Impact of the 2010 Icelandic Eyjafjallajökull Volcanic Eruptions on the GPS signals

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***Abstract*— This paper presents the impact of tropospheric ash cloud distribution on the GPS signal through precipitable water vapor (PWV) measurements during the sequence of 2010 Eyjafjallajökull volcanic eruption at Eyjafjöll in Iceland. The second phase event was occurred from 14 April to 25 May 2010 across western and northern Europe. GPS and the surface meteorological data for the period from 1 April to 31 May of 2010 at Husafell (HUSA) and Hoefn (HOFN) stations, both in Iceland together with Borowiec station (BOR1) in Poland are observed. Monitoring results showed that the lower atmospheric parameter (PWV) is increased during the volcanic ash cloud of about 11.35% (on average) in comparison to the average values before and after the eruptions.**

Keywords-GPS PWV, surface meteorology, volcanic ash, monitoring

I. INTRODUCTION

It is well known that a huge distribution of gases such as volcanic ash brings many problems such as in air pollution, the aviation industry and even in communication. Aeroplane engines are vulnerable to the bright volcanic ash ejected by a volcano into Earth's atmosphere. For example, the second sequence phase of recent eruptions of the Icelandic volcano Eyjafjallajökull recorded from 14 April to 25 May 2010 as reported by the UK's National Weather Service at Meteorology Office website [1] has caused massive disruption to air traffic across Northern Europe. The volcano eruption on 15 April has been clearly identified by its ash plume and emitted large quantities of ash and sulfur dioxide into the atmosphere. The plume was driven by strong winds, originated between a region of high pressure over the Atlantic and a cyclone over Scandinavia (http://modis.gsfc.nasa.gov/). The cloud band can be observed over Germany on 16 April with separating aerosol-polluted, but water vapor free air in the north began polluted than in the south. The cloud filaments show up over the Atlantic west of France on 17 April, and the initial ash plume has been disseminated over the southern North Sea, the English Channel, and the eastern Atlantic on 18 April. A small cyclonic eddy next to Island pushes rapid ashes-transport in the southwesterly direction on 19 April, followed by rapidly aerosol cloud stretched by wind shear strain, dissipating the narrow emission band into a wide fan on 20 April. The time series of the sequence eruption and detail image can be found at http://www.zki.dlr.de/applications/2010/island/189_en.html.

Although the eruption does not swallow the cost to the human lives, it has caused enormous economic disruption, strained patience and political infighting. The real impacts of these natural events are enormous financial losses because of global airline industries grounding all flights when Eyjafjallajokull erupted. During major explosive eruptions, huge amounts of greenhouse gases, aerosol droplets and ash have been injected into the atmosphere. The most abundant gas typically released into the atmosphere from volcanic systems is the water vapor, followed by carbon dioxide and sulfur dioxide [2]. Because enormous quantities of ash and gas have been released to the atmosphere, it is interesting to study their gas distribution that may impacts to the atmospheric composition.

The main purpose of this paper is to monitor the impacts of the distribution of volcanic ash clouds during the second phase of 2010 Eyjafjallajökull eruptions on the communication, such as GPS signal propagation. Distribution of greenhouse gas such as water vapor from volcanic ash sensed by GPS technique is observed. The precipitable water vapor (PWV) derived from GPS signal and the surface meteorology is used as an indicator of impacts. The GPS and the surface meteorological measurements for two months at Husafell station (HUSA) and Hoefn station (HOFN) in Iceland is analyzed together with Borowiec station (BOR1) in Poland for comparative results to carry out the similar or a different response on the PWV variation. The analysis is presented on a daily basis is to give clear the response of PWV and the surface meteorology (pressure, temperature and humidity) to the tropospheric ash clouds from volcanic eruptions. The expected results of this analysis can be considered for mitigation in the future especially in communication systems as well as climate change impacts.

