

Recent Advances in Phased Array Weather Radar

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SUMMARY Numerous meteorological disasters recur almost annually. One of the most effective means to observe these phenomena causing such disasters is meteorological radar. A group comprising Toshiba, the National Institute of Information and Communications Technology (NICT), and Osaka University has developed an X-band phased array radar, improving observation time from the conventional 10-minute duration to just 30 seconds by using phased array technology. The initial radar was installed at Osaka University in May 2012, and was recently replaced by a dual-polarization one. Phased array radar has demonstrated superior temporal and spatial resolution compared to conventional radars and has shown equivalent accuracy in observing variables such as rain rate. Future research is expected to illuminate the advantages and limitations of dual-polarization phased array radar networks, fostering their widespread adoption not only in Japan but also globally.

key words: weather radar, phased array radar

1. Introduction

In recent years, due to global warming, numerous meteorological disasters have been recurring almost annually. According to statistics from the Japan Meteorological Agency [1], there is an increasing trend in the number of heavy rainfall events exceeding 50 mm/h in recent decades. For instance, on July 28, 2008, a water-related accident [2] occurred in Nada county, Kobe City, Hyogo Prefecture, at the Toga River, where more than 10 people who were near the riverbank for activities such as playing in the water were swept away by a sudden rise in water levels. Among them, five individuals, including two elementary school students and one nursery school child, lost their lives.

The most effective means of observing these phenomena that lead to such disasters is through remote sensing technology utilizing electromagnetic waves, well-known as meteorological radar technology [3]. The advantage of this method lies in its capability to instantly observe the structure of rainfall events over extensive areas ranging from tens to hundreds of kilometers. Consequently, organizations like the Ministry of Land, Infrastructure, Transport, and Tourism, as well as the Japan Meteorological Agency, have established a radar network covering the entire country, aiding in current situation assessment and prediction. Consequently, through platforms like the web and news broadcasts, we can see the distribution of rainfall.

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The radar widely used today generally employs a parabolic antenna type and utilizes a mechanical scanning method where the antenna, with a beam width of about one degree, rotates 360 degrees in the azimuthal direction while gradually raising its elevation to observe [4]. However, with this method, for scanning near the ground level, it takes approximately 1 to 5 minutes, and for three-dimensional volumetric observation, it requires 5 to over 10 minutes. In contrast, cumulonimbus clouds that bring localized heavy rainfall rapidly develop in about 10 minutes, and tornadoes can form and move in just a few minutes. Consequently, using a parabolic antenna-based mechanical scanning method makes it difficult to continuously observe the process from formation to development and decaying of these atmospheric



Fig. 1 Photograph of the Dual Polarization Phased Array Weather Radar in Osaka University. At the top of the building in the electrical engineering department, the radar facilities of planar array configuration are equipped.

phenomena. This limitation has been a significant obstacle to understanding the generation mechanisms of these phenomena, discovering precursor events, and issuing swift warnings and predictions.

2. Phased Array Weather Radar

In such circumstances, electronically scanned radars utilizing phased array technology are more suitable than mechanically scanned radars. Phased array technology, proposed

since the early 1900s during the initial development of radar, has primarily been researched and developed for aircraft detection purposes [5]. Subsequently, research and development for meteorological applications were carried out by repurposing S-band radars initially designed for aircraft detection [6]. However, there have been few instances of phased array radar development specifically intended for radar networks using the X-band.

A group comprising Toshiba, the National Institute of Information and Communications Technology (NICT), and

