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Global Navigation Satellite System(GNSS)-Based Near-Realtime Analysis of Typhoon Track for Maritime Safety*

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해상안전을 위한 GNSS 기반 태풍경로 실시간 분석*

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ABSTRACT

In this study, in order to analyze the possibility of observing a typhoon track based on the Global Navigation Satellite System(GNSS), Typhoon NARI, the 11th typhoon of 2007, was analyzed in terms of the typhoon track as well as the local variation of perceptible water over time. The perceptible water was estimated using data obtained from observatories located on the typhoon track from Jeju to the southern coast of Korea for a total of 18 days from September 7(DOY 250) to September 24(DOY 267), 2007, including the period when the observatories were affected by the typhoon at full-scale, as well as one previous week and one following week. The results show that the trend of the variation of perceptible water was similar between the observatories near the typhoon track. Variation of perceptible water over time depending on the development and landing of the typhoon was distinctively observed. Several hours after the daily maximum of perceptible water was found at the JEJU Observatory, the first struck by the typhoon on the typhoon track, the maximum value was found at other observatories located on the southern coast. In the observation period, the time point at which the maximum perceptible water was recorded in each location was almost the same as the time point at which the typhoon landed at the location. To analyze the accuracy of the GNSS-based perceptible water measurement, the data were compared with radiosonde-based perceptible water data. The mean error was 0.0㎝, and the root mean square error and the standard deviation were both 0.3㎝, indicating that the GNSS-based perceptible water data were highly accurate and precise. The results of the

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this study show that the GNSS-based perceptible water data may be used as highly accurate information for the analysis of typhoon tracks over time.

KEYWORDS : GNSS,typhoon, precipitation, water vapor, maritime safety

요　　약

본 연구는 GNSS 기반 태풍경로 관측 가능성을 분석하기 위해 2007년 11호 태풍인 NARI의 태풍경로와 시간변화에 따른 지역별 가강수량을 분석하였다. 가강수량은 제주에서 남해안까지 태풍경로상에 위치한 관측소가 태풍의 영향을 직접적으로 받은 기간과 전·후 일주일을 포함하여(2007년 9월 7일(DOY250)부터 9월 24일(DOY267)까지) 총 18일간의 자료를 이용하여 추정 하였다. 그 결과 가강수량의 변화 추세는 태풍의 경로 근처 관측소의 결과와 유사하였으며 태풍의 발달과 지상에 도달하는 시간변화에 따라 달라지는 것을 확인하였다. 처음 태풍이 강타한 JEJU 관측소에서 일일 최대 가강수량이 관측된지 몇 시간 후, 남해안에 다른 관측소에서 가강수량이 최대값으로 나타났으며 각 관측소에서 최대 가강수량을 기록한 시점이 태풍이 해당 관측소에 도달한 시점과 거의 일치 하였다. GNSS기반 가강수량 측정의 정확도를 분석하기 위해, 데이터는 라디오존데 기반 가강수량 데이터와 비교하였다. 그 결과, 평균 오차 0.0㎝, RMSE 0.3㎝로 GNSS 기반 가강수량 데이터가 정확하고 정밀하다는 것을 보여주었다. 따라서, 본 연구 결과는 GNSS를 기반으로한 가강수량 데이터를 시간변화에 따른 태풍경로 분석에 사용할 수 있다는 것을 보여주고 있다.

주요어 : GNSS, 태풍, 강수, 수증기, 해상안전

INTRODUCTION

Weather conditions are critical factors to maritime safety. Particularly, typhoons cause very dangerous weather conditions, including localized torrential rain, gales, and surges. With the recent acceleration of global warming, the frequency of typhoon development has increased due to the climate change, resulting in nation-wide social and economic damage(Chen *et al.*, 2016; Zhang and Chen, 2018). Globally, about 30 typhoons are known to develop each year, and those that are not dissipated at sea but approach land may cause coastal erosion, destruction of port facilities, loss and collision of vessels, marine accidents, and deadly consequences. Furthermore, typhoons that strike land fluctuate in track and size, making it difficult to analyze tracks accurately. Therefore, many countries have established national disaster safety systems to provide information about typhoons and ensure preparedness against possible damage, and share observation and analysis data internationally to predict typhoon tracks (Jelesnianski, 1965; Jones and Davies, 2009; Mastenbroek, Burgers, and Janssen, 1993).

