

Special edition paper

Research on the Use of Doppler Radar in Railways



Ken-ichiro Arai*



Keiji Adachi*



Hiroyuki Morishima*

A train derailment on the Uetsu Line on December 25, 2005 was reported as having been caused by the train receiving localized gusts. JR East thus set up a Doppler weather radar on the roof of Amarume Station in March 2007 as such radars are considered to be suitable for observation of localized gusts. Utilizing the observation data of the radar, we are developing a prototype automatic gust detection system. The method of automatically extracting from weather radar data atmospheric vortices accompanying gusts at ground level was able to detect 10 cases of gusts—approx. 60% of the remarkable 16 gust cases observed by the high-density ground-level weather observation network at the Shonai Plain region of Yamagata Prefecture. At the same time, we are also proceeding with R&D to overcome technical problems revealed regarding the gust detection algorithm.

●Keywords: Doppler radar, Localized gust, Tornado, Downburst

1 Introduction

On December 25 2005, a derailment occurred near the Daini-Mogamigawa Bridge between Kita-Amarume and Sagoshi Stations on the Uetsu Main Line. Regarding the cause of the accident, the investigation results report of the Aircraft and Railway Accidents Investigation Commission (current Japan Transport Safety Board) pointed out that the accident occurred because the train received localized gusts exceeding the critical wind speed of overturning while it was running¹⁾.

In the field of railways, preventive measures against gusts are an important issue since gusts result in serious accidents and transport disruption. But, even though gusts such as tornados and downbursts (strong downdraft from cumulonimbus clouds) have destructive force, they form in a small space in a short span of time. That makes it difficult to detect those with existing anemometers placed at discrete points. Even if we could detect gusts with anemometers along the track, it would be too late to issue a gust warning and stop the train. Thus, for detecting gusts, it is necessary to make planar and continuous observation of motion of wind in a wide area at short cycles. Doppler radar is considered most appropriate for detecting such gusts, so we set up a small Doppler weather radar on the roof of Amarume Station on the Uetsu Line and started observation using that on March 1 2007 (Fig. 1, Table 1). The purpose of such observation was to verify performance in detecting gusts such as tornados and downbursts based on on-site observation and case analysis and to evaluate the feasibility of using Doppler radar in train operation control.

In this report, we will introduce efforts in gust detection at the Shonai Plain in Yamagata Prefecture. We will also introduce the method of the automatic gust detection algorithm using a small Doppler weather radar, actual cases of gust detection and development for application to railway operation control.



Fig. 1 Doppler Weather Radar on Roof of Amarume Station

2 Gust Detection with Doppler Radar: Principle and Flow

2.1 Doppler Weather Radar Characteristics and Gust Detection

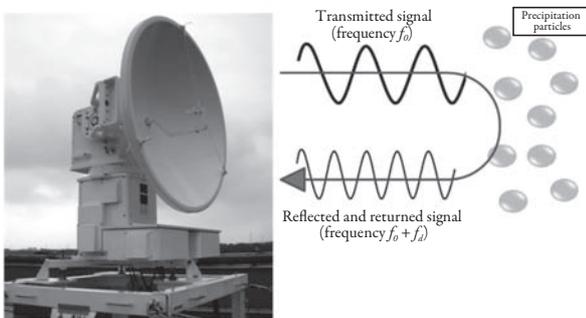
A Doppler weather radar is a device for weather observation that emits and receives signals while rotating its antenna to observe distribution of rain and wind in a wide area around it. It is thus considered the most suitable device for detecting gusts. The Japan Meteorological Agency (JMA) has already deployed larger Doppler radars nationwide. While those can observe a wide area, their spatial resolution is coarser at distances far away. Furthermore, they make observations higher in the atmosphere at greater distances. As they were not designed for railway use, larger radars are not entirely suitable for observing ground wind distribution that is important for railways. Smaller Doppler radars, while restricted in terms of observation area, are less expensive than larger ones and appropriate for focused observation of wind distribution in the lower atmosphere near railway lines.

Table 1 Major Specifications of Doppler Weather Radar at Amarume Station

Observation range	30 km
Range resolution	75 m
Azimuth resolution	0.7°
Antenna rotation rate	2 rpm
Frequency	9770 MHz
Peak transmitted power	40 kW
Antenna diameter	1.2 m

2.2 Principle of Gust Detection

Doppler weather radar emits signal beams from its antenna and utilizes the returned signal that is reflected by precipitation particles in the air to observe weather. Usual radars measure the positions of precipitation particles based on the time to receive the emitted signal that returns as a signal reflected by the particles, and they estimate the density of the particles based on the strength of the reflected signal (radar reflectivity). In this way, those radars estimate rainfall in the observation target area. In addition, Doppler radars figure out the velocity of the precipitation particles (Doppler velocity) based on the frequency shift of the reflected signal by the Doppler effect. They measure wind behavior by considering that velocity as the movement speed of the air (Fig. 2).



