectivity Z-R relationships (Uijlenhoet, 2001). The relationship between reflectivity (Z) and rain rate (R) is complex and subjected to several independent errors. Mountainous terrain affects radar echo patters by interfering with radar beam and providing erroneous precipitation estimates. When the radar beam is intercepted by terrain, clutter values include in the observations (Lin and Reilly, 1997).

The traditional way of using data from radars is in base scan only (two-dimensional), even though three-dimensional volumes are available. Compared to the traditional 2-D products used by hydro-meteorologists when analyzing radar data, the 3-D volumes provide more information that makes it easier for the users to understand the given weather situations. The three-dimensional structure contains information which can improve rainfall rate estimates which are crucial for hydrological modelling and simulations.

The raw data is given in a conical coordinate system. It is hard to match three-dimensional radar meshes on the two-dimensional terrain grids. Radar reflectivity data with volumes in traditional senses have been merged by Zhang et al. (2001). The merging system consists of volumetric data and using Cressman interpolation to create three-dimensional data set. In this paper, we discuss the methodology used in creating two-dimensional reflectivity mosaics over South Korea using three-dimensional gridded radar reflectivity databases to estimate rainfall rates more accurately.

2. Geo-referring of Radar Measurements

Weather radar scans the atmosphere and detects rain in the atmosphere, by sending out pulses of microwave from its antenna. When a radar pulse encounters rain drops or ice particles, part of its energy is reflected back to the antenna. The time delay in the returned echoes gives information on the distance of the rain area from the radar. Rain intensity is deduced from this distance and the received signal strength.

Initially, the antenna is instructed to point at a certain elevation angle: the angle between the radar ray and the horizon at the radar. Then the radar transmits a few pulses at one elevation with a constant horizontal rotational velocity starting from true north. Return echoes are deceived by the receiver. Transmitter and antenna proceed clockwise while increasing the azimuth angle in short steps from 0 to 360 degrees at the same elevation angle. Several scans for multiple elevation angles produce the three-dimensional radar volumes. The Korean Meteorological Agency (KMA) radar data for one volume is acquired in 10 minutes interval.

The polar volume can be arranged in a three-dimensional array to implicitly associate each value with its origin in space. In order to display this data in a 3-D scene, the coordinates (elevation, azimuth, range bin) need to be transformed into a cartesian (x, y, z) coordinate system. This transformation should take the ray bending into account.

For a radar ray traveling in a non-uniform atmosphere, the ray will bend more or less relative to the earth, depending on how much the refractive index changes with height. Radar rays appear to bend downward and its curvature (1/R') relative to the surface of the earth is less than *1/R*. It is satisfactory to use a 4/3 earth radius assumption that is used to approximate standard atmospheric refraction.

$$\frac{1}{R'} = \frac{1}{\frac{4}{3}R} \qquad (1)$$

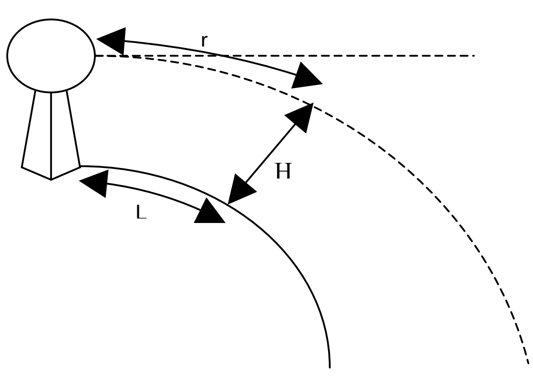

Fig. 1 Range, height and distance of a ray

where *R* is the radius of the earth.

Using this curvature, the range, height, and distance variables may be defined as shown in the grossly exaggerated in Fig. 1.

The range (r) of a certain radar sample is the distance from the radar to the sample, along the ray. The distance (Ld) is the corresponding distance from the radar along the earth's surface, to the point directly beneath the sample. And the height (H) of the sample is simply the sample's height above the surface of the earth. The range, height, and distance calculations are performed in order to calculate the Cartesian coordinates of a sample. In Fig. 2 (a), K_e is equal to 4/3.