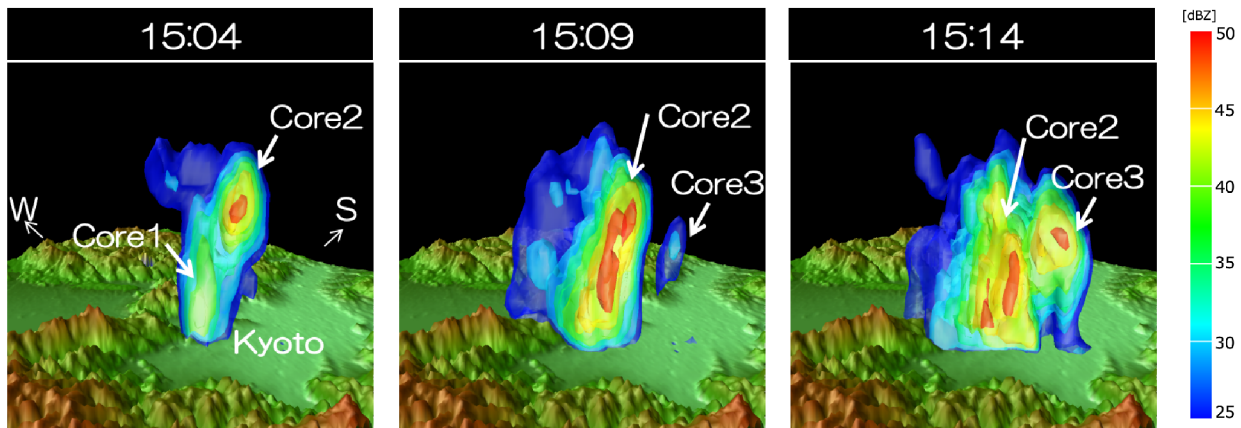


Fig. 2 One example of the observation by the Phased Array Weather Radar in Osaka University on August 5 in 2013.

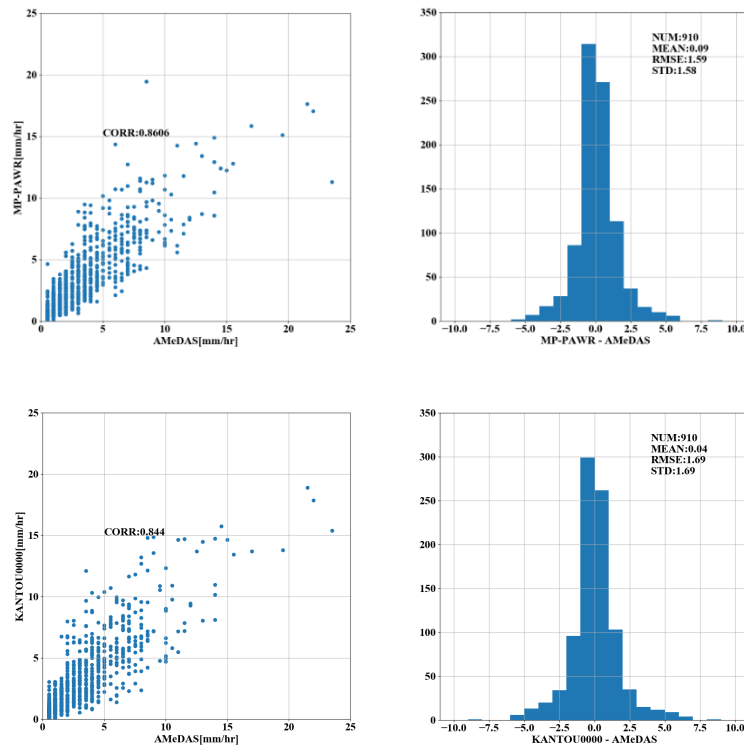


Fig. 3 Comparison of the rainfall estimation of Dual Polarization Phased Array Weather Radar (MP-PAWR: top two panel) with Parabola type Radar at X band (KANTOU) (low two panel). Scatter plots are shown on the left column, and histogram plots of rain rate measured by MP-PAWR and XRAIN compared to rain gauge measurements are on the right.

Osaka University developed an X-band phased array Doppler radar [7], [8] in 2012. Instead of mechanical antenna scanning, this radar employs an electronic and software-driven scanning method, significantly reducing observation time to a remarkably short duration of 10 to 30 seconds. This innovative approach enables detailed three-dimensional observation of rainfall in a fraction of the time previously required.

Figure 1 shows the external appearance and a photo of the antenna. Notably, the antenna's shape has transitioned from the conventional parabolic form to a planar configuration.

