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Monitoring of GPS Water Vapor Variability During ENSO Events over the Borneo Region

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ABSTRACT

The cycle of El Niño-Southern Oscillation (ENSO) is very crucial to affect the natural climate variability in a particular region. Direct measurement of ENSO cycle and to understand their comprehensive physical mechanism are still difficult for sustainable development. For that purpose, a Precipitable Water Vapor (PWV) derived from a ground-based Global Positioning System (GPS) receiver is proposed. The PWV for the year 2011 gathered from Universiti Malaysia Sabah located in Kota Kinabalu, Malaysia (UMSK) together with two other selected GPS stations centered the Borneo region in pathways of Niño 4 region, named Nanyang Technological University (NTUS) in the Singapore and Manila Observatory (PIMO) in Philippines were analyzed. The GPS PWV was also compared with PWV taken from Radiosonde (RS). The results found a good agreement between GPS PWV and RS PWV with correlation coefficients ranging from 0.6 to 0.8, significantly at the 99% confidence level. PWV at Philippine's station demonstrated a drop about 7.8 mm before the first monsoon and PWV in the whole station look like a bimodal pattern throughout the year. An investigation of ENSO episode in September with weak-to-moderate intensity between PWV and the sea-surface temperature anomaly demonstrated an inverse correlation due to La Niña events. This promising result indicates that during the La Niña event, the PWV is increased when the sea-surface temperatures getting cold and thereby slow down the GPS signals.

Key words: Global positioning system, precipitable water vapor, sea surface temperature anomaly, El Niño-southern oscillation, Borneo region

INTRODUCTION

One of the most significant concerns in the natural climate variability is the cycle of El Niño-Southern Oscillation (ENSO). An ENSO phenomenon is dry and cold phases, which exists over the equatorial central Pacific Ocean with abnormal pressure over the eastern tropical Pacific (Kousky and Ropelekwski, 1989). ENSO evolution can occur every 3-5 years and usually last for 9-12 months depend on the enormous seasonality effects in a certain region (Xiao and Mechoso, 2009). The occurrence of ENSO can be linked to environment problems such as drought/flooding, landslides and tropical storms.

Since the ENSO phenomenon is extremely widespread effects throughout the hemisphere, including Southeast Asia and remain periodically active in the circumstances of Borneo Island during the winter season from December to January (McBride *et al.*, 2003), some aspects of the ENSO mechanisms that affect the Borneo region in the West Pacific are still not well understood. Monitoring their cycle and variability is demanded for mitigation development. In contrast, water vapor variability as ones of the atmospheric components, has a very important role in the circulation of ENSO cycle. Moreover, water vapor is an important factor in greenhouse gas-induced climate change and their strongest positive feedback amplifies an externally forced climate fluctuation (Hall and Manabe, 1999). This fluctuation can be detected by delayed (refracted) Global Positioning System (GPS) signals in the lower atmosphere due to water vapor variability. In recent years, GPS has been extensively used a powerful tool to measure atmospheric water vapor in all weather conditions and on a global scale (Bevis *et al.*, 1992; Rocken *et al.*, 1993; Suparta *et al.*, 2009); quantitatively measured in terms of Precipitable Water Vapor (PWV). The equipment is a green technology with effective-cost that has proven used in detecting climate change. This study attempts to observe the ENSO activity through water vapor variability measured by ground-based GPS receivers. For this purpose, Kota Kinabalu Sabah located in Borneo (Fig. 1a) is selected as the main base of GPS observation to study the dynamics of PWV during ENSO activities.

