Improvement of Accuracy in Radar Precipitation Gauge System by an Alliance between Tokyo and Neighboring Municipalities

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ABSTRACT

“Tokyo Amesh” is real-time radar rain gauge system Bureau of Sewerage, Tokyo Metropolitan Government operates. The information is available on our network and internet. The data source of it is two X-band radars, Minato and Inagi. The radar can observe rainfall intensity at the smallest unit of 250m by 250m square mesh. Operators make the best of the information for the safest pump operation. No good solution has been given to “rainfall attenuation” and “bright band”, the inherent problems for X-band radar. Also, for changeable movement of rain clouds broader panorama vision has been in demand from a standpoint of preventive operation. With these needs, Tokyo worked on allying with neighboring municipalities to share rainfall information. Saitama Prefecture, Yokohama City and Kawasaki City. By integrating data from the four systems into one, with a new composition method a great progress has been attained to solve the problems.

KEYWORDS: Tokyo Amesh, radar rain gauge system, mesh, rainfall attenuation, bright band, composition

INTRODUCTION

Background
Bureau of Sewerage, Tokyo Metropolitan Government, has carried forward to establish discharge capacity of 50 mm/h rain, which is defined as the one-time per three years precipitation. In these years, however, rain often exceeds the definition for a span of time. Unpaved ground is scarce inside 23 wards in Tokyo as a result of urbanization, and lowlands of no-natural drainage topography are highly utilized for residential purpose. Thus, conditions surrounding rainfall drainage against inundation are very demanding. Also, operation jobs have been integrated by making use of remote-control system for efficient management, e.g. with small number of staff in charge of plural facilities. As of 2008, at 66 pumping stations of total 83, no operational men are staffed. In intensive operation to deal with rainwater, grasping the present state of rainfall closely is helpful for an operator to provide for his next action. “Tokyo Amesh” is a real-time radar rain gauge system Tokyo Sewerage operates. The data source of it is two X-band radars. They observe precipitation on and around Tokyo at twenty-four-hour basis.

In 2007, to improve “rainfall attenuation”, “bright band”, inherent problems for X-band radar, Tokyo worked on allying with neighboring municipalities to share rainfall information. From
here, we call it “the new system” and we call the system before the allying “the old system”. The new system has been successful to enhance accuracy and contributes for the safer operation.

**System of Tokyo Amesh**

“Amesh” is the combination of two words “Ame” and “Mesh”. “Ame” is the Japanese for rain and “Mesh” is a key word which characterizes the system. “Tokyo Amesh” has started in 1988, and the present Amesh, the 2nd system, has been in service since 2001. The data source of it is two X-band (9 GHz) radars, located at Minato and Inagi. The radar can observe rainfall intensity at the smallest unit of 250m by 250m square mesh within a circle of 50km radius. The data is updated every minute. Tokyo Amesh information has been open to the public on the Internet site since 2002. As a method of risk communication, it has contributed to crisis management.

**System Configuration**

Figure1 shows the configuration of the new system. We added the enclosed part by the dotted line in the figure for the new system. Data are collected from four municipalities to a processor which composes them. The composition job is consigned to an external agency which specializes in weather analysis. Consignment of the composition job is intended to facilitate procedure when a municipality begins to receive the composed information. Radar precipitation which Japan Meteorological Agency (JMA) deals with is also used to composition. In the figure, the general meteorological information means weather warnings/advisories thunderstorm, typhoon and more.

Composed data is received at the CPU-Distribution unit on Kuramae Water Reclamation Plant (WRP) and distributed to all operational and maintenance facilities. The unit also transmits the Amesh information to Internet, cellular phone and Disaster Information System which is managed by Disaster Prevention Division. Tokyo started to take in the composed data in 2007, and Saitama Prefecture has followed Tokyo from 2008. The other two are preparing now.
Figure 1. System Configuration
Sharing the Rainfall Information with Neighboring Municipalities
Following the increase of the number of radars, we investigate the method to compose the data. In data composition, we also use JMA radar. The errors caused by the height of passing radar beam and the distance between the radar and the target are corrected by using the ground gauge data and the data composition of the radars.

The precipitation measured by radar is the precipitation at a moment, but ground gauges measure precipitation for a certain period. The precipitation data needed for our operation job is not the momentary intensity of the rainfall but the amount of rainfall on the ground. Taking it into consideration, we compose and correct the radar data.