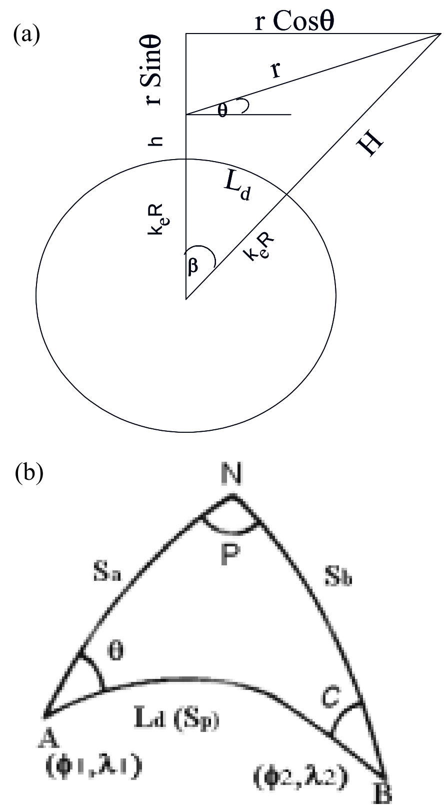

Fig. 2 Georeference of radar observations

From Fig 2 (a);

$$\beta = \mathrm{Tan}^{-1}[r\mathrm{Cos}\theta/(k_eR + h + r\mathrm{Cos}\theta)] \qquad (2)$$

$$Ld = k_eR\,(\beta * \pi/180) \qquad (3)$$

$$\mathrm{Sin}\beta = r\mathrm{Cos}\theta/(k_eR + H) \qquad (4)$$

$$H = (r\mathrm{Cos}\theta/\mathrm{Sin}\beta) - k_eR \qquad (5)$$

Applying the Cosine formula in Fig. 2(b);

$$\cos s_b = \cos s_a \cos s_p + \sin s_a \sin s_p \cos\theta' \quad (6)$$

$$Sa = \pi/2 - \Phi 1 * \pi/180 \quad (7)$$

$$Sp = Ld/R \quad (8)$$

$$\theta' = \theta * \pi/180 \quad (9)$$

$$\Phi 2 = 90 - 180/\pi \cos^{-1}\{\cos s_a \cos s_p + \sin s_a \sin s_p \cos\theta'\} \quad (10)$$

Appliing Sine formular to Fig, 2(b);

$$\lambda_2 = \lambda_1 + p \quad (11)$$

$$\lambda_2 = \lambda_1 + 180/\pi * \{\sin^{-1}(\sin\theta \sin sp \; / \sin sb\,) \quad (12)$$

where, Φ: Latitude, λ : Longitude and θ : Azimuth angle

Using Eqs. (5), (10) and (12) we identified the exact location of observation in geographical coordinate system. Three-dimensional databases for each radar station were created for the Typhoon RUSA event.

3. Problems in Using Radar to Estimate Precipitation Distributions

A fundamental problem before radar-derived rainfall amounts can be used for hydrological purposes is to make sure that they provide accurate and robust estimates of the spatially and temporally distributed rainfall amounts. The crucial step in tackling problems associated with radar remote sensing of rainfall is the conversion of radar reflectivity measured aloft to rain rates at the ground. Collier (1996) discussed the problems associated with estimating precipitation distributions over large areas using weather radar measurements.

Ground clutters where the main radar beam encounter ground targets such as mountains (Fig. 3), trees and man made structures are addressed in this study using digital elevation model (DEM) and dry ground clutter maps. Digital elevation model for the study region is depicted in Fig. 4.

Without appropriate precautions, these non-hydrometeorological echoes can be erroneously attributed to estimated precipitation. Dry ground clutter maps are created from the radar observations in non-precipitation times and they are reasonably accurate to apply as ground clutter filters. Reflectivity near earth at ground clutter locations were filled with the help of vertical gridding and mosaics using multiple radars.