MATERIALS AND METHODS

Data and location: The PWV data derived from GPS station installed at Universiti Malaysia Sabah, Kota Kinabalu (UMSK) (geographic: 6.03°N, 116.12°E and height of 63.49 m), Malaysia based on GPS Week from January 2 to December 31, 2011 were used for the study. The other GPS data for comparison were taken from the Nanyang Technological University (NTUS) (geographic: 1.35°N, 103.68°E and height 75.38 m) in Singapore and the Manila Observatory (PIMO) (geographic: 14.64°N, 121.08°E and height 95.53 m) in Philippines. GPS data other than UMSK were downloaded from the Scripps Orbit and Permanent Array Center (SOPAC) site (www.webstatsdomain.com/domains/sopac.ucsd.edu). At the same time, PWV data taken from Radiosonde (RS), so-called the RS PWV (http://weather.uwyo.edu/upperair/sounding.html) which archived by Wyoming University were used to compare the PWV from GPS (so-called the GPS PWV). GPS PWV data at NTUS were compared with RS PWV data at WSSS (geographic: 1.36°N, 1103.98°E) and GPS PWV data obtained at UMSK were compared with RS PWV data at WBKK (geographic (96471): 5.93°N, 116.05°E). As well, GPS PWV data at PIMO were compared with RS PWV data at TANAY (geographic (98433): 14.56°N, 121.36°E). Figure 1a shows the location of GPS stations of UMSK, NTUS and PIMO together with RS locations. The distance for GPS station of UMSK-NTUS and UMSK-PIMO are approximately 1,478 and 1,105 km, respectively. The measurement system to measure the PWV from GPS techniques is presented in Fig. 1b.

To correlate the ENSO occurrence with PWV response, the sea surface temperature anomaly (SSTa) Oceanic Nino Index (ONI) intensity based on the Japan Meteorological Agency (JMA) definition in pathways of Niño 4 region were employed. The data of SSTa ONI were taken from the National Oceanic and Atmospheric Administration (NOAA) (http://www.cpc.ncep.noaa.gov/data/indices/). All data were analyzed on a weekly basis because of the availability of SSTa. The PWV data were processed in two times a day (00:00 and 12:00 UT) following the Radisonde data collection, then made a daily average before emerged in a weekly average. In the data processing section, presents where and how data were collected for the study.

Data processing: Data cleaning in terms of time series missing and errors were solved properly by using MATLAB™. Matlab is used as a versatile tool to efficiently perform tasks, simply by providing a toolbox and can simulate different signals and the processing involved. Both GPS signals and the surface meteorological data (pressure (P in mbar), temperature (T in °C) and relative humidity (H in percent)) were processed to obtain the total zenith tropospheric delay. GPS

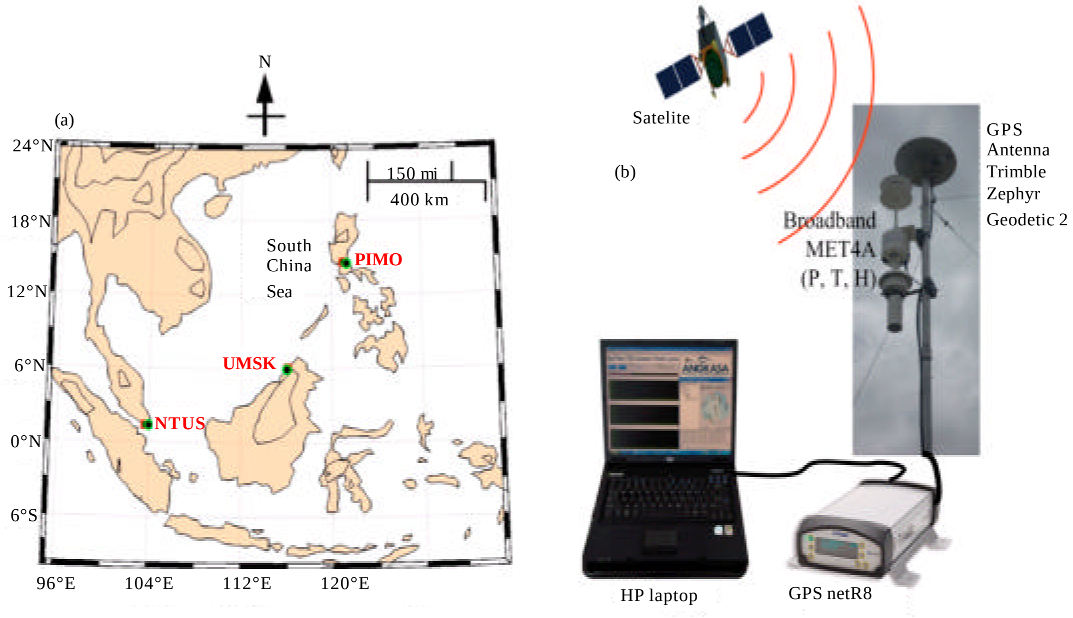

Fig. 1(a-b): (a): Location of observation and (b): GPS PWV measurements system at UMSK with a Trimble NetR8 receiver, filled circles shows the Radiosonde (RS) measurement at WSSS, WBKK and TANAY, the geographic distance between NTUS-WSSS, UMSK-WBKK and PIMO-TANAY are approximately of about 33.37, 13.57 and 32.38 km, respectively

data from all stations were collected with 30 sec intervals. For UMSK station, the meteorological data were recorded every 4 sec, while NTUS was recorded every minute. For PIMO station, the surface meteorological data were collected every hour. Meteorological data for NTUS and PIMO stations were taken from the weather underground website (www.wunderground.com).