Weak Point of X-band Radar
The present Amesh, the 2nd system, has been in service since 2001. Compared to the 1st system which is called “Tokyo Amesh 500”, the 2nd system has been improved in specification such as accuracy and update periods as shown in Table 1. But it still has the problem caused by rainfall attenuation and bright band.

Figure 2 shows an observation image of the old system in which the “rainfall attenuation” can be seen. The reflected wave was attenuated because of heavy rain around radars. The radar data within Tokyo were compensated by the ground gauges and heavy rains were shown there. But, no ground gauge data were available beyond the boundary of Tokyo and weaker indication was given.

Figure 3 shows an occurrence of the bright band. The radar indicated heavy rains for weak ones. This effect is resulted from the property that melting layer of precipitation has its high radar reflectivity. In the same way as “rainfall attenuation”, the ground gauges compensated the radar data within the areas of Tokyo.

These effects give misinformation to operators dealing with rainwater, and may cause a serious mistake in their decision. C-band (5GHz band) beam cannot be employed in place of X-band, because it cannot perform the fine mesh observation, and also, permission to use it cannot be guaranteed for the future.

Table 1. Specification of the System of Tokyo Amesh

<table>
<thead>
<tr>
<th>Name of system (operation term)</th>
<th>Measurement Area</th>
<th>Size of a Mesh (distance from radar)</th>
<th>Update Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tokyo Amesh 500 (1988 – 2001)</td>
<td>105km (east to west) 40km (north to south)</td>
<td>500m(0 – 40km)</td>
<td>2.5min</td>
</tr>
<tr>
<td>Tokyo Amesh The old system The new system (2001 – )</td>
<td>125km (east to west) 50km (north to south)</td>
<td>250m(0 – 20km) 500m(20 – 50km)</td>
<td>1.0min</td>
</tr>
</tbody>
</table>
Figures 2 and 3: Rainfall Attenuation and Bright Band

*) Precipitation in Tokyo area is corrected by ground gauge data

**METHODOLOGY**

**Approach**

Saitama prefecture abutting on Tokyo in the south, Yokohama city and Kawasaki city in the north, operates their own radar gauge system (Figure 4).

They use X-band radar, and have the common problem with Tokyo Amesh. And JMA has its own radar system using C-band which covers all over Japan. Combining information of their systems with that of Tokyo Amesh is considered to be an effective method to complement radar attenuation or bright band.

Starting the data composition, Tokyo, Saitama, Yokohama, and Kawasaki have concluded an agreement on the handling of the raw data and the composed data. Tokyo is the first municipality to use the composed data and the other municipalities will follow it. And Saitama began to use the data from the year 2008. The agreement stipulates that the allied municipalities own the composed data commonly and also includes the rule for how to split the expense among participants. We will minutely describe how we composed the data below.

Figure 4: Tokyo and Neighboring Municipalities
Principle of Radar System

A weather radar is a radar used to observe the atmosphere. These radars sense precipitation by measuring a radio wave reflecting from targets, such as raindrops and snowdrops floating in the air. By measuring the power of the reflecting wave $P_r$, we can calculate rainfall intensity $R$. The average power returned to the radar from targets and the radar reflectivity factor $Z$, which relates to the amount of the raindrops in the path of passing radar beam, has a relation written as:

$$P_r = \frac{CFZ}{4r^2} \quad (1)$$

where $C$ is a radar dependent constant, $F$ is a coefficient of revision, $r$ is the distance between a radar and target.

The radar reflectivity factor $Z$ and rainfall intensity $R$ has a correlation called “$Z - R$ relation”, so we can calculate $R$ by using a conversion line based on the statistics.

Radar system consists of two parts. One is the antenna where radio wave is sent and received. The other is the data processing device where $P_r$ and $Z$ is translated to $R$. (Takashi, 1996)

“$Z - R$ relation” is affected by how heavy the rain is, so Tokyo amesh adopted "rainfall-intensity adjustment" to make the rainfall data more accurate. By using the basic conversion line "rainfall-intensity adjustment" calculate the amount of rainfall, and determines $Z - R$ relation by choosing one from 3 types. 3 types are defined by rainfall intensity, "severe", "moderate" and "weak".

![Figure 5. Radar System](image-url)
Correction of Rainfall Attenuation by Increasing the Number of Radars

Even if one radar cannot measure the point of rainfall attenuation accurately because of rainfall attenuation, there is a possibility of other radars located in other areas to be able to measure correctly (Figure 6). We propose a method to complement rainfall attenuated data by increasing the number of the radar system.

