The development and application of PPP technology with multi-constellation GNSS

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Precise point positioning (PPP) was introduced in 1990s as an efficient and robust analysis technique for data provided by global navigation satellite system (GNSS) receivers on the ground. PPP can estimate a single receiver position without generating a baseline by fixing orbits and clocks of GNSS satellites to previously determined precise values. PPP can continuously support many users distributed in world-wide without any reference station.
In data processing in PPP, ionospheric effect is usually eliminated by dual-frequency GNSS signals. Tropospheric term is also estimated as an unknown parameter of zenith total delay (ZTD) with an appropriate mapping function. The ZTD can bee easily translated to precipitable water vapor (PWV) at the site. GNSS meteorology has consequently been a popular application of PPP.
For the precise satellite orbits and clocks for PPP, International GNSS Service (IGS) has been make great contributions to develop models, algorithms and products since 1990s. Recently IGS has started to provide real-time products in addition to conventional post-processing ones.
In 2011, Japan Aerospace Exploration Agency (JAXA) started to develop a new suite of software to provide precise orbits and clocks of GNSS satellites called MADOCA (multi-GNSS advanced demonstration tool for orbit and clock analysis). MADOCA intends to support all of multi-GNSS-constellation, including GPS, GLONASS, QZSS, Galileo and BeiDou, both for post-processing and real-time mode. For a client of MADOCA-PPP, an extension of RTKLIB, which was a popular open-source GNSS data analysis software developed by the author, is used including ambiguity resolution (AR) feature.
The lecture summarizes development, implementation, evaluation, application and future of MADOCA and RTKLIB.

Keywords: GNSS, PPP, MADOCA, RTKLIB

Possibility of real-time volcanic plume monitoring using GNSS phase residual and SNR data

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A volcanic explosion is one of the largest energy release phenomena on earth. The ash fall can seriously affect human activity. Thus, the monitoring and prediction of ash fall is very important. Unfortunately, visible light cameras cannot be used to observe eruptions that occur at night and/or when skies are cloudy. Several researchers have investigated the applicability of meteorological radar to the monitoring of the spatiotemporal distribution of eruption clouds, including the ash. Global Navigation Satellite System (GNSS) data provide a useful alternative to meteorological radar for detecting volcanic plumes (e.g. Ohta and Iguchi, 2015).
Recently, the GSI and Tohoku University have developed a nationwide (>1200 sites) real-time crustal deformation monitoring system (REGARD), based on kinematic GNSS analysis, to determine the coseismic fault model of large earthquakes. We will discuss the possibility of the real-time volcanic plume monitoring using GNSS phase residual and SNR data based on the REGARD system.

Keywords: GNSS, volcanic plume, real-time

GNSS Buoy Array in the Ocean for a Synthetic Geohazards Monitoring System

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The GNSS buoy system for tsunami early warning has been developed in Japan and has been implemented as the national wave monitoring system since around 2008. Its record was used to update the tsunami warning at the 11 March 2011 Tohoku-oki earthquake and tsunami, Japan. Yet, the buoys are placed only less than 20km from the coast and are not far enough for effective evacuation of people. We are thus trying to improve the system for putting the buoys much farther from the coast. For this purpose, we employ a new PPP-AR analysis algorithm, instead of conventional RTK-GPS, for positioning. In addition, we use a two-way satellite data transmission in contrast with current surface radio system. We have conducted a series of experiments using this new system in 2013 and 2014, using a buoy used for a fish bed located about 40km south of Cape Muroto, Shikoku, southwest Japan. GEONET data were used to obtain precise orbits and clocks of satellites. Then, the information was transferred to the GNSS buoy using a satellite communication system of the Japanese positioning satellite called Michibiki. The received information on the buoy were used for real-time PPP-AR analysis for every second. The obtained buoy position was then transmitted back to the ground base through a geostationary satellite called ETS-VIII. The received data was then disseminated to public through the internet. The success of these experiments indicate that the GNSS buoy can be placed at nearly anywhere in the ocean. Given this success, we made up a new research plan in which we test a commercially available satellite communication system and try to develop a new GPS-acoustic system for monitoring ocean bottom crustal movements nearly continuously. Moreover, we seek for further application of GNSS data for ionospheric and atmospheric researches. Deployment of such GNSS buoy system as an array in a wide ocean will be a powerful tool for monitoring geohazards in the region as well as for other basic research on earth sciences. The new project started in June 2016 and we are now designing a regional GNSS buoy array in the western Pacific. The first newly designed GNSS system is established at another buoy for fish bed, located about 40km south of Cape Ashizuri, southwest Japan. The system is now under testing. We are planning to implement a GNSS-acoustic system for monitoring crustal movements of the sea floor in early 2017 fiscal year at the same buoy.