The Zenith Tropospheric Delay (ZTD) is composed of Zenith Hydrostatic Delay (ZHD) and Zenith Wet Delay (ZWD), which was calculated based on the improved modified Hopfield model. The ZHD was calculated using the Saastamoinen model. A Vienna Mapping Function (VMF1) was employed to reduce the atmospheric bias in the ZTD estimation (Suparta *et al*., 2011). The ZWD was computed by subtracting ZHD from ZTD. The ZWD was then transformed into an estimate PWV with a conversion factor, $\pi(T_m)$ that dependent on the surface temperature measured at a particular site. The total PWV (in mm) from a receiver position to the top of the atmosphere was calculated based on the formula proposed by Bevis *et al*. (1994). The algorithm of PWV determination is demonstrated in Fig. 2:

$$PVW = \pi(T_m)ZWD \tag{1}$$

where, the dimensionless $\pi(T_m)$ parameter is a conversion factor that varies with the summation on the local climate (e.g., location, elevation, season and weather). Detailed of PWV determination from GPS for this work can be found in the study of Suparta *et al*. (2008). To process and analyze all the above parameters, a set of MATLAB code, namely the tropospheric water vapor program

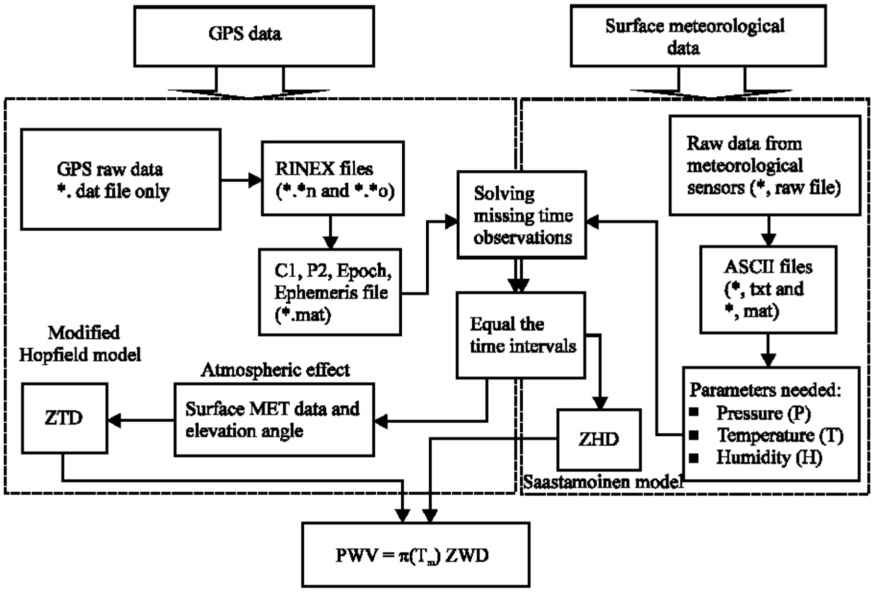

Fig. 2: Determination of PWV from GPS and the surface meteorological data adapted from Suparta (2010)

(TroWav) developed by Suparta *et al.* (2008, 2011) and Suparta (2010) was employed. The flowchart of the TroWav is presented in Fig. 2. A correlation analysis was then conducted to study the relationship between GPW PWV and ENSO activities.