![The point of rainfall attenuation]

Other radar can measure the point correctly

Figure 6. Correction of Rainfall Attenuation by Increasing the Number of the Radar

Bright Band Error Minimization and Correction of Rainfall Attenuation by Ground Gauge

By complementing the radar data with the ground gauge data, we can eliminate the internal error of the radar and the bright band. And we can also correct the data lacked by rainfall attenuation. We can know the amount of rainfall in area around Kanto more accurately than before by increasing the number of ground gauge.

Improvement of the Data Reliability

By defining the reliability of the radar data, we compose the data measured by some radars. The rainfall value of the same area will be measured differently by each radar because of the difference of the height of the beam of each radar. For that reason, inside the measurement area of the new system there are differences between each radar’s data.

Low-height data has less error because low-height means radar measures the rainfall near the ground. And the distance between the antenna and the target produce errors on the radar data because radar beam is attenuated through the path.

Therefore by using the data from a lot of radars and giving weights based on the reliability of the data, we can improve the reliability of the data overall.

We will next revise the radar data by using ground gauge data to measure the rainfall accurately. Update periods of Ground gauges and radars are not the same, so we adjust them to suit for the information we use for reclamation of sewerage.
Flow of Data Composition
Our new system determines the amount of precipitation on the ground by revising the radar data by ground gauge data. Radar can measure precipitation in the mid air inside the measurable area divided to minute meshes. Table 2 shows the specification of the radars we use. According to the Table 2, each radar has the difference in the specification. Therefore we divide 6 radars into 3 groups. Group A, which includes Tokyo and Saitama radars, can measure rainfall by minute meshes in short update period. We use group A data in data composition and determine the amount of precipitation. Then we use group B and C data to complement the area where group A cannot measure. It is difficult for radars to define the absolute value of the amount of precipitation. So we use ground gauge data in calibration process to match the radar data to the ground gauge data.

Figure 7 shows the schematic of flow in the proposed radar data composition.

Figure 7. The Schematic of Flow
Table 2. The Specification of Each Radar

<table>
<thead>
<tr>
<th></th>
<th>Tokyo radar (Inagi and Minato)</th>
<th>Saitama radar</th>
<th>Yokohama radar</th>
<th>Kawasaki radar</th>
<th>JMA radar</th>
</tr>
</thead>
<tbody>
<tr>
<td>the update period</td>
<td>1 min</td>
<td>1 min</td>
<td>2.5 min</td>
<td>2.5 min</td>
<td>10 min</td>
</tr>
<tr>
<td>Size of the mesh</td>
<td>250m (0 – 20km) 500m (20 – 50km)</td>
<td>250m (0 – 20km) 500m (20 – 50km)</td>
<td>250m (0 – 20km) 500m (20 – 40km) 1km (40 – 50km)</td>
<td>500m (0 – 40km) 1km (40 – 100km)</td>
<td>1km (All area)</td>
</tr>
<tr>
<td>Group</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>C</td>
</tr>
</tbody>
</table>
Data Processing of Group A

- Making Attenuation Map by Evaluating the Radar Data

By evaluating the power of the reflecting wave $P_r$ obtained from each prefecture measured from each distance and angle using polar coordinate, we can determine the attenuation of the radar beam. Doing that for 360 degrees, we can make an attenuation map, which can be used to eliminate rainfall attenuation. By using Attenuation map we can know where the reliable data is in the measurable area of each radar.

![Diagram showing the process of making an attenuation map](image)

**Figure 8. Making Attenuation Map**
• **Composition of Group A Radar Data**

By giving two weights based on the reliability to each mesh of each group A radar and composing each radar data, we can improve the reliability of the radar data overall. We translate the group A radar data from polar coordinate to orthogonal coordinate in order to match them to the map of Kanto area divided into the minute meshes. We call the radar data composed in this process “composed radar data”.

1. Set 2 weights on the mesh of each radar written below:
   a) weights table of beam heights
   We set weights table of beam heights according to the height of the passing beam.
   b) weights table of the mesh-radar distance
   We set weights table of the mesh-radar distance according to the distance between the mesh and the radar.