The phased array radar, unlike conventional radars that mechanically move antennas in various directions, synthesizes electromagnetic waves emitted from numerous small antennas arranged in a planar configuration by controlling

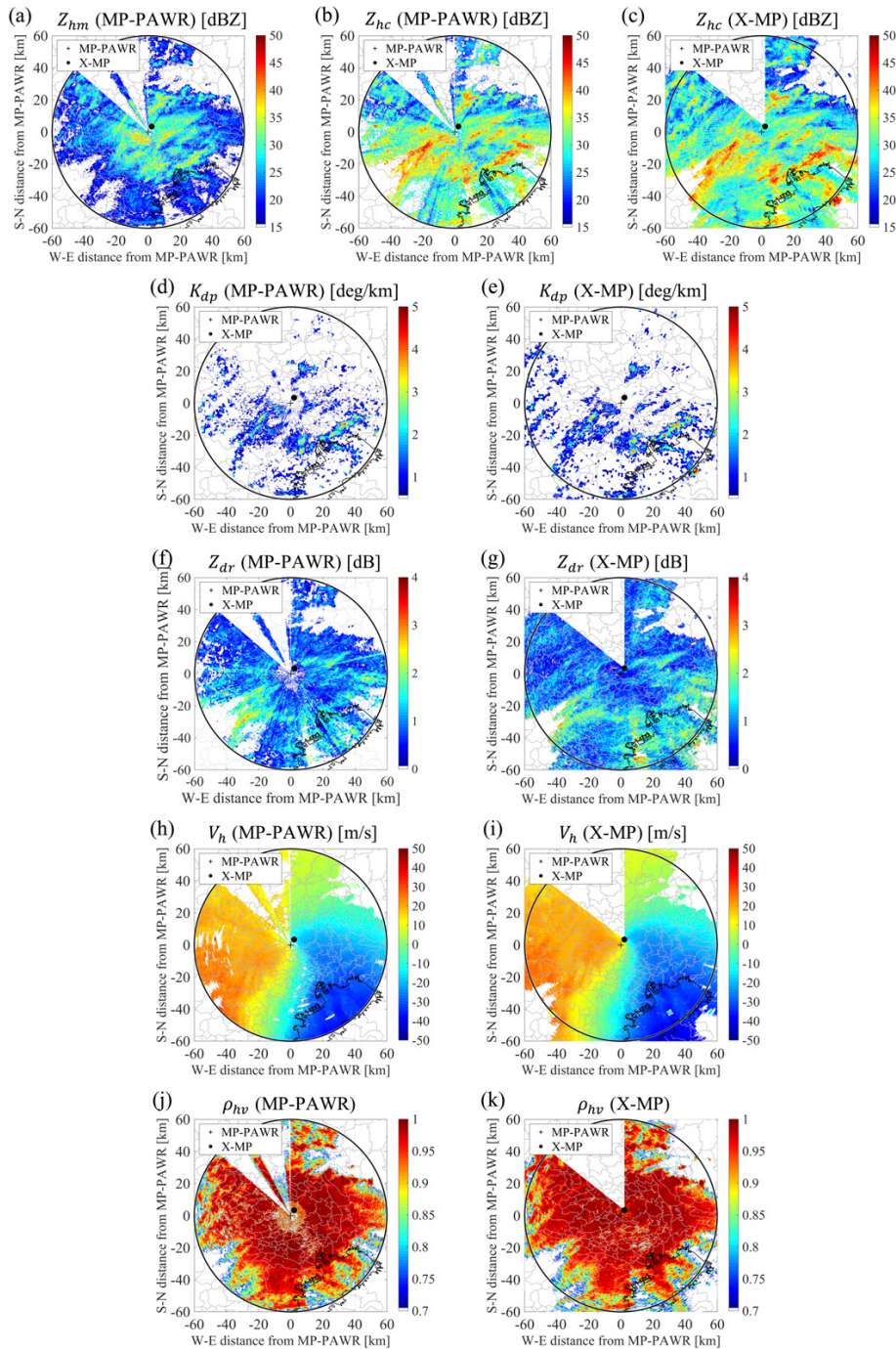


Fig. 4 Comparisons of observation parameters of Dual Polarization Phased Array Weather Radar with Parabolic type radar system (X-MP). Left column is from the MP-PAWR measurements and the right is from the X-MP measurements. Adapted from [8] @ American Meteorological Society. Used with permission.

the phase of these waves through circuits. This radar scans by swiftly forming beams, making it well-suited for high-speed scanning compared to mechanically driven systems.