RESULTS

Figure 3 shows the PWV variation from GPS and RS data on a daily and weekly basis. The average daily variation was chosen due to lack of Radisonde data. The PWV in Philippines stations (Fig. 3a) shows a drop about 7.8 mm from yearly mean value during February-March compared to the station in Malaysia (Fig. 3b) and Singapore (Fig. 3c). During the first inter-monsoon (Apr-May), all stations showing an increase in PWV. Then the PWV variation is decreasing until reach the winter and oscillates with a bimodal pattern. The results showed that PWV from GPS and RS shown a similar trend, although the PWV measured by GPS at UMSK was incomplete. GPS PWV value at PIMO was 16.5 mm higher compared with the PWV from RS. In contrast of Fig. 3b, the PWV from RS was 12.0 mm higher than those of PWV from GPS. Interestingly, the PWV value from the two measurements of Fig. 3c showed a bit different which RS PWV was 1.2 mm higher.

Furthermore, looking at the weekly average (Fig. 3d-f), it is clearly observed that all stations show similar PWV variation. All stations were also experiencing the effects of first inter-monsoon to each region. For June-July-August, PWV showed declined and increased in September due to the second inter-monsoon. During these periods, the PWV measured by GPS at PIMO show an opposite pattern to those of PWV from RS at TANAY. In contrast, the PWV during a winter monsoon (from May to September) show an increase compared to other months. At UMSK, the PWV value varies from 38 mm to 56 mm (with average value of 45 mm). Details of PWV values obtained by GPS and RS on a daily basis are presented in Table 1. Moreover, the bias between GPS PWV and RS PWV for PIMO and TANAY on a weekly basis was 23.2% higher, 18% lower for

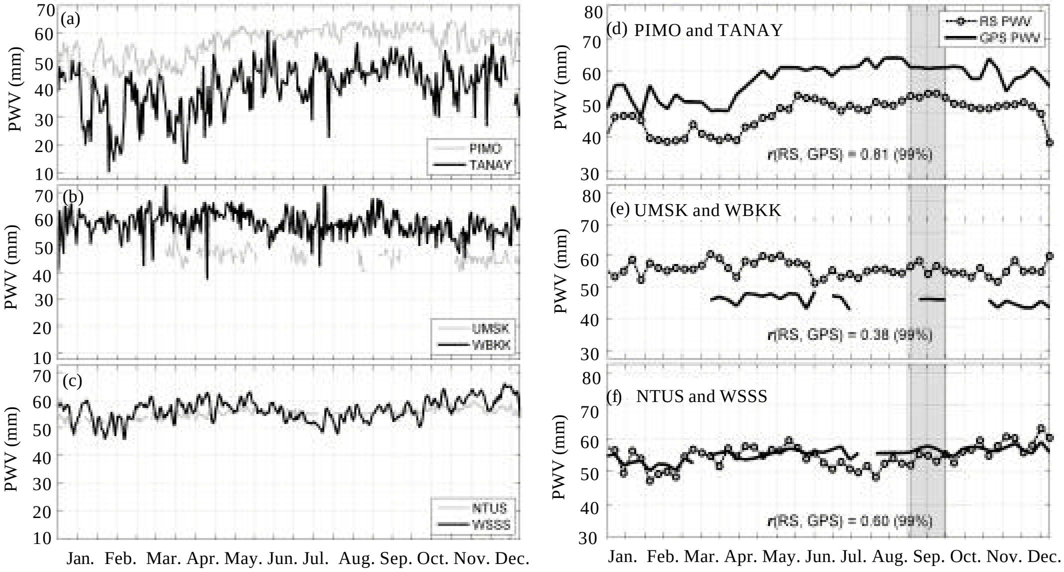

Fig. 3(a-f): PWV variations from GPS and Radiosonde for the year 2011 with (a-c) on a daily average and (d-f) on a weekly average and the gray background in Fig. 3(d-f) identifying the phase of September La Niña

Table 1: Statistical value of PWV between GPS and RS over the year 2011 on a daily average

Station	Min. (mm)	Mean (mm)	Max (mm)	SD (mm)	RMSE
PIMO (G)	39.66	56.44	64.48	5.63	PIMO-TANAY
UMSK (G)	38.90	44.69	56.38	2.46	17. 89
NTUS (G)	47.64	55.00	60.29	1.95	UMSK-WBKK
TANAY (R)	10.25	40.31	61.11	8.82	12.67
WBKK (R)	37.50	58.08	66.22	4.57	NTUS-WSSS
WSSS (R)	45.81	56.50	64.42	3.94	3.31

G and R stands for GPS and Radiosonde, respectively

UMSK and 1% higher for WSSS. The PWV different between GPS and RS demonstrated by the root-mean square error (RMSE) calculation showing that the station in Philippines was higher with value of 17.89 mm.