II. Measurement System and Data Analysis

A. Measurement System

The main point observation of PWV for this work is at HUSA (Geographic: 64.67°N, 21.03°W), which is located at around 135 km away from Reykjavik or 128 km from Eyjafjallajökull Volcanic Point (EVP). EVP is located at 63.63°N latitude and 19.60°W longitude. The main purpose of GPS system at HUSA is originally for studying the upper-lower atmospheric coupling. Since the circulation of volcanic ash traveled thousands of kilometers from its Iceland source, moving eastwards, it crossed over the UK and into mainland European airspace, HOFN (Geographic: 64.26°N, 15.20°W) in Iceland and BOR1 at Wielkopolska, Poland (Geographic: 52.28°N, 17.07°E), which both away ~226 km and ~1300 km from EVP respectively, are selected for comparison.

The measurement systems employed at HUSA consist of a permanent GPS receiving system and broadband meteorological sensors. The GPS was installed on 6 September 2008 under collaboration between UKM and NIPR and between UKM and SIUI. It consists of a Leica GRX1200 Pro GPS reference station with a high performance permanent dual-frequency GPS receiver, AT504 chock-ring antenna equipped by a dorne margolin with weather-protection radome and a notebook contains of Leica GPS Spider (GPS reference station software) for data logging. The meteorological system employed the Paroscientific broadband MET4A sensors to precise measures the surface pressure (in bar), air temperature (in degrees Celsius) and relative humidity (in percent). The sensor was set logged at the 1-minute sampling period. The GPS receiver was set to track GPS signals at a one-second interval (in UT) and the cutoff elevation angle was set to 15° to eliminate the possible multipath effects on GPS data. The three surface meteorology quantities together with GPS signals are then used to determine the PWV. The GPS and the surface meteorology data for both HOFN and BOR1 are obtained from the European Reference Frame (EUREF) at Scripps Orbit and Permanent Array Center (SOPAC) homepage (http://sopac.ucsd.edu).

B. Data Analysis

Two months of data at three stations gathered from 1 April to 31 May of 2010 were processed. The data processing and analysis programs, namely the Tropospheric Water Vapour Program (*TroWav*) written in Matlab was used to produce the PWV data. The algorithm of the *TroWav* is weather-related signals delays-based to produce the PWV. It includes satellite elevation angle, Zenith Tropospheric Delay (ZTD), Zenith Hydrostatic Delay (ZHD), Zenith Wet Delay (ZWD) and mapping function calculations. Detail calculation of PWV and the models adopted, readers are referred to Suparta et al. [3]. The GPS PWV products at HUSA, HOFN and BOR1 for this work were available at one-min, 15-min and 10-min intervals, respectively.

III. Results and Discussion

A. Surface Meteorological Conditions

Figure 1(a) shows the daily surface meteorological data condition at third stations. As shown, both dash vertical lines in the figure are interval time during the second phase of volcanic ash took place from 14 April to 25 May 2010, and grey background indicated is missing data observed on 20 April 2010, which possibly due to the new phase eruption in Eyjafjallajökull entered one day before [1]. The high viscosity of magma from this volcano to the surface enhanced development of explosive and heavy sound blast might be affecting the electrical system in Iceland. Figure 1(b) shows the comparison of surface meteorological response during the volcanic ash and otherwise events.