The first unit was installed atop Building E3 on Osaka University's Suita Campus in May 2012. Subsequently, a dual-polarization phased array weather radar was installed in the Greater Tokyo Area in December 2017, incorporating dual-polarization capabilities and was utilized during the Tokyo Olympics. Additionally, in December 2022, Osaka University's single-polarization phased array radar was also upgraded to dual-polarization. An example of observational results, an isolated thunderstorm observed on August 5, 2013, is depicted in Fig. 2. This high-resolution image of the three-dimensional structure of the cumulonimbus cloud from dense observations of nearly 100 elevation angles demonstrates the radar's capabilities with high spatiotemporal resolution. While the presented data is shown in 5-minute intervals for publication purposes, the radar's performance allows for observations every 30 seconds to 1 minute. Leveraging such information can significantly enhance the accuracy of predictions regarding heavy rainfall.

Since its implementation, various types of precipitation events and cumulonimbus clouds have been observed, prompting numerous research projects. For instance, a project with the RIKEN 'K' computer in Kobe conducted data transmission from this radar to 'K,' inputting it into the latest weather forecasting technique known as data assimilation to assess the extent of prediction and mitigation possibilities [9], [10]. Moreover, the data was made publicly available on platforms like YAHOO's website. These accomplishments garnered attention in numerous TV news broadcasts and newspapers as representative research achievements of 'K' during its transition to 'Fugaku.'

As mentioned earlier, in December 2022, Osaka University's phased array radar was dual-polarized, enabling more precise estimation of precipitation and particle identification. Additionally, similar radar installations were set up at NICT Kobe, facilitating network observations by multiple units. Presently, these radars are utilized for precise calibration experiments and evaluating rainfall estimation accuracy. Figure 3 shows a comparison of rainfall estimation of the dual polarization Phased Array Weather Radar with parabolic type radar system at X band. In this study, rain fall estimation from the rain gauges are regarded as truth. Both correlation and RMSE show that the estimation from the Phased Array Weather Radar is better than the conventional radar, probably because the Phased Array Weather Radar can obtain more independent samples from the multiple elevations than the parabolic type can.

Comparisons between observations from the phased array radar and conventional parabolic radar installed near the phased array radar can be found in [11]. Figure 4 shows one example of comparison for reflectivity factor (Z), specific differential phase (KDP), differential reflectivity (Z_{dr}), doppler velocity (V), and co-polar correlation coefficient (ρ). Observations concerning radar reflectivity after rainfall attenuation correction showed a correlation coefficient of

approximately 0.88 between both methods, with an RMSE of a few dBZ. It is also shown that other parameters show similar pattern. Note that the observation by the Phased Array Weather Radar have comparable qualities in radar measurements to the conventional radar system.

Thus, the phased array radar has demonstrated not only superior time and spatial resolution but also equivalent accuracy in observing variables compared to conventional radars. It is anticipated that through such investigations, the advantages and limitations of dual-polarization phased array radar networks will be shown. Additionally beamforming technologies will also increase the potential of phased array radar [12]–[16].

3. Future Perspectives

As seen from the data captured by this radar, the images or videos showcased are profoundly impactful, highlighting the remarkable potential of phased array radar technology, expecting to be used in applications such nowcast and data assimilation [17]–[20]. The detailed three-dimensional observational data obtained using these radars has been poised to unravel the mechanisms behind cumulonimbus clouds that swiftly trigger heavy rainfall [21]–[24]. This progression is expected to lead the world in fundamental scientific fields, elucidating mechanisms related to heavy rainfall, gusts, tornadoes, and cumulonimbus cloud development.

Moreover, the collaborative research and development with 'Fugaku' aimed at enhancing the precision and sophistication of weather forecasting are anticipated to significantly transform the conventional concepts of meteorological prediction. It's expected that the advancement in these studies will bring about a notable impact, potentially reshaping the very concepts ingrained in meteorological observation and disaster prevention systems.