DISCUSSION

Here, we discuss the potential use of GPS PWV for monitoring an ENSO activity. We first discuss on the comparison between GPS PWV and RS PWV. The statistical result of comparison from Fig. 3 is presented in Table 1, which show that the STD values for PIMO and TANAY stations were approximately 36% higher than the other stations. The smallest STD was observed at NTUS and WBKK stations. In addition to the RMSE value between GPS and RS at PIMO-TANAY pair station, it was observed higher to that of STD which notify that the tropospheric phenomena surrounding the stations is complex. This clearly justified that the Philippines region is more disturbed compared to other regions. Looking at the strong relationship of PWV between GPS and RS (characterized by a correlation coefficient, r significant at the 99% confidence level), the pair

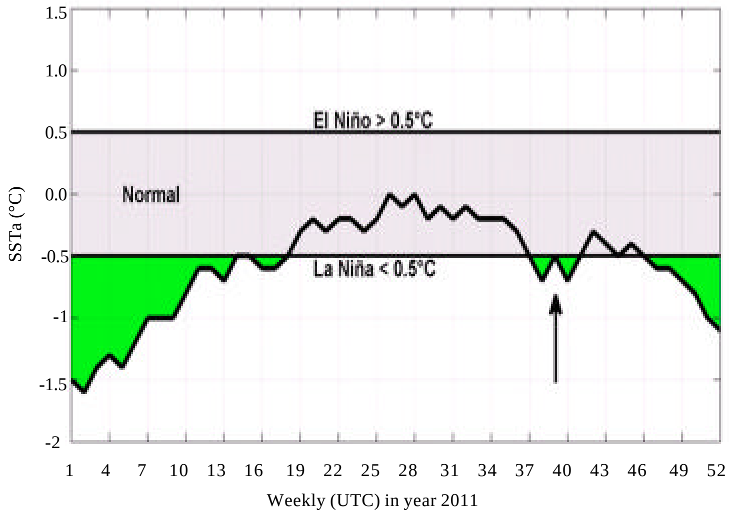

Fig. 4: SSTa ONI variability for Niño 4 region during the year 2011 taken from NOAA

station between PIMO and TANAY shows a strong correlation. In contrast, pair of UMSK and WBKK demonstrated lowest correlation due to incomplete GPS data for UMSK station (from January to March, July to August and October), but their variations exhibited a similar trend. Lack of data was due to system installation at the end of March and other months were missing due to the system was not well functional. The similar trend of PWV variation between GPS and RS offer a high confident of GPS PWV for retrieving a climate parameter that can be used to detect ENSO activities.

The second discussion is to use the GPS PWV for ENSO monitoring, which is analyzed through the relationship between SSTa and PWV. Figure 4 shows the SSTa variability for Niño 4 region to indicate the ENSO phase. From the figure, there was no El Niño episode recorded in 2011. The beginning of January until March, September and at the end of the year (from November to December) is considered as La Niña episodes. For La Niña case, the event was observed moderate with SSTa of -0.7°C and the event was moves from West Pacific to South Pacific throughout part of the Southeast Asia region. Since La Niña events for January-March and November-December is regarded as a relatively weak phase, a La Niña phase in September investigated as indicated by an arrow up. The selection of this phase was due to the La Niña intensity from Niño 4 region had an impact to the Southeast Asian country, such as Indonesia, Philippines, Vietnam and Thailand. The activities of these ENSO were reported by IFRC (2011). From IFRC update, the impact of La Niña brought more rainfalls, floods, wind damage and landslide risks. In addition to the end of the Southwest monsoon, the La Niña brought rainfalls to the western side of Peninsular Malaysia.