Keywords: GNSS buoy, geohazard monitoring, tsunami, ocean bottom crustal movement, GNSS meteorology, ionosphere

Tomographic studies of 3-D structures of daytime mid-latitude sporadic-E patches from a dense GNSS array

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A dense array of continuously operating Global Navigation Satellite System (GNSS) receivers is useful for drawing 2-dimensional maps of sporadic-E (Es) patches. From changes in the ionospheric total electron content (TEC) observed with Japanese GEONET, Maeda and Heki (2014) revealed that Es irregularities often show frontal structure extending predominantly in east-west. We further performed systematic studies of the morphology and dynamics of Es patches analyzing ˜70 cases of daytime mid-latitude Es (Maeda and Heki, 2015). In our recent paper (Maeda et al., 2016), we used Interferometric Synthetic Aperture Radar (InSAR) to draw a high resolution of map of an Es irregularity in Southwest Japan. In the GNSS-TEC method, however, we often assume that the irregularities lie at height of ˜100 km, and draw 2-D maps using the penetration point of the line-of-sight (LOS) vectors with the thin layer of prescribed height.
Here we try to infer 3-D structure of the Es patches using the 3-D tomography technique of the ionosphere. We set up 2000-3000 small blocks, with dimensions of a few tens of kilometers, covering the altitudes ranging from the D region to the F region, above a certain district of 300 km x 500 km in Japan. We also make a data set composed of slant TEC anomalies with thousands of LOS connecting ground GNSS stations and satellites (we use both GPS and GLONASS) that penetrate these blocks. Finally, we invert for the electron density anomalies of individual blocks, applying a certain continuity constraint. Before an actual tomography with the real data, we performed checkerboard test using synthesized data, and confirmed the resolution of the inversion.
The attached figure shows the map view at the height of 100 km and longitudinal and latitudinal profiles for the northward drifting frontal-shape Es patches that appeared around 4 UT on 22 May, 2010, shown in Figure 1d of Maeda and Heki (2015). We could confirm that the positive electron density anomalies extend east-west at the E region height. One interesting feature is that positive anomalies extend upward and southward. We also studied a case of the southward drifting Es patches that appeared on the Kanto District at around 8 UT on 21 May, 2010 first studied by Maeda and Heki (2014). In that case, we found the Es patch extend upward and northward. The extension direction might be controlled by the drift directions of the Es patches.