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References

- [1] https://www.data.jma.go.jp/cpdinfo/extreme/extreme_p.html
- [2] http://www.thr.mlit.go.jp/sendai/kasen_kaigan/river-attention/pdf/02.pdf
- [3] H.B. Bluestein, "Severe Convective Storms and Tornadoes," *Observations and Dynamics*, Springer Praxis Books, Berlin, 2013
- [4] V. Chandrasekar, R.M. Beauchamp, R. Bechini, "Introduction to Dual Polarization Weather Radar," Cambridge University Press, 2023.
- [5] R. Palmer, D. Bodine, P. Kollias, D. Schwartzman, D. Zrnić, P. Kirstetter, G. Zhang, T.-Y. Yu, M. Kumjian, B. Cheong, S. Collis, S. Frasier, C. Fulton, K. Hondl, J. Kurdzo, T. Ushio, A. Rowe, J. Salazar-Cerreño, S. Torres, M. Weber, and M. Yeary, "A primer on phased array radar technology for the atmospheric sciences," vol. 103, no. 10, pp. E2391–E2416, 2022.
- [6] D.S. Zrnic, J.F. Kimpel, D.E. Forsyth, A. Shapiro, G. Crain, R. Ferek, J. Heimmer, W. Benner, F.T.J. McNellis, and R.J. Vogt, "Agile-Beam Phased Array Radar for Weather Observations," *Bulletin of*