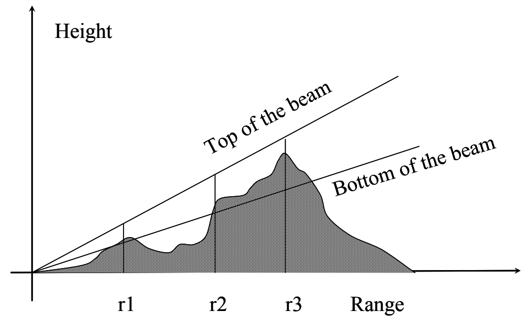

Fig. 3 Ground clutter in radar observation due to terrain

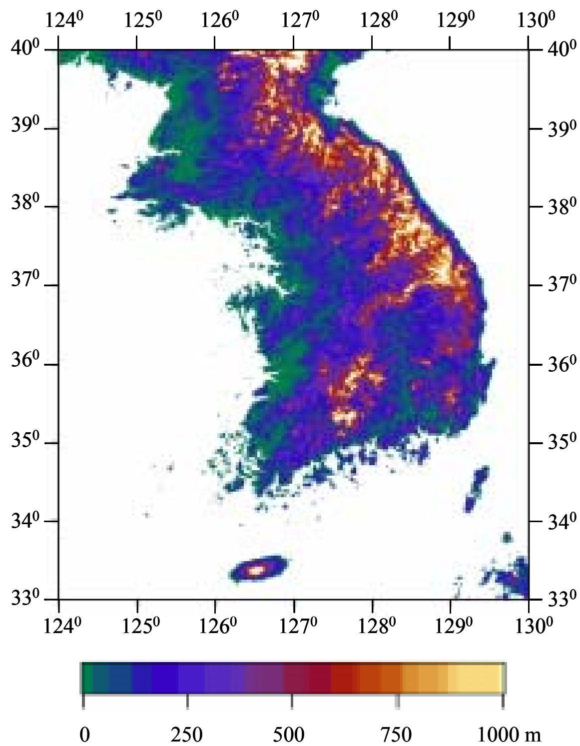

Fig. 4 Digital elevation model of the study region

Occultation results where part of the radar beam is intercepted by the ground and reduction of ground beam power at range beyond the obstacle. In the study, if 50 % of the radar beam is intercepted an obstacle (at r2 of Fig. 3), data beyond that point are not considered in further processing.

One way of solving the problem of ground clutter is to use higher elevation angle observation. Figure 6 shows the sweeps at different elevation angles at Cheju on August 30, 2002 : 22:00 (GMT). Eastern part of Chuju is subjected to ground clutter problem at lower elevation angles. Even though we could solve the problem of ground clutter using this approach, due to the altitude difference between measurements and relevant ground location, this approach is not very suitable. Work had been carried out to find the nearest ray sample location using three-dimensional data and mosaicking schemes.

4. Three-Dimensional Gridding

Most of the current weather radars are capable of scanning atmosphere three-dimensionally with high spatial and temporal resolutions, and therefore useful for monitoring and predicting the atmospheric conditions.

For a radar station, observations made at native conical coordinates were transformed to longitude, latitude and altitude (x, y, z) coordinated system. And results were transformed into 30” x 30” x 500 m resolution. Two methods were used to vertically interpolate the data. In nearest neighbourhood method, for any given grid cell, if the center is in between the lowest and highest elevation angles, then it takes the value of the nearest radar bin. Vertical cross section of observed reflectivity created using the nearest neighbourhood method is illustrated in Fig. 5(a).

In the vertical adaptive Barnes method, if the center is in between the lowest and highest elevation angles, then it will take the weighted mean of the two nearest radar bin values, one at the tilt above and the other below. Vertical cross section of observed reflectivity created using vertical adaptive Barnes method is illustrated in Fig 5(b).

From the result, nearest neighbourhood method produces discontinuities in the resulting reflectivity image. Vertical adaptive Barnes method produces smooth vertical profiles of reflectivity.