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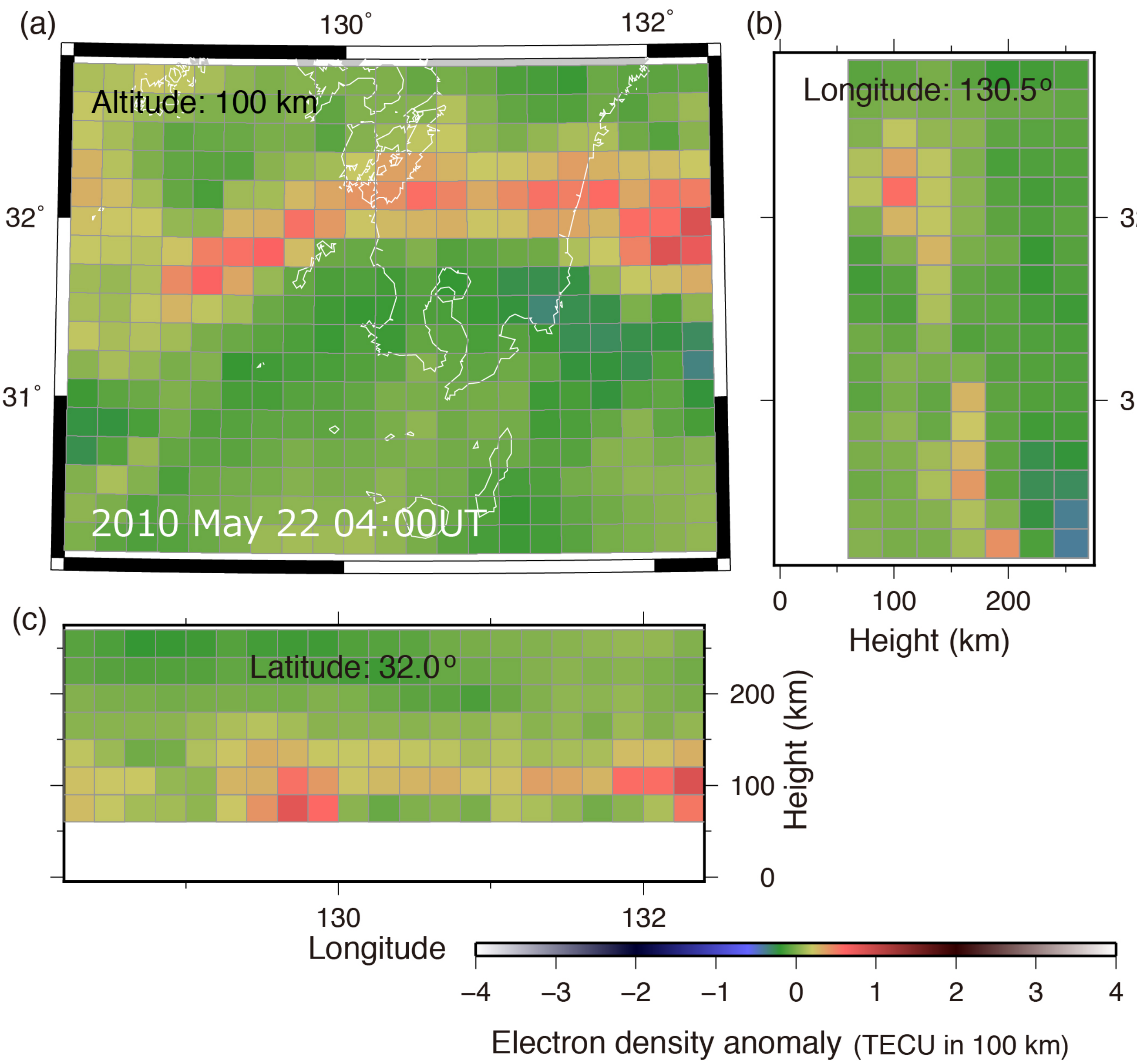
Figure caption: Results of 3-D tomography of the Es irregularity patch that appeared around 4:00 UT (13:00 LT) on May 22, 2010 above the Kyushu, Southwest Japan, see Fig.1d of Maeda and Heki (2015).

Frontal shape Es patches extend east-west, and migrate northward. We show the map view at altitude 100 km (a), longitudinal profile (longitude: 130.5E) (b), and latitudinal profile (latitude: 32N) (c). Blocks in red indicate positive electron density anomaly and correspond to the Es patch. In (b), we can see upward continuation of the Es extending southward, reaching the height of 200 km at the southernmost part of the studied region.

Keywords: sporadic-E, GNSS, TEC, 3-D tomography



Extreme water vapor increase as a function of surface temperatures around Japan

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Extreme heavy precipitation is a key phenomenon that impacts on human society and natural environments, which demands our understanding on its behavior under warming climate. Recently, many efforts have been paid for investigating observed extreme precipitation in association with water vapor holdings, which increases with surface air temperature. However, a relationship between atmospheric moisture content and surface air temperature is poorly understood due to the lack of reliable the moisture products for statistical analysis. In this study, we investigate the relationship between atmospheric moisture content and surface air temperature around Japan by using precipitable water vapor (PWV) dataset derived from Global Positioning System satellites that offers high spatial and temporal resolution measurement. We will show the significant PWV increment with surface temperature beyond the Clausius-Clapeyron rate, and the effect of upper air temperature on PWV that can consistently explain the reason for super-CC rate.

Keywords: GPS-PWV, Climate change

Data Assimilation Experiment of Radio Occultation Refractivity Data by using a Mesoscale LETKF System

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An assimilation method of radio occultation (RO) data for a mesoscale Local Ensemble Transform Kalman Filter (LETKF) (Miyoshi and Aranami, 2006) system has been developed (Seko and Tsuda, 2015). There are the following two difficulties in the assimilation of RO data: (1) An assumption of uniform distribution of refractivity, which is used in the estimation of refractivity profiles at tangent points, is not always valid, and (2) path averaged data is difficult to be assimilated by LETKF system because data assimilation using LETKF is conducted by each grid point. To solve these difficulties, (1) the path averaged refractivity was reproduced from the tangent point data and (2) path- averaged refractivity was divided into the refractivity at grid points around the path by using the statistical data of ensemble forecasts (ensemble average and spread) obtained by LETKF system. This developed method was applied to the RO data observed on 29 July 2011. The assimilation result of this RO data shows that the sign of the difference between the first guess and observation may be changed when the large mesoscale perturbation of refractivity exists around the tangent points, and that the temperature and water vapor are modified more widely when the path-averaged refractivity is assimilated.