(2) Compose the mesh data measured by group A

We show how we calculate the each mesh’s precipitation value \( R \) on the same mesh where the group A radars measure independently.

   a) Each radar’s weight given to each mesh is calculated by multiplying weights table of beam heights with weights table of the mesh-radar distance.
   b) Each mesh’s precipitation value is calculated by adding \( R \) measured by each radar multiplied with each radar’s weights.

If one radar data has invalid value set by attenuation map, we ignore the weight of the radar and use 2 radar data. Therefore, we can improve the data reliability, and we can grasp the rainfall without the effect of rainfall attenuation.

**Data Processing of Group B**

The size of mesh and the update period of group B radars are large and long compared to those of group A, so we can think group A radars indicate the precipitation on the ground more accurately. Therefore, we recalculate the group B radar data by using composed radar data.

For meshes which satisfy the below conditions, we compare the composed radar data with the group B radar data. There are some areas where the size of mesh are not equal to the group A radar, we divide some mesh of group B radar in order to match it to that of the composed radar data.

   1 composed radar data which over 0 mm
   2 the group B radar data which over 0 mm

We calculate the ratio by dividing the total amount of composed radar data with the total amount of the previously measured group B radar data. Then we recalculate the group B radar data by multiplying each mesh of the group B radar data with the ratio. Figure 9 show the process of correction.
**Data Processing of Group C**

The height of passing radar beam of JMA radar is high, and the size of mesh and the update period of JMA radar are large and long compared to those of group A, so we can think group A radars indicate the precipitation on the ground more accurately. Therefore, we recalculate JMA radar data by using composed radar data. We divide all meshes of JMA radar to match it to the composed radar data.

For meshes which satisfy the below conditions, we compare the composed radar data with JMA radar data.

1. composed radar data which over 0 mm
2. JMA radar data which over 0 mm

We calculate the ratio by dividing the total amount of composed radar data with the total amount of the previously measured JMA radar data. Then we recalculate the group JMA radar data by multiplying each mesh of JMA radar data with the ratio. Figure 10 show the process of correction.
Figure 10. Correction of Group C Radar Data

Data Composition of the Group A, B and C
We compose group A, B and C data by overwriting the data in order of C, B, A in the same map divided into 250m mesh (Figure 11). In short, we use B and C group data in the area where A group radar cannot measure. This method is based on the idea we prioritize the data in order of the data reliability of each group. We call the radar data composed in this process “composed ABC radar data”.

The total amount of JMA radar data=1031
The total amount of the composed radar data=744
The ratio=744/1031=0.72
Figure 11. Data Composition of the Group A, B and C
**Calibration Process**

Radar data is not coincident with ground gauge data because radar system measures rainfall in high location. We use a radar dependent constant in translating $P_r$ to $R$, but a radar dependent constant is affected by the rainfall intensity. In translating process, it is difficult to change a radar dependent constant according to the rainfall intensity because the amount of calculation becomes too large to update the rainfall data in one minute. So we propose the calibration method to make radar data coincident with ground gauge data. There are 86 ground gauges in Tokyo, 27 in Saitama, 22 in Yokohama and 18 in Kawasaki. New system uses all these 153 ground gauges.

- **First Calibration**
  
  We correct the total amount of the precipitation value in all meshes of composed ABC radar data by using all ground gauges. We avoid the sudden changes over all meshes by making the total amount of precipitation measured by the radar data coincident to that of ground gauge data in First calibration. Taking update periods of radar and ground gauge into consideration, we correct radar data as the steps described below.
  
  Step 1: Calculate the amount of the precipitation measured by radar and ground gauges in the past ten minutes
  
  Step 2: For all areas covered by weather radars, we make a primary analysis by the least square method in order to correct the radar data to coincide with the ground gauge data in average. In this process, we can calculate the calibration coefficient. Defining the calibration coefficient by using feedback process, we can avoid the sudden changes in total amount of precipitation.

- **Second Calibration**
  
  We correct each mesh’s rainfall value by using ground gauge near each mesh (Figure 12). Centering around an optional mesh, we use some ground gauges within a radius of 10km, 7.5km, 5km. Considering the distance between the mesh and the ground gauge, we correct the mesh’s rainfall value to match to the precipitation on the ground by using the ground gauge in order of 10, 7.5, 5 km in a radius. This is how we make the radar data coincident to the ground gauge data in a local area.