Doppler velocity $V_r \Rightarrow$ Velocity of rain and snow (considered as velocity of air)

$$V_r = -f_d \lambda / 2$$

Approaching radar: Negative
Receding from radar: Positive

λ : Wavelength of transmitted signal f_d : Frequency deviation by the Doppler effect

Fig. 2 Principle of Doppler Weather Radar

When observing counterclockwise vortices such as low-pressure areas, there is a pattern where wind speed elements relatively approaching are located on the left side of the radar and elements receding are located on the right side (Fig. 3). In cases where the difference between those two wind speed elements is locally large, there is a possibility that a strong spiral air flow such as a tornado exists there.

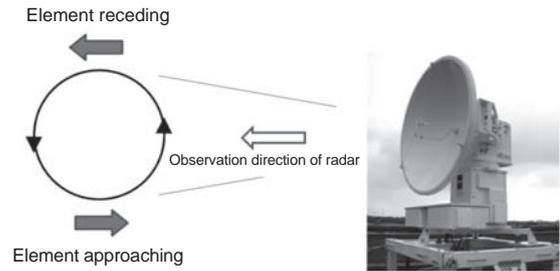


Fig. 3 Observation of Counterclockwise Vortex by Doppler Radar

2.3 Gust Observation in the Shonai Plain

From July 2007 to March 2010, we carried out basic research on a gust detection system using small Doppler radars for safe railway operation. That research was conducted with the Meteorological Research Institute (MRI) of the JMA, the Railway Technical Research Institute (RTRI) and the Disaster Prevention Research Institute of Kyoto University (DPRI), receiving support from the Japan Railway Construction, Transport and Technology Agency (JRJT). In this project, we set up a high-density ground-level weather observation network where a total of 26 weather observation devices measure items such as wind direction, wind speed and temperature at approx. 4 km intervals. That is in addition to the small Doppler weather radar on the roof of the Amarume Station (the JR radar). Using those, we investigated the relation between precipitation particle and wind behavior in the atmosphere detected by the JR radar and gust phenomena at ground level. In winters during the project period, the MRI set up a small Doppler radar on the roof of the Shonai Airport building (the MRI radar) to make 3D observations of the behavior of precipitation particles and wind (Fig. 4). In April 2009, we started joint research with the MRI.

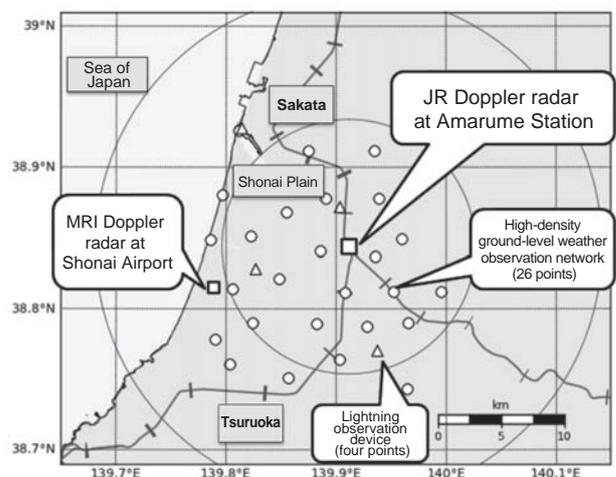


Fig. 4 Weather Observation Network at the Shonai Plain

Through those on-site observations and case analyses of strong cumulonimbus clouds that are considered to cause gust generation, we accumulated findings about gusts. Taking into account findings that gusts are observable by Doppler weather radar because of accompanying rainfall and that detected gusts accompanied small vortices up to a few kilometers in diameter, we have started development of a prototype automatic

gust detection system based on technologies for detection and monitoring of atmospheric vortices by smaller Doppler radar.

2.4 Gust Detection System Flow

In the on-site observations by the JR radar, we found a spiral air flow pattern in the Doppler velocity data in many cases of gust generation at ground level. With the gust detection system, we aim to accurately detect the vortices that cause gusts by automatically detecting this vortex pattern using the Doppler velocity distribution and narrowing down the vortices with the different parameters calculated from the Doppler velocity (Fig. 5). The core component of the system for detecting vortices is the system improved on and developed based on the mesocyclone detection algorithm²⁾ developed by the MRI.