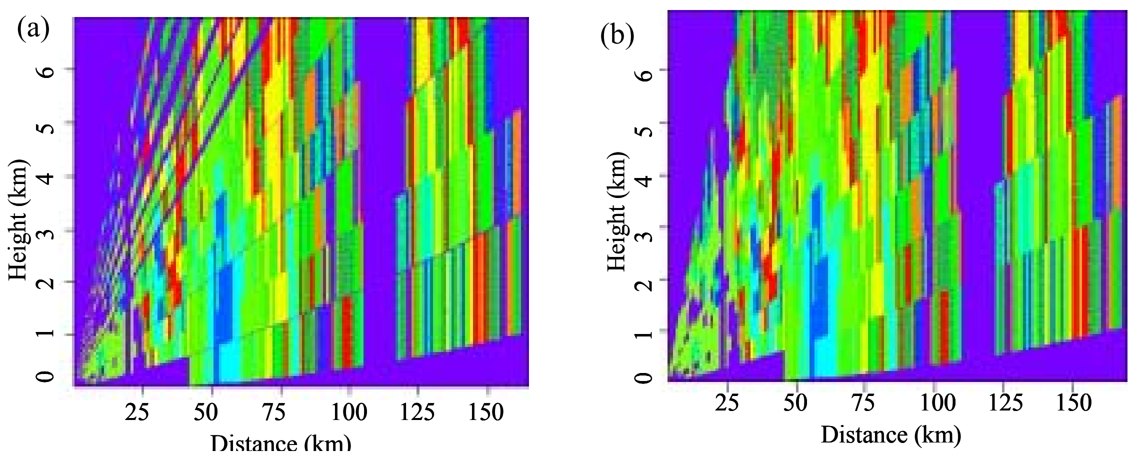

Fig. 5 Vertical cross section of reflectivity field (a) - nearest neighbourhood method and (b) - Vertical adaptive Barnes method.