Keywords: GNSS, Data assimilation

The measurement of the water vapor in the atmosphere using INACORS-BIG, for weather forecasts

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Water vapor is an important component of the earth's climate system. Rain is the condensation of water vapor in atmospheric into drops weight enough water to fall and usually arrive on the mainland. The measurement of water vapor in the atmosphere using GPS is an accurate method, who has done some countries. In Indonesia, research with this method is still relatively new. And held still in the area around the island of Java. As research from Realini et al. (2014) proved that the GPS meteorology technique is useful to investigate severe weather conditions over West Java.

The purpose of this research is to provide estimates of the contents of water vapor in the atmosphere, using GPS stations in Indonesia, is known as INACORS-BIG. In this research also shows the accuracy of the test that compared with meteorological data that has been obtained from BMKG. Therefore, this research needs to be done for the benefit of weather forecasts especially rain. And to test the measurement of water vapor using GPS in Indonesia.

Weather forecast models require three-dimensional temperature, moisture, pressure, and wind data (four dimensional in time). Typically this data is obtained through radiosondes and other techniques. These techniques are often limited spatially and temporally, thus limiting the effectiveness of the forecast models. By better understanding water vapor, as well as the other inputs to the models, more accurate forecast models can be developed and new observational techniques can be investigated.

The GPS techniques discussed here will provide additional atmospheric data to increase vertical resolution in the case of space-based GPS receivers and horizontal resolution in the case of ground-based GPS receivers. With both techniques, the temporal resolution will be greatly improved.

Keywords: INA-CORS, Water Vapor, Weather Forecasts

Impact of advanced ZTD estimate method (Part 2) –Comparison with PWV values by radiosonde observations –

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In the previous paper (Shimada et al., 2015), we propose the new procedure to estimate Zenith Total Delay (ZTD) to obtain GNSS Precipitable Water Vapor (GNSS PWV). In this procedure, we fix the accurate site coordinates in the estimation of ZTD to exclude the trade-off between the vertical coordinates simultaneously estimated in the conventional procedure. The proposed procedure is as follows:
In the first step of the procedure, we estimate daily site coordinates as well as hourly ZTD, every four-hourly atmospheric gradient, and independent ambiguities of all regional network sites as well as the IGS fiducial sites applying the GAMIT program. In the second step, we estimate the accurate present-day site coordinates, estimating from the recent 30-days' time series of the site coordinates solutions applying the Kalman filtering of the GLOBK program, constraining the IGS fiducial site coordinates. Then in the final step of the procedure, we estimate every hourly ZTD, as well as every four-hourly gradients of regional sites and independent ambiguities, fixing the site coordinates obtained in the second step.
In this paper we compare thus obtained GNSS PWV values with the radiosonde PWV observation values, as well as the GNSS PWV values estimated applyig the conventional method. We calculate GNSS PWV values of the GEONET 92110 (Tsukuba1) site and 93002 (Yasato) site using surface barometric and temperature values observed in JMA Aerological Observatory around 6km SSE of Tsukuba1 site and 24km SSW of Yasato1 site. The standard deviation of the difference between the Tsukuba1 site GNSS PWV and radiosonde PWV in Aerological Observatory, for instance, is 15.8mm in every 12h UT observations from March to December 2010, although the standard deviation by the conventional GNSS PWV and radiosonde PWV 17.8mm. Thus we conclude the proposed method estimates more precise PWV values compared with the conventional method.

Keywords: Zenith Total Delay, GNSS precipitable water vapor, Radiosonde precipitable water vapor

Water vapor estimation using digital terrestrial broadcasting waves

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A method of estimating water vapor (propagation delay due to water vapor) using digital terrestrial broadcasting waves is proposed. Our target is to improve the accuracy of numerical weather forecast for severe weather phenomena such as localized heavy rainstorms in urban areas through data assimilation. In this method, we estimate water vapor near a ground surface from the horizontal propagation delay of digital terrestrial broadcasting waves. The basic idea of using propagation delay is the same as that of retrieving PWV by using GNSS, in which vertical propagation paths are used. In this study, we use horizontal propagation paths of digital terrestrial broadcasting waves to obtain water vapor information. The main features of this observation are, no need for transmitters (receiving only), applicability wherever digital terrestrial broadcasting is available, and its high time resolution. The vertical and horizontal observations would be complementary to each other.