To clarify the PWV responses on La Niña event, correlation between PWV and SSTa for a La Niña phase of September is conducted (Fig. 5). The PWV in that relationship was processed based on the weekly average between GPS and RS following the GPS Week time. Convincingly, a decreasing trend at all stations indicated the amount of rainfall during the event was moving from low to high and vice versa. The strong correlation was observed for station in Philippines (PIMO and TANAY) and in Singapore (NTUS and WSSS) with correlation coefficients were -0.96 and -0.89, respectively. This suggest that the enhanced precipitation over northern Australia and

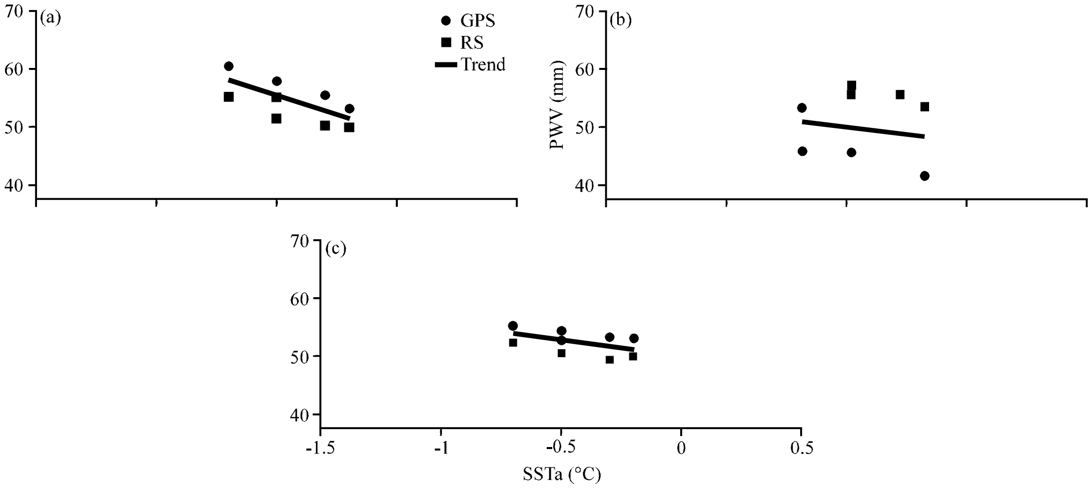

Fig. 5(a-c): Relationship between PWV and SSTa for La Niña phase of September 2011, (a): PIMO and TANAY with r(PWV, SSTa) = -0.96(99%), (b): UMSK and WBKK with r(PWV, SSTa) = -0.44(99%) and (c): NTUS and WSSS with r(PWV, SSTa) = -0.89(99%)

Indonesia during winter and spring which stronger than the normal Walker circulation can cause of this phenomenon. A low correlation between PWV and SSTa (r = -0.44) was observed for UMSK and WBKK stations. One possible explanation of a low correlation in these stations is probably due to differences in topography between the two positions of the instrument. Topographical features such as curvature, slope and upslope area can influence the hydrological conditions of a location and generate different soil moisture (Seibert *et al.*, 2007). Conclusively, the low PWV in the atmosphere during a La Niña is the result from its condensed and formed clouds through ocean-atmospheric coupling. When the rainfall occurred, the amounts of water vapor in the atmosphere in this typical region will be decreased because much of water vapors precipitated as rainwater (Suparta *et al.*, 2012).

CONCLUSION

The study constitutes a significant contribution to the applications of GPS meteorology for ENSO studies. The use of GPS derived PWV to detect and characterize a specific climate event such as ENSO is an innovation, in particular, for the targeted region. Observation of PWV variation over 2011 at three selected GPS stations (UMSK, NTUS and PIMO) in the pathways of Niño 4 region showed that the GPS PWV result concurred with RS PWV. Analyses of La Niña episode through SSTa for the phase of September found a stronger inverse correlation, except for station in Malaysia (UMSK and WBKK) which could be attributed to differences in topographical features and inadequate GPS data. During the La Niña event, changes into water vapor related to unusually wet conditions had an adverse effect on the Southeast Asian region. The decreasing trend of water vapor provides insight to understand the movement of warm air mass in the central Pacific to west Pacific through the strengthening of trade winds, leading to lack of air molecules over the sea surface (upward air movement). The effects will bring a consequence to increase in rainfalls that possible to drought/flooding and severe storms occurs.

In conclusion, the ENSO activity can be investigated from atmospheric path delay of GPS signals, this equipment hold promise method for monitoring ENSO platforms. However, additional new location in pathways of ENSO in the Southeast Asia region and the availability of long-term GPS data will be considered for future studies to proof the proposed concept of monitoring platform.

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