- the American Meteorological Society, vol.88, no.11, pp.1753–1766, 2007, DOI: 10.1175/BAMS-88-11-1753
- [7] E. Yoshikawa, T. Ushio, Z. Kawasaki, S. Yoshida, T. Morimoto, F. Mizutani, and M. Wada, “MMSE Beam Forming on Fast-Scanning Phased Array Weather Radar,” *IEEE Trans. Geosci. Remote Sens.*, vol.51, no.5, pp.3077–3088, 2013.
 - [8] F. Mizutani, T. Ushio, E. Yoshikawa, S. Shimamura, H. Kikuchi, M. Wada, S. Satoh, and T. Iguchi, “Fast-Scanning Phased Array Weather Radar with Angular Imaging Technique,” *IEEE Trans. Geosci. Remote Sens.*, vol.56, no.5, pp.2664–2673, 2018, DOI: 10.1109/TGRS.2017.2780847
 - [9] T. Miyoshi, G.-Y. Lien, S. Satoh, T. Ushio, K. Bessho, H. Tomita, S. Nishizawa, R. Yoshida, S. Adachi, J. Liao, B. Gerofi, Y. Ishikawa, M. Kunii, J. Ruiz, Y. Maejima, S. Otsuka, M. Otsuka, K. Okamoto, and H. Seko, ““Big Data Assimilation” Toward Post-Petascale Severe Weather Prediction: An Overview and Progress,” *Proc. IEEE*, vol.104, no.11, pp.2155–2179, 2016.
 - [10] T. Miyoshi, M. Kunii, J. Ruiz, G. Lien, S. Satoh, T. Ushio, K. Bessho, H. Seko, H. Tomita, and Y. Ishikawa, ““Big Data Assimilation” Revolutionizing Severe Weather Prediction,” *Bull. Amer. Meteor. Soc.*, vol.97, no.8, pp.1347–1354, 2016, DOI: 10.1175/BAMS-D-15-00144.1
 - [11] K. Asai, H. Kikuchi, T. Ushio, and Y. Hobara, “Validation of X-Band Multiparameter Phased-Array Weather Radar by Comparing Data from Doppler Weather Radar with a Parabolic Dish Antenna,” *J. Atmos. Ocean. Tech.*, vol.38, no.9, pp.1561–1570, 2021.
 - [12] H. Kikuchi, T. Wu, E. Yoshikawa, T. Ushio, H. Goto, F. Mizutani, M. Wada, V. Chandrasekar, “Performance of Minimum Mean-Square Error Beam Forming for Polarimetric Phased Array Weather Radar,” *IEEE Trans. Geosci. Remote Sens.*, vol.55, no.5, pp.2757–2770, 2017.
 - [13] H. Kikuchi, E. Yoshikawa, T. Ushio, F. Mizutani, and M. Wada, “Application of Adaptive Digital Beamforming to Osaka University Phased Array Weather Radar,” *IEEE Trans. Geosci. Remote Sens.*, vol.55, no.7, pp.3875–3884, 2017, DOI: 10.1109/TGRS.2017.2682886
 - [14] D. Kitahara, H. Kuroda, A. Hirabayashi, E. Yoshikawa, H. Kikuchi, T. Ushio, “Nonlinear beamforming based on group-sparsities of periodograms for phased array weather radar,” *IEEE Trans. Geosci. Remote Sens.*, vol.60, pp.1–19, 2022, DOI: 10.1109/TGRS.2022.3154118
 - [15] H. Kuroda, D. Kitahara, E. Yoshikawa, H. Kikuchi, T. Ushio, “Convex Estimation of Sparse-Smooth Power Spectral Densities From Mixtures of Realizations With Application to Weather Radar,” *IEEE Access*, vol.11, pp.128859–128874, 2023, DOI: 10.1109/ACCESS.2023.3333524
 - [16] Y. Wada, Y. Takata, H. Kikuchi, D. Kitahara, E. Yoshikawa, S. Shimamura, and T. Ushio, “Mitigation of Ground-Clutter Effects by Digital Beamforming with Precomputed Weighting Matrix for Phased Array Weather Radar,” *IEEE Trans. Geosci. Remote Sens.*, vol.62, pp.1–14, 2024, DOI: 10.1109/TGRS.2024.3357879
 - [17] S. Otsuka, G. Tuerhong, R. Kikuchi, Y. Kitano, Y. Taniguchi, J.J. Ruiz, S. Satoh, T. Ushio, and T. Miyoshi, “Precipitation Nowcasting with Three-Dimensional Space-Time Extrapolation of Dense and Frequent Phased-Array Weather Radar Observations,” *Wea. Forecasting*, vol.31, pp.329–340, 2016, DOI: 10.1175/WAF-D-15-0063.1
 - [18] D.-K. Kim, T. Suezawa, T. Mega, H. Kikuchi, E. Yoshikawa, P. Baron, and T. Ushio, “Improving precipitation nowcasting using a three-dimensional convolutional neural network model from Multi Parameter Phased Array Weather Radar Observations,” *Atmos. Res.*, vol.262, p.105774, 2021.
 - [19] D. Kim and T. Ushio, “Nowcasting Meso-r-Scale Convective Storms Using Convolutional LSTM Models and High-Resolution Radar Observations,” *Tellus A*, vol.74, no.1, pp.17–32, 2022, DOI: 10.16993/tellusa.37
 - [20] P. Baron, K. Kawashima, D. Kim, H. Hanado, S. Kawamura, T. Maesaka, K. Nakagawa, S. Satoh, and T. Ushio, “Nowcasting Multi-parameter Phased-Array Weather Radar (MP-PAWR) Echoes of Localized Heavy Precipitation Using a 3D Recurrent Neural Network Trained with an Adversarial Technique,” *J. Atmos. Ocean. Tech.*, pp.803–821, 2023, DOI: 10.1175/JTECH-D-22-0109.1
 - [21] T. Adachi, K. Kusunoki, S. Yoshida, K. Arai, and T. Ushio, “High-Speed Volumetric Observation of Wet Microburst using X-band Phased Array Weather Radar in Japan,” *Mon. Weather Rev.*, pp.3749–3765, 2016, DOI: 10.1175/MWR-D-16-0125.1
 - [22] T. Adachi, K. Kusunoki, S. Yoshida, H. Inoue, K. Arai, and T. Ushio, “Rapid volumetric growth of mesocyclone and vault-like structure in horizontal shear observed by phased array weather radar,” *SOLA*, vol.12, pp.314–319, 2016, DOI: 10.2151/sola.2016-061.
 - [23] S. Yoshida, T. Adachi, K. Kusunoki, S. Hayashi, T. Wu, T. Ushio, and E. Yoshikawa, “Relationship between thunderstorm electrification and storm kinetics revealed by phased array weather radar,” *J. Geophys. Res.*, vol.122, no.7, pp.3821–3836, 2017, DOI: 10.1002/2016JD025947
 - [24] T. Wu, Y. Takayanagi, S. Yoshida, T. Funaki, T. Ushio, and Z. Kawasaki, “Spatial relationship between lightning narrow bipolar events and parent thunderstorms as revealed by phased array radar,” *Geophys. Res. Lett.*, vol.40, no.3, pp.618–623, 2013, DOI: 10.1002/grl.50112
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