![Ground gauge](image.png)

*Figure 12. Image of Calibration*
RESULTS

Rainfall Attenuation
Figure 13 shows the result of the elimination of rainfall attenuation in our new system. At that time, there was a heavy rain around Minato and Inagi radars. This rain became an obstruction which caused the conventional system to produce inaccurate measurement values around Saitama [shown as star in the figure]. On the other hand, a heavy rain in Saitama was able to be detected by Saitama radar, which is a part of our new system. For example, Table 3 shows the data from JMA. It shows the rainfall intensity of the star location shown in the figure. The new system shows the colors (pink 50 – 70 mm/h), which matches to the ground gauge data (69.0 mm/h). In this way, the new system can complement the limitation of the conventional system. New system increases its reliability and accuracy.

Table 3. Ground Gauge Data by JMA

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Area</th>
<th>Ground Gauge Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>July.30.2007</td>
<td>12:30 – 12:40</td>
<td>Koshigaya-City, Saitama-Pref</td>
<td>11.5 mm (10 min)</td>
</tr>
</tbody>
</table>
**Bright Band**

Figure 14 shows the time of the occurrence of bright band. Radar beam passes around the height of bright band, so the radar indicates heavy rains for weak ones. The left side of Figure 14 shows heavy rains outside Tokyo area caused by the effect of bright band. The right side of the same figure shows the result of increasing the number of ground gauge which successfully eliminates the effect of bright band. Table 4 shows the data from JMA. It shows the rainfall intensity of the star location shown in the figure. The new system shows the colors (blue 10 – 19 mm/h), which matches to the ground gauge data (12.0 mm/h). In this way, the new system can complement eliminate the effect of the bright band.

![Figure 14. Elimination of Bright Band](image)

(Left: the Old System, Right: the New System)

**Table 4. Ground Gauge Data by the JMA**

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Area</th>
<th>Ground Gauge Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec.29.2007</td>
<td>1:50 – 2:00</td>
<td>Hiyoshi, Kouhoukou-Ward, Yokohama-City</td>
<td>2.0 mm (10 min) 12.0 mm (60 min)</td>
</tr>
</tbody>
</table>
**Improvement of the Data Reliability**

Figure 15 shows the time of the long span rain in Kanto area. From 15:30 to 16:30, not a single ground gauges inside the area enclosed by red line in Figure 15 indicated over 15 mm. At that time, the old system had indicated the color which matches to over 20 mm/h rain for 20 minutes. But the new system show the color which match to below 20 mm/h rain during that time. This result shows composing the radar data and compensation by the ground gauge improve the radar accuracy.

![Figure 15. Improvement of the Data Reliability (Left: the Old System, Right: the New System)](image)

**DISCUSSION**

We can eliminate the effect of rainfall attenuation and bright band by composing the radar data and using the ground gauge data. And we can improve the accuracy of radar by using the reliability based on the specification of each radar. So we can say we succeeded in grasping the rainfall on the ground more accurately than ever.

However, in our current system, unnatural result will sometimes appear because of the difference of the height of the passing radar beam, the precision and the update period of the radar system. We show several examples below.

**Radiation Pattern**

Figure 16 shows a result of a situation in which it is difficult for our new system to determine the threshold we use in making an attenuation map because the attenuation is influenced by how heavy the rain is and the shape of the raindrops. It is difficult for us to determine the threshold by considering the shape of raindrops. Therefore, radiation pattern sometimes occurs in our results.
The precipitation on the same point will be measured differently by each radar because of the difference of the measurement period and the height of the beam of each radar. Especially, the specification of JMA radar system is inaccurate compared to the other systems, which caused a circle of the measurable area to appear shown as in the Figure 17.

These are the cases in which the radar will produce unnatural results like shown above. However, the measurable area has greatly expanded by using our new system and the accuracy has also increased. To alleviate these problems, we can approach from the software side such as
improving the method to define the threshold, or from the hardware side such as improving the accuracy of the system.

**CONCLUSION**
We can eliminate the effect of rainfall attenuation and bright band by composing the radar data and using the ground gauge data. And we can improve the accuracy of radar by using the reliability based on the specification of each radar. We confirmed that the composed data was effective for operation jobs through some cases of rainfall. Now, we consider the method of sensing the rainfall attenuation and compensating the lacked data by radar itself.

The new system has been used in the Bureau of Sewage, Tokyo Metropolitan Government in since April 2007 and the information obtained from the system has been updated to the Internet for public use since July 2007. These days, more and more people living in Tokyo have been accessing our website for the purpose of crisis management. We will keep trying to improving the accuracy of the rainfall data.

**REFERENCES**