Observing the amount of vapor in the atmosphere is necessary to investigate and predict a typhoon track. The representative meteorological observation instruments are microwave radiometer(MWR) and radiosonde. When a typhoon develops, a radiosonde is used to intensively observe the air temperature, atmospheric pressure, and vapor content of the upper atmosphere. A radiosonde is atmospheric observation equipment that is sent aloft with attached meteorological sensors. Therefore, observation failure often occurs due to gales at locations near typhoons. MWR is electromagnetic wave-based equipment for continuous observation; it has no limitations resulting from observation method such as those of a radiosonde. However, the water drops formed on the sensors during torrential rain may disturb the continuity of observation data or increase error. On the other hand, the Global Navigation Satellite System(GNSS) allows continuous observation based on electromagnetic wave, regardless of gales and torrential rainfall, and provides analytical results of excellent accuracy; thus, the efficacy of GNSS as an meteorological observation instrument has been recognized (Bevis *et al.*, 1992; Baker *et al.*, 2001; Gutman and Benjamin, 2001). In meteorological observation using GNSS, the amount of atmospheric vapor is estimated from the inverse of the propagation delay error (Davis *et al.*, 1985), and the observation performance of GNSS is almost the same as that of radiosonde(Gutman and Benjamin, 2001; Ha *et al.*, 2003; Ha *et al.*, 2010). In this study, for the purpose of improving maritime safety, perceptible water vapor (PWV) was analyzed using GNSS observatories in the track of a typhoon, and the possibility of observing typhoon tracks using GNSS was analyzed.

METHODS

In this paper, to analyze the possibility of observing typhoon tracks using GNSS, the PWV was analyzed using GNSS observatories in the track of a typhoon. The observatories used in the analysis were in the area between Jeju and the southern coast of Korea, areas that are common in tracks of typhoons approaching the Korean Peninsula and places where many ships navigate. The analyzed typhoon was Typhoon NARI, the 11th typhoon of 2007, which landed in the area and caused relatively large damage. Typhoon NARI was active between September 13 and September 17, 2007, and first appeared on September 11, 2007 out at sea southeast of Okinawa, Japan. The early forecast predicted that the typhoon would move to the northwest and gradually turn to the north and reach the southern sea of Korea. The typhoon in the southern sea of Korea was expected not to be very strong, as the central pressure was predicted to be 990hPa(intensity level 'weak'). However, in contrast to the initial forecast, as the typhoon was moving to the west-north-west, it rapidly developed, within 24 hours, from its initial formation to one that had an intensity level of 'strong', with a central pressure of 960hPa. While maintaining the intensity, the typhoon passed through the sea about 20㎞ south of Seoguipo at noon (KST) on September 16(03 o'clock UTC); it landed at Goheung-gun, Jeonnam, at about 6 o'clock in the evening of the same day(09 o'clock UTC), and penetrated the southern inlands of the Korean Peninsula. The areas struck by Typhoon NARI were declared special disaster areas. Within just the one day of September 16, the torrential rainfall reached 536.5㎜ at Witsaeorem near Mt. Hala and 239㎜ at Goheung-gun, Jeonnam. FIGURE 1 shows the track of

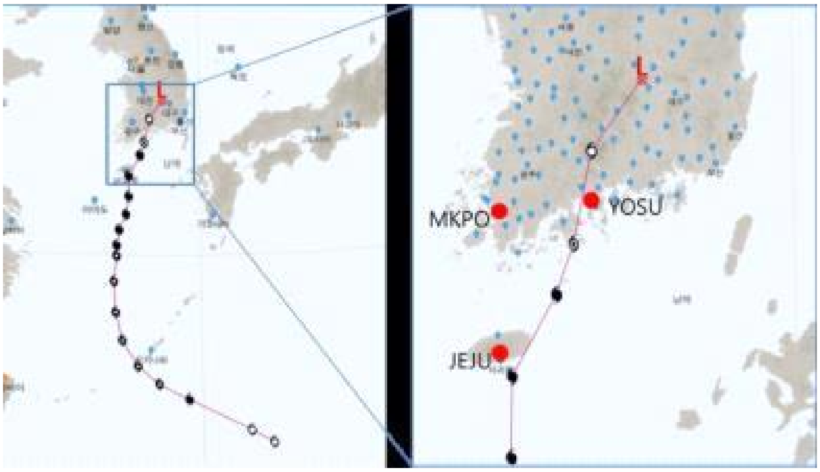

FIGURE 1. Track of Typhoon NARI from September 13 to 17, 2007 (Korea Meteorological Administration) and locations of GNSS observatories.

Typhoon NARI(Korea Meteorological Administration).