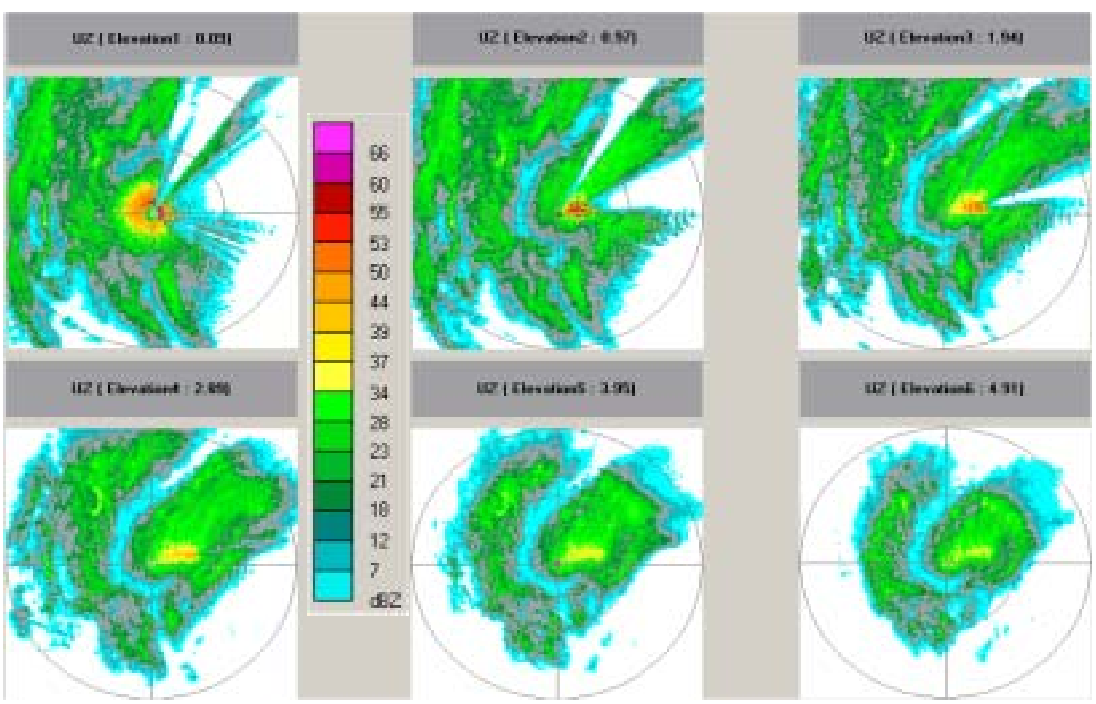

Fig. 6 Reflectivity sweeps at different elevation angles at Cheju, South Korea on 2002.08.30 at 22:00 (GMT)

5. Use of Multiple Radars to Create Reflectivity Mosaics

While single radar provides good local information, an application often needs information over a wider area. As weather systems span over multiple radar umbrellas, establishment of an overlapping network of radars provides this expanded coverage. With a network of weather radars in place, it is important to use time synchronized multi-radar coverage observations for accurate rainfall estimations for processing.

The merging scheme, referred to as "mosaicking", consists of obtaining volumetric radar data periodically to create two-dimensional reflectivity from available three-dimensional datasets. Radar algorithms could be expanded to utilize data from multiple radars to more accurately determine rainfall distribution over a large area. If there are multiple radar values in clutter free radar values near to ground surface, maximum, average, weighted distance or nearest neighbourhood schemes could be

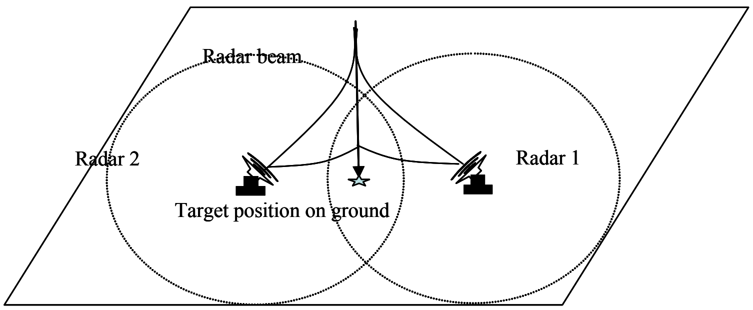

Fig. 7 Schematic illustration of multiple three-dimensional radar observations to create reflectivity mosaic