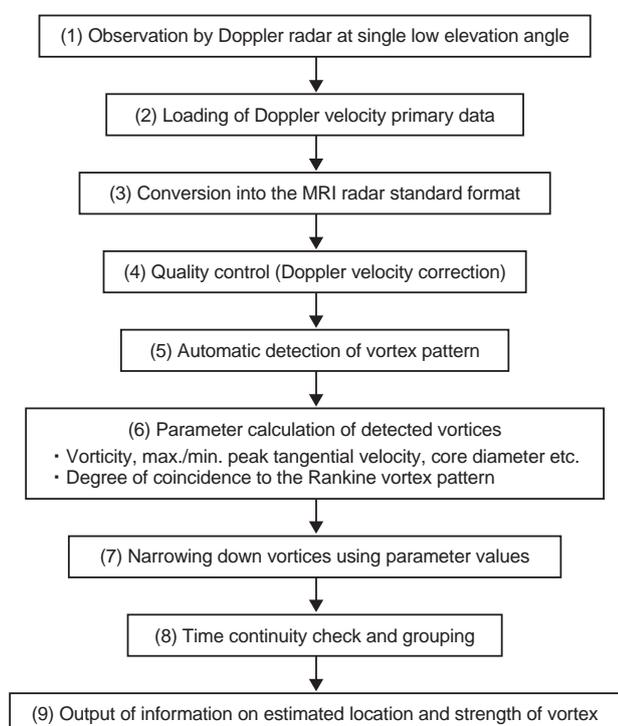


Fig. 5 Gust Detection Flow (method based on detection of atmospheric vortices)

2.5 Difference from JMA Tornado Nowcasts

The JMA has been announcing tornado watches since March 2008. And in May 2010, it started providing “tornado generation probability nowcasts” that analyze probability of a tornado being generated in a 10 km grid and offer prediction for one hour in the future updated every 10 minutes.

Tornado generation probability nowcasts and tornado watches are announced simply as information on the weather conditions where gusts tend to occur. They thus do not actually detect gust generation. In order to decide on train operation control, we need to temporally and spatially narrow down the gust location and movement direction at an early stage of gust generation.

In the automatic gust detection tests using the JR radar, we employed findings obtained through past observations to identify the diameter of the vortices to be detected as 200 m–2 km. We thus decided to fix the antenna elevation angle at 3.0° and

make observations at the frequency of one rotation every approx. 30 seconds. That enables high time resolution, achieving detection of gust phenomena that are small in size and short in time.

3 Examples of Detection in Automatic Gust Detection Tests

3.1 Actual Case of Automatic Gust Detection

At around 19:30 on December 3, 2010, a strong nimbus cloud accompanied by high winds passed near Sakata City. In this case, the results of the automatic real-time gust detection tests using the JR radar show that the radar started detecting a vortex from the data at 19:27:03 and continued detecting it until 19:43:08 (Fig. 6 and Fig. 7). The radar reflectivity data proved that the spiral nimbus cloud passed to the east-northeast of Sakata City and the system intermittently detected the gust area around the center of the vortex. The trajectory of the point of detection of the vortex clarified that a vortex was generated over the Sea of Japan, made landfall and passed near Higashi-Sakata Station on the Uetsu Main Line at around 19:41. The maximum wind speed estimated from the detection records was approx. 36 m/s, recorded over the Sea of Japan just before making landfall. There were no reports of gusts or damage at ground level accompanying the spiral nimbus cloud.

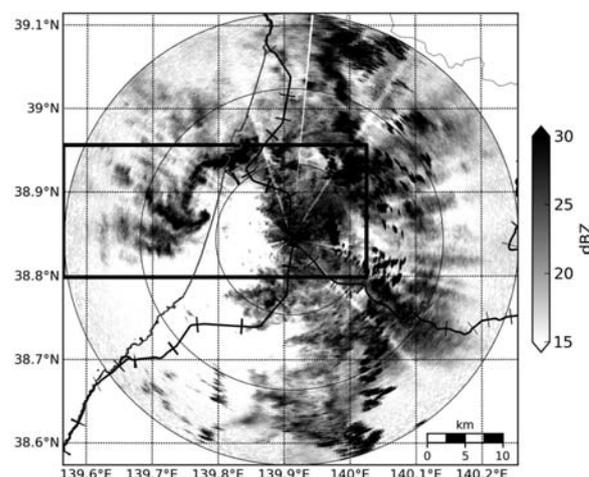


Fig. 6 Radar Reflectivity at 19:33:53 on December 3, 2010

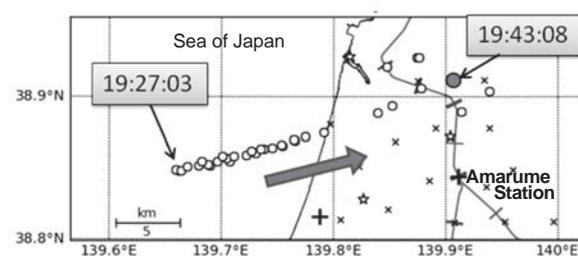


Fig. 7 Trajectory of a Vortex Detected from 19:27:03 to 19:43:08 on December 3, 2010 (area enclosed with black frame in Fig. 6)

3.2 Verification of the Automatic Gust Detection System

Of the cases where the high-density ground-level weather observation network confirmed gust generation in the period from November 2007 to February 2010, researchers of the MRI found spiral nimbus clouds in 16 cases using the reflectivity data of the JR radar. In verification of the automatic gust detection system using the Doppler velocity data of the JR radar in those 16 cases, we found 10 cases where the system could detect atmospheric vortices that accompanied gusts at ground level (including partial detection). In the remaining six cases, the system could not detect vortices.