In the this study, in order to calculate the variation of the PWV over time depending on the movement of the typhoon and to analyze the variation of the PWV in comparison with torrential rainfall records in individual locations, data were obtained from the GNSS observatory located on Jeju, the island in the track of the Typhoon NARI, and from the observatories located in Yeosu and Mokpo, Jeonnam, which are cities having important harbors, with Goheung in the middle. The PWV was estimated using the JEJU, MKPO, and YOSU observatories, which are the permanent GNSS observatories operated in Korea by the Korea Astronomy and Space Science Institute(KASI). The KASI operates nine permanent GNSS observatories in Korea; Paroscientific MET sensors are installed in all the observatories for atmospheric observation. The GNSS observation data used in the analysis were the data for the period when Jeju Island was affected by the typhoon at full-scale, from September 14(DOY 257) to 17(DOY 260), as well as data for one previous week and one following week. Therefore, the data used were the epoch data of 24 hours and 30 seconds observed over a total of 18 days between September 7 (DOY 250) and 24(DOY 267), 2007. The data were obtained simultaneously from the MET sensors, which are interconnected with the GNSS observation instruments.

TABLE 1. Positions of GNSS observatores in track of Typhoon NARI.

	Latitude (°)	Longitude (°)	Height (m)
JEJU	33.288344277	126.462174975	431.2262086
MKPO	34.816851259	126.381408837	65.382885
YOSU	34.757224051	127.706274306	121.8725183

Table 1 shows the positions of the observatories.

The GPS Inferred Positioning System-Orbit Analysis and Simulation Software (GIPSY-OASIS) and the ultra-rapid orbit were used for the GPS processing. The variation of the amount of vapor was corrected in accordance with the antenna phase center variation(PCV), the ocean tidal loading displacement, and the azimuthal gradient. The critical altitude was determined to be 10° . The absolute calibration model was employed for PCV calibration, and the FES2004 model was employed for ocean tidal loading displacement calibration. The tropospheric delay was estimated at intervals of five minutes by random walk process based on prior values. The estimated GNSS-based tropospheric delay was substituted with the Korean version of the mean temperature equation to calculate the PWV. For validation of PWVs derived from GNSS measurements, radiosonde or MWR observations are used(Niell *et al.*, 2001). The accuracy of the PWV calculated on the basis of the GNSS data was analyzed in comparison with the radiosonde data.

RESULTS

In this study, data obtained from the GNSS observatories between Jeju and the southern coast of Korea, which are in the track of Typhoon NARI on the Korean Peninsula, were used to estimate the PWV and analyze the moving distance over time in order to analyze the possibility of observing the typhoon track on the basis of the GNSS data. FIGURE 2 shows the weather conditions of the JEJU Observatory when approached by Typhoon NARI. The data shown in FIGURE 2 are values recorded by the MET sensors of the JEJU

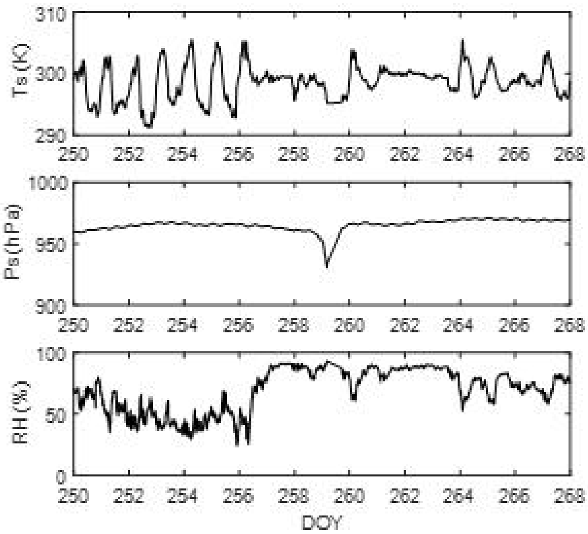

FIGURE 2. Ground air temperature, ground air pressure, and relative humidity at JEJU Observatory from September 7(DOY 250) to 24(DOY 267), 2007.

Observatory, including, from the top to the bottom, the ground air temperature, ground air pressure, and relative humidity.