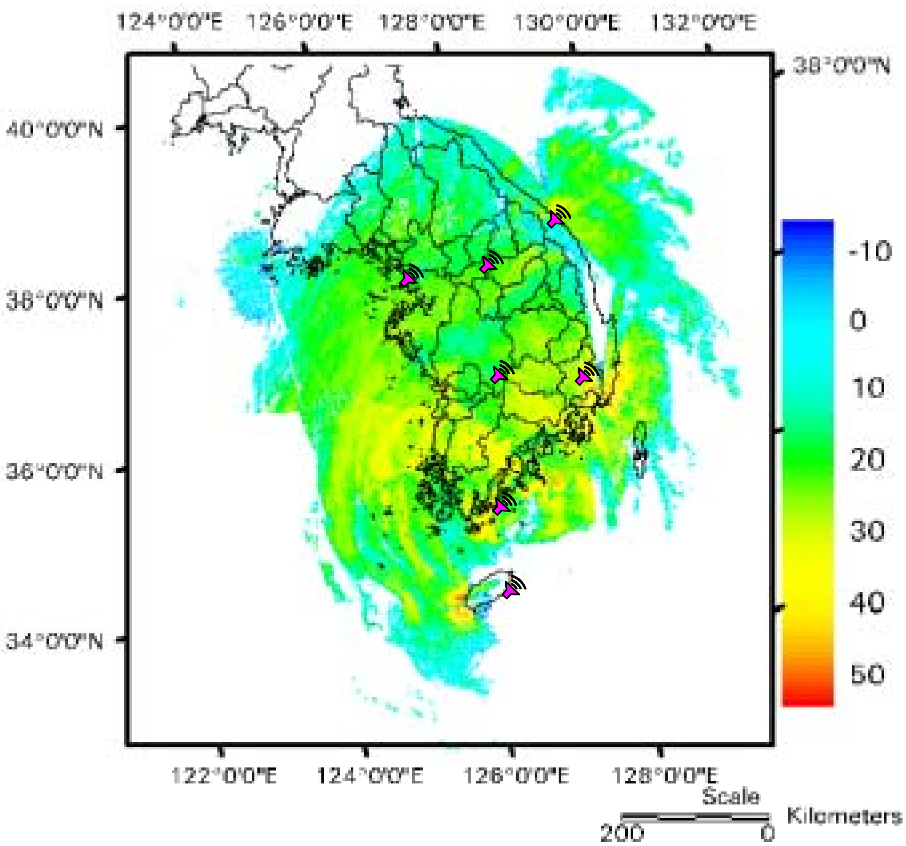

Fig 8 Composite QC reflectivity (dBZ) in the study region on August 31, 2002 at 15:00 LT

used to merge data from multiple sensors (Fig. 7). If there is no any clutter free value near to ground, higher altitude values were used to avoid blunders.

6. Reflectivity Mosaic over South Korea during Typhoon RUSA.

Typhoon RUSA, the most powerful tropical storm to hit South Korea in 43 years, ripped through the country, leaving at least 246 people dead or missing in torrential rains, flash floods and mudslides. The Typhoon left a trail of destruction and inundation of infrastructures and houses in the Northeastern parts of the country, and caused massive property damage. It resulted 900 mm of rain less than two days in Kangnung city area. This is the highest amount of precipitation measured since official records begau in the 1930s during month of August. In comparison, the average monthly rainfall for August is just 294 mm in Seoul and 204 mm in Pusan. Most of the damage was mainly caused by floods, reservoir washouts and mudslides. Table 1 provides an overall picture of losses, damages and nature of the Typhoon RUSA.

Radar reflectivity data in Universal format acquired from Korean Meteorological Agency for Cheju, Baekryungdo, Dong-Hae, Jindo, Kunsan, Mt. Kwanak and Pusan ground stations were used in this study. TRMM Radar Software Library (RSL) was used to transform above data into radar data format in which two-dimensional spatial resolutions at any point are based on the range and azimuth of different elevations. These data of different volumes was used to create the three-dimensional reflectivity data bases.

Figure 9 shows the base reflectivity images observed at Kwangdu san, Kwanak san, Dong-Hae and Gunsan stations on August 31, 2002 at 8:20 GMT. Those stations can be used to estimate reflectivity in the upper part of South Korea. Figures clearly show the effect of ground clutter depicting different values for the same location. Even though all the observations were made simultaneously, there are clear differences of output reflectivities images. It raised importance of considering multiple overlapping radars to determine reflectivity which could be used to estimate spatial distribution of rain rate over the area.

Time synchronized multi-radar coverage observations were used to avoid ground clutters for accurate rainfall estimations. If there are multiple radar values in clutter-free radar values near to ground surface, maximum, average, weighted distance or nearest neighbourhood schemes were used to merge data from multiple sensors. Radar reflectivity mosaics were created to estimate rainfall distribution for South Korean region for the Typhoon RUSA which hit the Korean peninsular on August 31 and September 1, 2002, causing 246 deaths and US$ 4.2 Billions of economic losses. A multiple radar reflectivity mosaic scheme has been developed in geographical coordinate system. Figure 8 shows the reflectivity composite image created using maximum value algorithm at 15:00 hrs local time on August 31, 2002.