The top panel of Fig. 1(a) presents the surface pressure variation at HUSA with mean pressure value was higher 1% compared with the BOR1. The pressure variations at both HUSA and HOFN shown dropped significantly prior to the events on 5 April 2010 due to the seismic event of magma pathways in relative location of Eyjafjallajökull volcano [1]. The pressure drops at HUSA and HOFN were about 39.5 mb and 46.7 mb, respectively. This significant drop indicated that a volcanic activity would be taking place for eruption. At the post of the second eruption started on 14 April, there are two significant pressure variation drops at both HUSA and HOFN on 27 April and 12 May 2010, where the pressure values had dropped by about 23 mb and 24 mb, respectively. There was closely the variation of surface pressures between HUSA and HOFN, where a significant drop of pressure signature of cyclonic activity [4]. The middle of Fig. 1(a) presents the temperature variations at third stations. The fluctuation of temperature at all stations seems to have a very similar pattern. The high temperature variation at BOR1 is probably this station receives more solar radiation than at stations in Iceland. At the onset of eruption on 14 April, the temperature pattern had shown increased before a drop on 21 April. One week after the first explosion occurred from 20 April to the end of April, temperatures at all stations had shown increased with gradients are 10°C and 17.1°C, respectively. Temperature slightly varied and increased back when the pressure significant drop on 12 May, and the temperature at BOR1 has increased to a maximum in one week to 20°C before the volcanic ash subsided on 25 May. The bottom of Fig. 1(a) presents the variations in relative humidity at the third stations. Before the eruption, temperatures vary from 40 to 100%, and high fluctuation of humidity was seen from 11 to 30 April, the possibility formation of dust clouds. At the post of the event, relative humidity showed fluctuated higher and almost reaches 100% and dropped to about 45% when the volcanic ash ended.

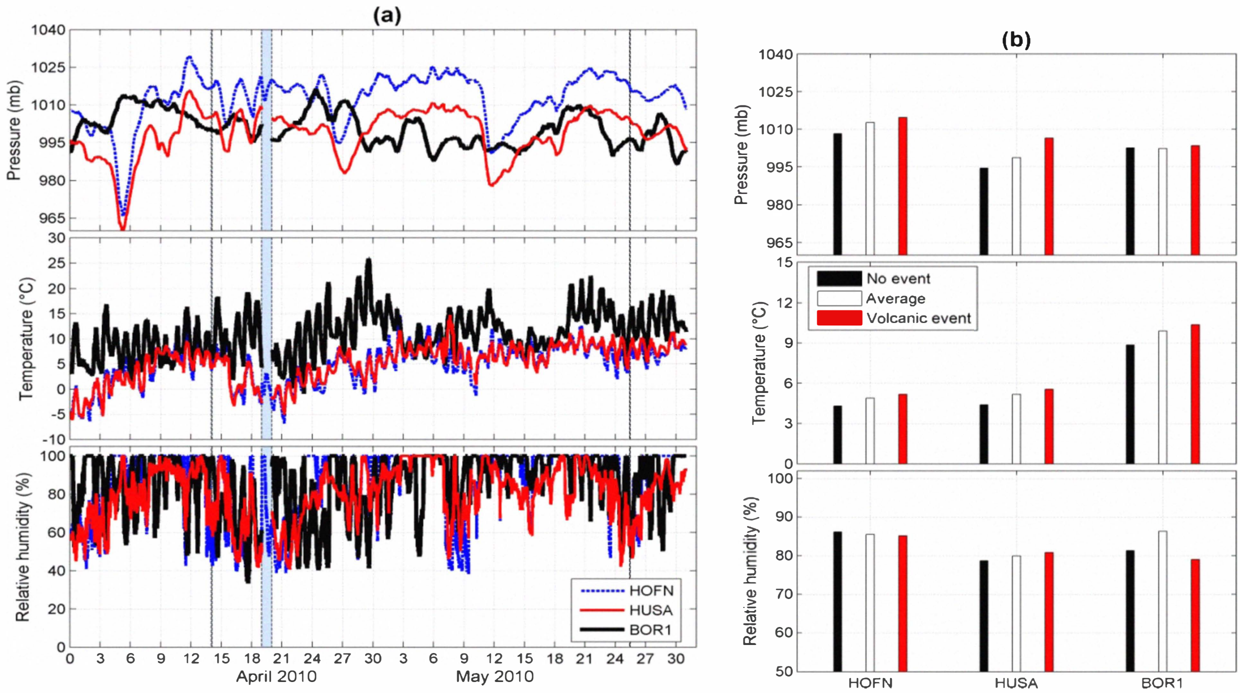

Figure 1. Daily surface meteorological variations from 1 April to 31 May of 2010 at HOFN, HUSA and BOR1 stations and their comparison. '*No event'* in the legend showing the average value outside the volcanic event (1-13 April and 26-31 May 2010), while '*Average*' is means value during the observation periods.