Between DOY 257 and DOY 264, during which time the area was affected by the typhoon at full scale. Except for DOY 260, the ground air temperature remained at about 300K and the relative humidity at over 90%. On the other hand, the ground air pressure drastically decreased to 930 hPa on DOY 259; the time of day(03:50 UTC) was almost the same as the time when the typhoon passed over Jeju Island. Therefore, the data in FIGURE 2 indicate that the ground air pressure at the observatory decreased when the typhoon passed through the area, whereas the ground air temperature temporarily increased and the relatively humidity temporarily decreased after the typhoon passed through. However, the relative humidity remained slightly high even after the typhoon passed through. Since the observation data provided by the Korea Meteorological Administration show that rainfall continued during this period, the high relative humidity may have been because of the increase of vapor due to rainfall. FIGURE 3 shows the PWV estimated using the rainfall data and the GNSS data obtained for the period. The horizontal axis of FIGURE 3 represents time, the left vertical axis precipitation, and the right vertical axis the GNSS PWV. The precipitation is expressed in bar graphs in units of cm, while the GNSS PWV is expressed in dots. Except for DOY 260, the ground air temperature remained at about 300K and the relative humidity at over 90%. On the other hand, the ground air pressure drastically decreased to 930 hPa on data in FIGURE 2 indicate that the ground air pressure at the observatory decreased when the typhoon passed through the area, whereas the ground air temperature temporarily increased and the relatively humidity temporarily decreased after the typhoon passed through. However, the relative humidity remained slightly high even after the typhoon passed through. Since the observation data provided by the Korea Meteorological Administration show that rainfall continued during this period, the high relative

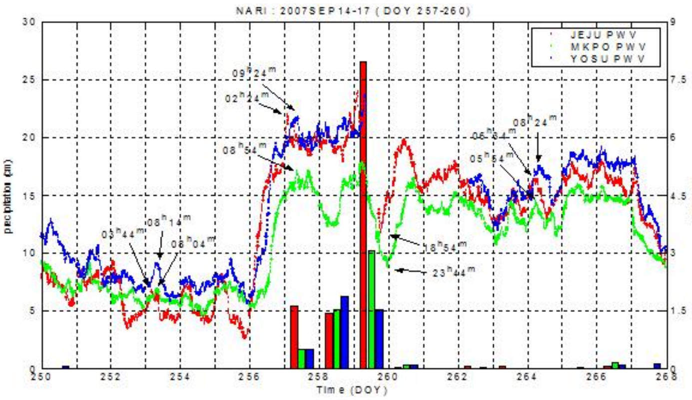

FIGURE 3. Precipitation and GNSS PWV between September 7(DOY 250) and 24(DOY 267), 2007.

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The horizontal axis of FIGURE 3 represents time, the left vertical axis precipitation, and the right vertical axis the GNSS PWV. The precipitation is expressed in bar graphs in units of cm, while the GNSS PWV is expressed in dots. In FIGURE 3, the red color represents the data from JEJU, the green color that from MKOP, and the blue color that from YOSU. The precipitation data in FIGURE 3 show that the torrential rain started from DOY 257, when the area started to be fully affected by the typhoon, and that the highest precipitation occurred on DOY 259, when the typhoon landed on the inland. Rainfall was continuous even after September 19(DOY 260), when the typhoon turned into a tropical cyclone. In view of the locations, the precipitation was highest at JEJU, the first area affected by the typhoon. As the typhoon moved to the north toward the inland, the precipitation drastically increased at MKPO and YOSU, which are located in the track of the typhoon. The variation of GNSS PWV shows that GNSS PWV was about 1 to 3㎝ from DOY 250 to DOY 255, although it varied among locations. The GNSS PWV rapidly increased from September 13(DOY 256), when the typhoon started to develop; it almost doubled to 5 to 7㎝ within just one day. Particularly at JEJU, the PWV increased from 1㎝ at midnight on DOY 256 to 6㎝ at midnight on DOY 257, and it maintained a high level of about 6㎝ even after the torrential rain started. Torrential rainfall reached 26㎝ on DOY 259 when the typhoon landed on the inland, and then the PWV rapidly decreased to about 3.5㎝.

A careful review of the trend of the PWV variation over time at each location shows that PWV variation was different among locations between DOY 250 and DOY 253, but became similar between JEJU and YOSU from DOY 253. The time at which the first peak was found on DOY 253 was 03:44(UTC) at JEJU and 08:14 (UTC) at YOSU, which was 4 hours and 30 minutes after the daily PWV peak was found at JEJU. Afterwards, on DOY 257 when the area started to be directly affected by the typhoon, as well as on DOY 260 when the typhoon turned into a tropical cyclone, the time when the daily PWV peak was found at JEJU continuously preceded that of YOSU by several hours. This indicates that vapor was continuously supplied through the same path even after the typhoon had disappeared. On the other hand, the PWV peak on DOY 257 was 6.6 ㎝ at JEJU at 02:24(UTC) and 6.5㎝ at YOSU at 09:24(UTC), which was seven hours after it was found at JEJU. As described above, Typhoon NARI passed through the sea about 20㎞ south of Seoguipo at noon(KST) on DOY 259(03 o'clock UTC), and landed on Goheung-gun, Jeonnam, at about 6 o'clock in the evening of the same day(09 o'clock UTC). Therefore, the trend of the variation of the GNSS PWV over time at each location was highly correlated with the movement of the typhoon along the track. One notable finding is that the variation of the PWV was significantly different among locations from DOY 257 to 259, when the area was directly affected by the typhoon. The PWV at YOSU varied in magnitude and trend very similarly to the value at JEJU, despite the bias, as both locations were in the track of the typhoon. On the other hand, the variation of PWV at MKPO, which was relatively distant from the typhoon, was significantly different from those of the two other observatories, even though the landing time of the typhoon was similar between MKPO and YOSU. The PWV was continuously high at JEJU and YOSU in spite of the torrential rainfall during the period; however, the value at MKPO repeatedly fluctuated by a large magnitude. This finding indicates that not only the PWV value but also the PWV variation at individual locations is significant in the analysis of typhoon track based on GNSS PWV data.