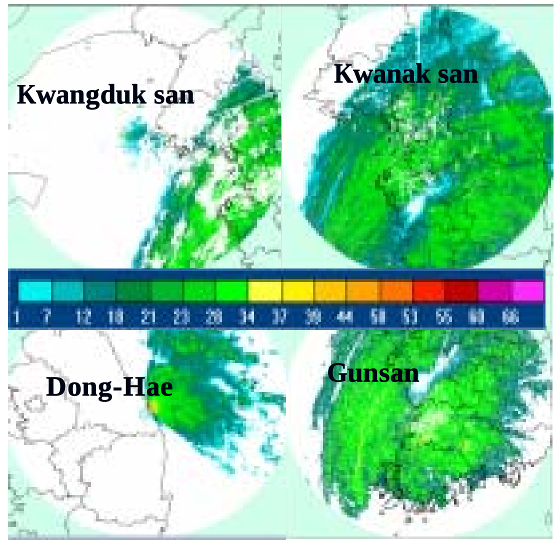

Fig. 9 Radar reflectivity observation on August 31, 2002: 8:20 GMT

Table 1 Economic and Human Loss due to Typhoon RUSA

Economic Loss	US$ 4.2 Billions
Ships, agricultural areas and fish farms	42%
Bridges and Roads	13%
Buildings	3%
Other including dams and dikes	42%
Human loss	246
Main disaster area	S. and N.E. parts of S. Korea
24 hr Max Rainfall	880 mm (Kangnung)

7. Radar Reflectivity and Rain Rate Relationships

The radar measures power return which is expressed as a reflectivity factor Z. Theoretically, Z is proportional to the dimension of rain drops to the sixth power. In practice, the reflectivity factor is converted to a radar estimate of rain rate, through an empirical Z-R relation:

$$Z = aR^b \quad (13)$$

where *a* and *b* are determined by fitting *Z* against rain rate measured by rain gauge observations. The coefficient may vary from one location to the other and from one season to the next, but those are independent of *R* itself. Those coefficients reflect the climatological character of a particular location or season, or more specifically the type of rain for which they are derived. For stratiform rain, a = 200 and b = 1.6 in Eq. (13) forms the conventional Marshall-Palmer equation (Marshall *et al*., 1948). Other relations include those for orographic rain (a=31, b=1.71) and thunderstorm rain (a=486, b=1.37) (Battan, 1973). The Marshall-Palmer relation is often used when no other relationship is known despite its well known limitations. When rainfall data are based solely on weather radar observations, the uncertainty is high particularly over complex terrain (Dinku *et al*., 2002).

Research will be extended to determine the coefficient *a* and *b* for the Typhoon event for the seven ground radars using hourly observed cumulative rainfall data.

8. Conclusions

Radar reflectivity mosaics over South Korea during Typhoon RUSA were created using three-dimensional measurements. Necessity of creating reflectivity mosaics to estimate rain rate was identified and different mosaicking schemes were used. Dry ground clutter maps created from the radar observed in non precipitation times and DEM were used to filter ground clutters. Missing reflectivity at ground clutter locations were filled with the help of vertical gridding and mosaics from other radars. In vertical gridding, nearest neighbourhood method produces discontinuities in the resulting reflectivity image. Vertical Adaptive Barnes method produces smooth vertical profiles of reflectivity.

Final target of this research is to develop software which enables the integration of high resolution three-dimensional multiple radars into a single framework to depict and forecast the short-term rainfall distribution over the Korean peninsular. Use of three-dimensional radar reflectivity data reduces the uncertainties in the retrieved surface rainfall pattern.

Acknowledgments

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要　旨

3次元気象レーダーによるレーダー反射因子を合成して広域の降雨時空間分布を推定する。2002年8月30日から9月1日にかけて韓国を来襲した台風RUSAによる豪雨を対象としてレーダー反射因子モザイクを生成した。対象となるレーダーデータがすべて障害物の陰に隠れる場合は、3次元データを利用して、同じ地点のより高高度のクラッターの含まれないデータを用いるように合成アルゴリズムを設計している。

キーワード：レーダー反射因，モザイク，台風 RUSA

COE-18

3 次元気象レーダーを用いたレーダーコンポジット作成アルゴリズムの開発

Development of composite algorithms to create rainfall mosaics using 3-D weather radar