The top panel of Fig. 1(b) presents the surface pressure comparison for all stations, which are consisting of '*No event*', '*Average*' and '*Volcanic ash*', respectively. Pressures were increased during the volcanic ash to about 5 mb on average in comparison with their average values. Similar characters of temperatures in the middle of Fig. 1(b) are also increased of about 1.35°C and 3.0°C compared to the average and no event values, respectively. In contrast, relative humidity in the bottom of Fig. 1(b) shows an increase to about 1.8°C, but only for HUSA. In general, it can be stated that the surface meteorology represented by pressure and temperature showed increased during the volcanic ash, while humidity above the earth's surface was contaminated by other particulates in the atmosphere, indicates the volcanic ash can heat the atmospheric layer.

B. GPS Time Series Displacement

Figure 2 shows the displacement of GPS time series recorded at continuous GPS (CGPS) of Skogaheidi station (SKOG). The other GPS time series during the 2010 Eyjafjallajökull Volcanic Eruption can be found at the Nordic Volcanological Center website (http://notendur.hi.is/runa/eyja_gps.html). At SKOG, there are 2.3 cm and 1.8 cm of displacement of the local crust in northward and eastward directions, respectively started on 20 March 2010 indicated as fissure eruption and lava flows from E flank. In the figure, a similar response also shown between eastward and upward directions, indicating that the volcanic eruption significantly affects the GPS signals.

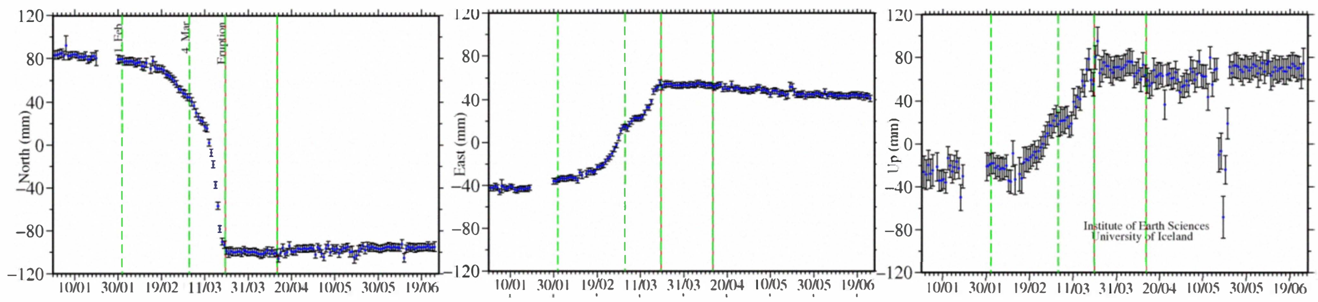

Figure 2. GPS time series displacement recoded from 1 January to 29 June 2010 at SKOG station (Courtesy of the Institute of Earth Sciences, University of Iceland).