Accuracy Analysis

In this study, the track of a typhoon was analyzed using GNSS PWV data. To verify the accuracy of the analysis, the GNSS PWV data were compared with the PWV data obtained using a radiosonde in the same period. The radiosonde observation was performed twice a day at 00 and 12 UTC at seven observatories in Korea. In this study, the radiosonde data were obtained from the GNSS JEJU Observatory and the Gosan Meteorological Observatory at Jeju Island. FIGURE 4 compares the radiosonde observation data and the GNSS −based PWV data.

The bias between the GNSS and radiosonde PWV data is generally known to be about 1㎝(Niell *et al.* 2001; Ha *et al.*, 2010). FIGURE 4(a) shows that a similar bias of the PWV data existed between the two instruments, and the size of the bias was about 0.7㎝. FIGURE 4(b)

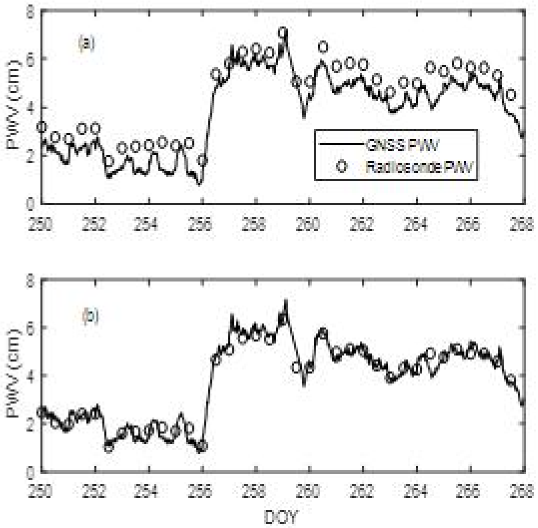

FIGURE 4 (a) Radiosonde and GNSS PWV data for Jeju Island between September 7(DOY 250) and 24(DOY 267), 2007; (b) Radiosonde and GNSS PWV data after removing bias.

shows the PWV data after removing the bias, indicating that the PWV was almost the same between the two instruments. After the bias was removed, the mean error of the PWV data between the two instruments was 0.0㎝, and the root mean square error and the standard deviation were both 0.3㎝, indicating that the GNSS-based PWV data obtained in the present study were highly accurate and precise.

CONCLUSIONS

In order to analyze the possibility of using GNSS to observe a typhoon track, Typhoon NARI, the 11th typhoon of 2007, was analyzed in terms of typhoon track as well as local variation of PWV over time. The result show that the PWV variation was very similar between observatories that were near the track of the typhoon. The PWV variation observed at the one observatory that was relatively distant from the typhoon track was significantly different, despite a similar typhoon landing time. As the typhoon developed and moved inland, the PWV rapidly changed. The distinctively observed trend of PWV variation was that the PWV reached peak values as the typhoon landed and torrential rainfall started; PWV then rapidly decreased after the typhoon disappeared. A careful review of the trend of PWV variation over time at each location, depending on typhoon movement along the track, shows that the daily PWV peak was found first at the JEJU Observatory, which was struck first by the typhoon; it was then found several hours later at the observatories on the southern coast of Korea. During the observation period, the time at which the peak PWV value was found at each location was almost the same as the time at which the typhoon landed at that location. In order to verify the accuracy of the analysis performed in the present study, the estimated GNSS PWV data were compared with the PWV values observed using the radiosonde. The comparison showed that the mean error was 0.0 cm; the root mean square error and the standard deviation were both 0.3 cm, indicating that the GNSS-based PWV data were highly accurate and precise. In summary, the results of the present study show that, with respect to the temporal and local trends, the GNSS data were highly correlated with the typhoon track, and thus may be used for highly accurate analysis of typhoon tracks. KAGIS

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