When radio waves propagate at a 5 km distance, a 1% increase in relative humidity causes a propagation delay of about 17 ps (about 5 mm in length). Because the delay due to water vapor is quite small, very precise measurements (at least several tens of picosecond order) are needed for effective observations. We can derive delay profiles using the received digital terrestrial broadcasting signals. The delay profiles are determined as the power of a certain broadcasting wave as a function of path delay. Each peak in a delay profile corresponds to a signal from a certain source through a certain propagation path. Therefore, using delay profiles enables us to identify the radio waves in a multipath or a multisource. The range resolution of a delay profile, which corresponds to the resolution to identify each signal, is about 50 m because the bandwidth of each channel is 6 MHz. By measuring the phase at a peak of a delay profile continuously, we can monitor the variation of the propagation path length of a certain broadcasting signal. We can estimate the delay due to water vapor from the variation of the propagation path length. The wavelength of a broadcasting wave whose frequency is 500 MHz is about 60 cm. If we measure the phase at a peak of a delay profile of this broadcasting wave with the accuracy of a degree, the accuracy of the propagation path change is about 1.7 (= 600/360) mm. Thus, we can monitor the variation of the propagation path change (i.e., delay) in millimeter order. The ISDB-T system, which is adopted in Japan, uses Orthogonal Frequency Division Multiplexing (OFDM) for the modulation. The bandwidth of a single channel is 6 MHz, and 5617 carriers are used within it. In each carrier, scattered pilots (SPs, known signals) are embedded every 4 symbols. A symbol is the base unit of OFDM modulation, whose length is 1.134 ms. Therefore, the transfer functions, i.e., the Fourier transforms of the impulse responses, are calculated every 4.536 ms using SPs. The delay profiles are derived as the inverse Fourier transforms of the transfer functions with this time resolution. We can measure the variation of propagation delay in millimeter order using the phase of a delay profile in principle.

However, there remains a technical problem. Because the propagation delay is quite small, phase noises of local oscillators at radio towers and receivers are major error factors. Threfore, we observe direct and reflected waves at a single receiving site. If there is a reflector at the opposite side from the radio tower, we can observe direct waves and reflected waves simultaneously. Measurement is conducted using single local oscillator at the observing point. The phase noises of this local oscillator and the radio tower, which

remain in sampled signals of both direct and reflected waves, are cancelled out by taking the difference between both signals. We can measure a roundtrip propagation delay between the observing point and the reflector without synchronizing the local oscillators. The data obtained using digital terrestrial broadcasting waves show good agreement with those obtained by ground-based meteorological observation.

Keywords: water vapor, propagation delay, digital terrestrial broadcasting waves

A New Index Indicating the Degree of Water Vapor Inhomogeneity Utilizing GNSS Slant Path Delay and its Relation with Short-term Heavy Rainfall

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Water vapor plays a significant role on development of hazardous cumulus convection. Water vapor monitoring with high temporal and spatial resolution is indispensable for both predicting and monitoring of such disastrous weather phenomenon. In Japan, a nationwide dense continuous ground based GNSS (global navigation satellite system) network named GEONET (GNSS Earth Observation Network, http://www.gsi.go.jp/ENGLISH/page_e30030.html) has also been utilized as a continuous water vapor monitoring network by the Japan Meteorological Agency since 2009.

In order to capture finer water vapor variation, we have been developing GNSS slant-path delay (SPD) utilization to detect strong horizontal water vapor gradient within several kilometer which associated with convective activities.

Shoji (2013) developed procedures for retrieving two indices indicating the degree of inhomogeneity of water vapor using the carrier phase of GNSS measured by each GNSS receiver. One index (WVC) describes the spatial concentration of water vapor, while the other (WVI) indicates higher-order water vapor inhomogeneity. Horizontal scales of the two indices are approximately considered to be 60 km and 2-3 km, respectively. A statistical assessment indicates that the two inhomogeneity indices are correlated with strong rainfall.

One of the most important points of the application is its real-time availability. We have tested MADOCA (Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis) real-time ephemerides (https://ssl.tksc.jaxa.jp/madoca/public/public_index_en.html) applied to the program package for GNSS positioning “RTKLIB (http://www.rtklib.com/)” version 2.4.2 (patch 11).

A three-month comparison of WVI index and short-time heavy precipitation in summer (July –September, 2016) in Japan revealed potential of the WVI index for monitoring development hazardous cumulus convection.

Keywords: Watervapor, GNSS, Cumulus convection