C. Lower Atmospheric Response

Figure 3(a) shows the daily variation of GPS meteorology such as satellite elevation angle, ZTD and PWV as lower atmospheric parameters. For the top of Fig. 3(a), total satellite elevation angle at HUSA at every day showing in oscillation (diurnal) pattern. The range of elevation values varies from 49 to 84 degrees, which is high in the daytime and low at night. Three days after the seismic eruption on 17 April 2010 (volcano plume), satellite elevation angle had suddenly increased to 84 degrees. The ZTD variation in the middle of Fig. 3(a) represents the total atmospheric delay derived from GPS signals. The ZTD pattern at HUSA and HOFN showed a closely similar character. The ZTDs at both stations were increased 5 and 2 days before the volcanic eruption took place on 14 April 2010 with average values are 2.44 m and 2.43 m, respectively, while ZTD variation at BOR1 before the eruptions is shown quiet normal. At all stations, the ZTD showed a drop together at the onset of eruption on 14 April 2010 and increased its values during the volcanic ash took place. The higher variation of ZTD in Iceland's station demonstrated approximately a week before the eruption, which is from 8 April to 13 April 2010 and after the eruption from 2 May to 24 May 2010, with average ZTD for both episodes is about 2.40 m. On the other hand, the higher variation of ZTD at BOR1 shown after the eruption event about a month occurred from 24 April to 24 May 2010 with average value of 2.39 m. On the bottom panel of Fig. 3(a) presents the PWV content observed at HOFN, HUSA and BOR1 stations. As shown in the figure, the PWV demonstrated higher variation at prior and post of the events. At prior of the event, the PWV at HOFN and HUSA shown higher variation around 7 April to 14 April of 2010 with a maximum value of about 22.94 mm on 8 April 2010, this due to changing processes the chemical content of the underground gasses and water vapor during pre-eruptive phase. Further, the PWV at post-eruptive phase is also higher variations at approximately from 24 April to 19 May 2010 for both HOFN and HUSA, and for BOR1 was from 26 April to 24 May 2010. By comparing the variations of ZTD and PWV, their patterns were closely to one another; this indicates that the tropospheric disturbances such as volcanic eruptions tend to hold more water vapor in the atmosphere.