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気象レーダーシステムによって得られる降雨情報は地上観測システムによる降雨情報よりもはるかに空間分解能の高い情報を得ることができる。また、実時間でのレーダー雨量観測は広い領域での短時間降雨予測に用いることが可能であり、分布型の降雨流出モデルと組み合わせて用いることにより、洪水予測など水に関連する自然災害を防止・軽減するための非常に強力なツールとなる。

レーダーによって観測される降雨強度は通常、レーダー反射因子 Z を関係式 $Z = A*R^b$ によって降雨強度 R に変換する。係数 A と b はレーダーシステムごとに定まる定数であり、地上観測降雨とレーダー観測降雨とで回帰直線を定めることによって得られる。本研究では 2002 年 9 月、韓国を襲った台風 RUSA による豪雨を解析することを目的とし、まず始めに Cheju, KMABRI, Dong-Hae, Jindo, Kunsan, Mt Kwanak および Pusan で観測されたレーダー雨量データを合成して得られるレーダモザイクデータを自動的に生成するアルゴリズムを開発した。

観測された生データはレーダーサイトを中心とする 3 次元極座標形式のデータとなっており、これを洪水予測システムに導入するためには、共通の座標系を有する平面 2 次元データとして合成する必要がある。したがって、30 秒(約 1km)ごとの緯軽度格子を設定し、その格子に最も隣接する極座標系のレーダーデータを探索するアルゴリズムを構築して面的なコンポジットデータを作成した。なお、同じ領域を複数のレーダーシステムがカバーしており、かつそれらのデータがいずれもグランドクラッターを含まない場合は、複数の観測値の最大値、平均値、距離の重みつき平均値、あるいは対象とする 2 次元格子にもっとも近い位置の観測データを選択できるようにしている。また、対象となるレーダーデータがすべて障害物の陰に隠れる場合は、3 次元データを利用して、同じ地点のより高高度のクラッターの含まれないデータを用いるように設計されている。

朝鮮半島南部を対象に作成したレーダーモザイク画像の一例を図 1 に示す。この画像は 2002 年に台風 RUSA が朝鮮半島に上陸したときの 2002 年 8 月 31 日 15 時の画像であり、同じ格子に複数観測データが存在する場合には、それらのうちの最大値を取った場合の例である。この台風は、2002 年 8 月 31 日から 9 月 1 日にかけて朝鮮半島煮上陸し、豪雨・土砂・洪水災害によって 246 名の人名が失われ、約 5200 億円もの経済的損失を被った。

今後、現時点の合成アルゴリズムを発展させて、実時間で 3 次元データから最も推定精度の高い 2 次元コンポジットを作成するアルゴリズムを開発し、それと分布型流出モデルとを組み合わせて洪水域の面的な予測を可能とするシステムを開発する予定である。

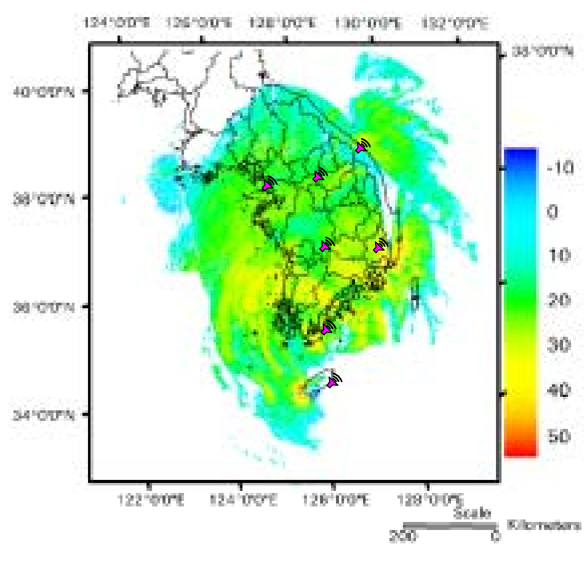

図 1 合成されたレーダーコンポジット画像 (2002 年 8 月 31 日 15 時)