3.3 Issues with the Automatic Gust Detection System

Tracing the time history of detection in successful detection cases mentioned in 3.1 has revealed technical issues with the current automatic gust detection system (Fig. 8).

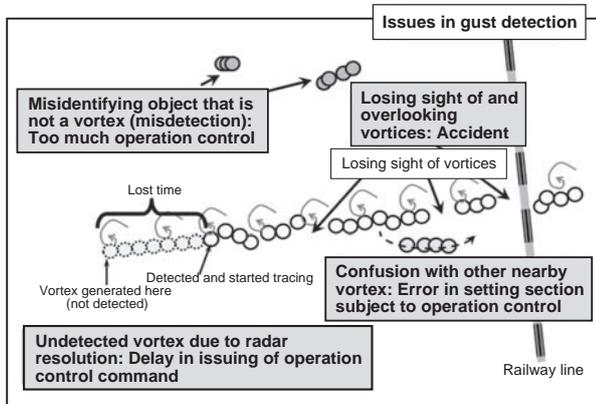


Fig. 8 Issues with Automatic Gust Detection System

- (1) At distances far away from the radar, the system sometimes cannot automatically detect vortices at the initial stage of generation. This leads to a delay in issuing train operation control commands.
- (2) The system sometimes loses sight of a vortex temporarily or intermittently. If the system misidentifies the loss as the dissipation of the vortex, we lose sight of the movement of the gust area, preventing necessary operation control commands from being issued.
- (3) If another vortex exists near the vortex being traced, the system becomes confused in predicting the direction of the vortex. This leads to errors in designating sections subject to train operation control.
- (4) If the system misidentifies something as a vortex when it is not, this will lead to incorrect operation control, disrupting stable transport.

Since the algorithm of the current automatic gust detection system completely depends on the detection of vortices, the system overlooks or misdetects gusts without an atmospheric vortex or vortices without gusts, even though it can correctly detect gusts at ground level accompanying an atmospheric vortex. Such incidents may cause an accident or excessive operation control (Fig. 9).

In order to overcome those issues, we will make detailed high-density ground-level observation that can clarify the detailed structure of gusts at ground level. And we will investigate the relation of that structure to characteristics seen in the radar data of the sky as well as repeatedly improve on and test the gust detection algorithm. Moreover, we must work to improve detection accuracy through these efforts.

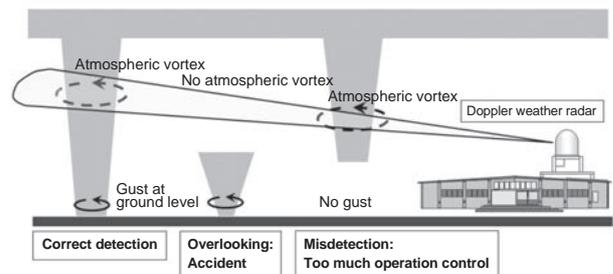


Fig. 9 Deterioration of Detection Ability Due to Complete Dependence on Detection of Atmospheric Vortices and Effect on Operation Control

4 Conclusion

Doppler radars are the most suitable meteorological observation devices for detecting gusts. However, the issues of detection accuracy improvement and cost of introduction must be overcome before they can be practically introduced. We thus focused on lightning that occurs under similar conditions to gusts and started research on lightning discharge and gusts at ground level in fiscal 2009. In October 2010, we set up at the Shonai Plain four lightning observation devices jointly developed with the MRI to make 3D observations of lightning discharge. We are exploring the possibilities of improving gust detection ability and compensating the area without radar by combining the data with gust detection by Doppler radar. We will also set ultrasonic anemometers and barometers at intervals of 100 m or less on a 500 m or longer straight-line area for observation to acquire a detailed horizontal structure of gusts. This is in addition to the current on-ground weather observation network. Moreover, we will work to further improve detection accuracy through that research.

Acknowledgement:

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Reference:

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- 2) Osamu Suzuki, Hiroshi Yamauchi, Masahisa Nakazato and Kenji Akaeda, “A new multi-scale meso-vortex/divergence detection algorithm with modified Rankine combined vortex,” *Preprint, 33rd Conference on Radar Meteorology* (2007)