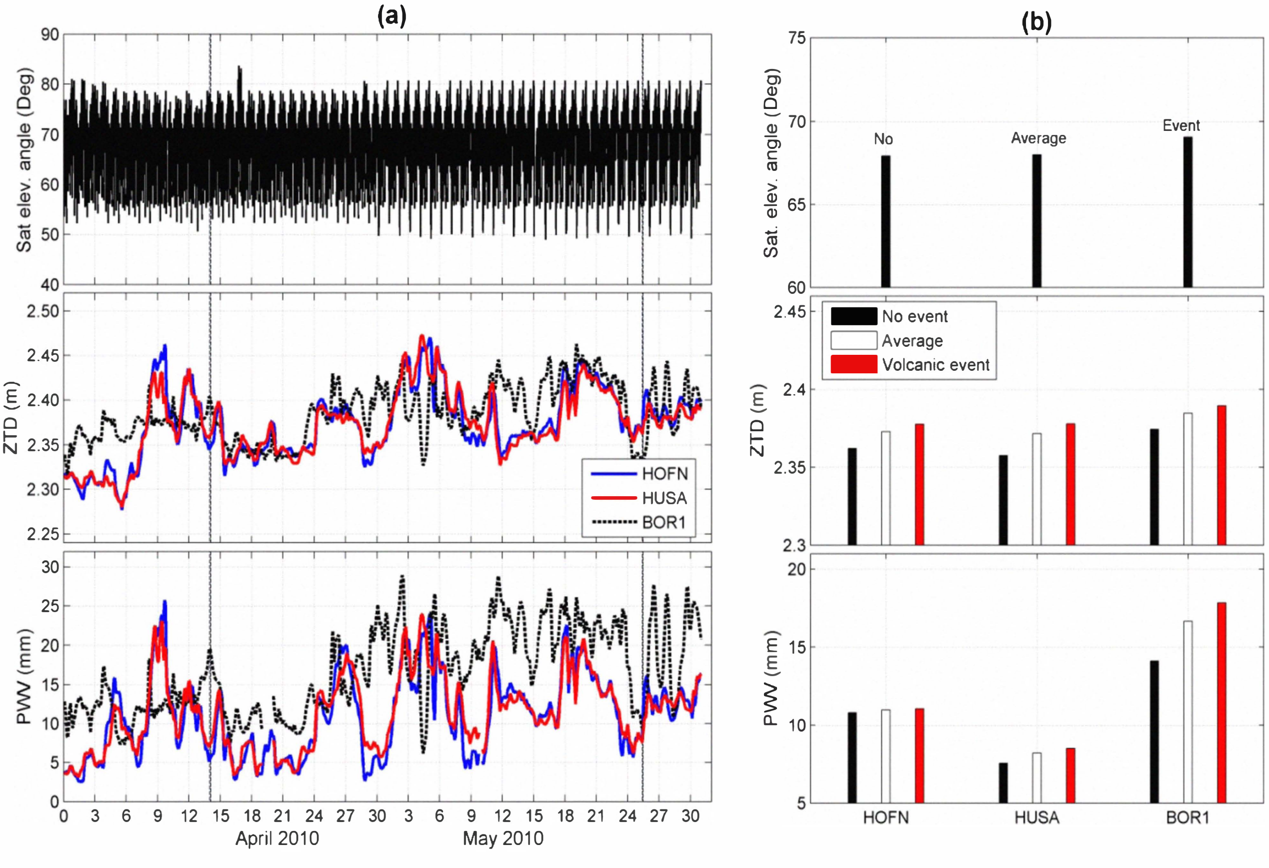

Figure 3. Daily lower atmospheric variation from 1 April to 31 May of 2010 at HOFN, HUSA and BOR1 stations, and their comparison.

The top panels of Fig. 3(b) present the comparison of total satellite elevation angle at HUSA. Satellite elevation angle had shown increased by about 1.6% in comparison to the values before and after the eruptions. This increase is linked tightly with the displacement of GPS time series showed in Fig. 2. The comparison of ZTD in the middle of Fig. 3(b) at all stations showed that their values (on averages) were increased to about 0.25% and 0.70% compared with the average and no event values, respectively. The high increasing of ZTD indicated that the GPS signals to have been disturbed by distribution of volcanic ash cloud as well as formation of water vapor. Since ZTD increased, the comparison of PWV on the bottom panel of a Fig. 3(b) show increased to about 2.14% and 0.67% for HOFN, 11.25% and 3.55% for HUSA, and 20.78% and 6.58% for BOR1 compared with the day no event and average values, respectively. PWV at HOFN and BOR1 are shown higher due to the station located close to the sea. The increase variation of PWV during the post of volcanic eruption probably due to the development and distribution of ash clouds across the Europe and therefore, it disturbed the quality of GPS signal through the significant increasing of ZTD and PWV content.

IV. CONCLUSION

This paper presents the impact of tropospheric ash cloud distribution from the Eyjafjallajökull volcanic eruption event on the GPS PWV variations. Nine days before the eruption, pressure values at the observation station in Iceland had dropped significantly to 960 mb and 4 days before the eruption on 14 April 2010, the pressure decreased again slightly. In the post-eruption events, the satellite elevation angle and ZTD demonstrated higher variations at HUSA and HOFN as well at BOR1 in comparison to the days before the eruption. The PWV variations at all stations showing increased in comparison to the days before and post of the event with values approximately 18% and 24%, respectively. The increased PWV was likely due to the increasing of distribution of volcanic ash cloud, this means that the propagation of GPS signals received on the Earth has been potential to be delayed by this event. Further investigation over many months and over of all the phases of volcanic eruption are needed to accurately to quantify the impact of these results and to be better to describe its physical interpretation.

ACKNOWLEDGMENT

The authors would like to thank the Institute of Space Science (ANGKASA), Universiti Kebangsaan Malaysia (UKM) for supporting this research. Thanks also go to SOPAC for their archives of GPS and surface meteorology data. We would like to thank to Snorri Johannesson for maintaining the GPS system in Iceland under collaboration between UKM and National Institute of Polar Research Japan (NIPR) and between UKM and Science Institute of University of Iceland (SIUI). This paper was sponsored under UKM-OUP-NBT-30-153/2010 grant.

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