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.

キーワード：GNSS、噴煙、リアルタイム
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

稠密GNSS網を用いた中緯度スポラディックＥの三次元トモグラフィー
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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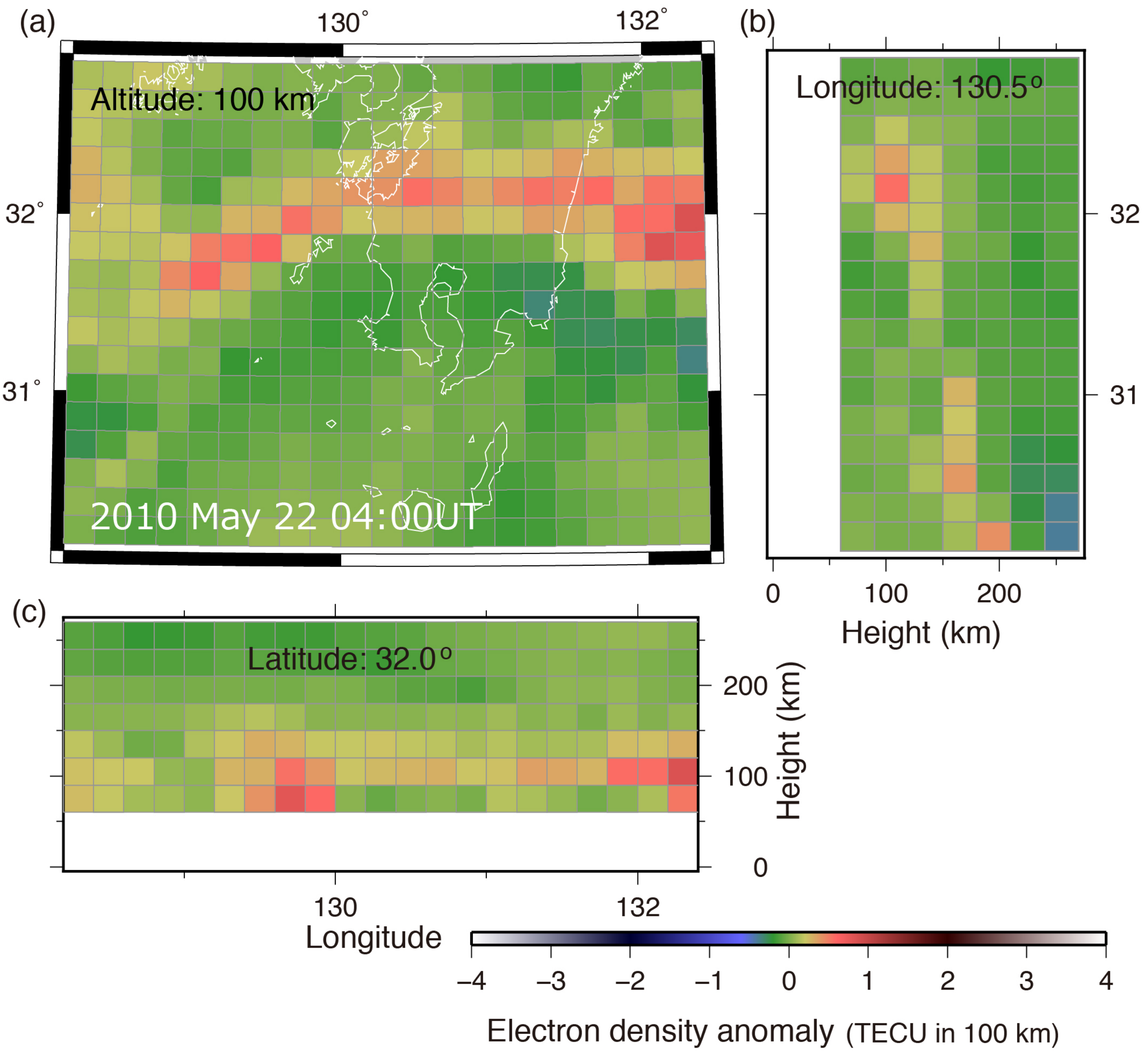
Figure caption: Results of 3-D tomography of the Es irregularity patch that appeared around 4:00 UT (13:00 LT) on May 22, 2010 above the Kyushu, Southwest Japan, see Fig.1d of Maeda and Heki (2015). Frontal shape Es patches extend east-west, and migrate northward. We show the map view at altitude 100 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.

キーワード：スポラディックE、全地球航法衛星システム、電離圏全電子数、三次元トモグラフィー
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.

キーワード：GPS可降水量、気候変動
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.

キーワード：GNSS、データ同化
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

新しい大気天頂遅延量推定方法とその評価（その２）－ラジオゾンデ可降水量との比較

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

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2015年の連合学会において，新しいGNSS天頂遅延量（GNSS ZTD）の推定手法を紹介し，気象数値モデルにこの手法により推定した可降水量（PWV）を同化して2010年7月15日の岐阜県南部豪雨を計算し，従来の手法によるPWVを同化した場合と比較して再現性を評価した．

新しい推定方法では，① GAMITプログラムを用いて，従来の手法で毎日のGNSS観測データから観測点の座標値を，毎時ZTD値・４時間毎の大気勾配値・独立なambiguity値とともに，IGS座標基準点の座標値を強く拘束して推定する．②直近30日間の日値座標値解から，GLOBKプログラムを用いてKalmanフィルターにより，当日の精密な観測点座標値を推定する．③こうして得られた当日の精密な観測点座標値を固定して，毎時ZTD値を４時間毎の大気勾配値・独立なambiguity値とともに推定する．

このようにして，従来の方法ではZTD解とtrade-offを生じる上下座標値を推定しないことにより，より正確なZTD解を推定することができる．

今回の発表では，新しい手法で推定されたGNSS PWVをラジオゾンデPWVと比較した．GEONET 92110（つくば１）観測点及び93002（八郷）観測点のZTD解から，気象庁つくば高層気象台の地上気圧・地上気温を用いてGNSS PWVを計算して，つくば高層気象台のラジオゾンデ観測により得られたPWVと比較した．つくば高層気象台は，92110観測点の6km南南東，93002観測点の24km南南西に位置している．例えば，2010年3月～12月の毎日の12時UTの92110点GNSS PWVと高層気象台ラジオゾンデPWVとの差は，標準偏差15.8mmで一致していた．一方，同じ観測点の従来の方法により推定したGNSS PWVと高層気象台ラジオゾンデPWVとの差では，標準偏差が17.8mmであった．新しい手法により計算したGNSS PWVの方がラジオゾンデPWVとの差のばらつきが小さく，より精度がよいと考えられる．

キーワード：天頂遅延量、GNSS可降水量、ラジオゾンデ可降水量
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.

キーワード：水蒸気、伝搬遅延、地上デジタル放送波
Keywords: water vapor, propagation delay, digital terrestrial broadcasting waves

GNSS視線遅延を用いた水蒸気非一様性の度合いを示す新しい指標と、その短時間強雨との関係

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.

キーワード：水蒸気、GNSS、積乱雲
Keywords: Watervapor, GNSS, Cumulus convection

Building An Online System For Managing, Analyzing And Serving Of Geospatial And Geodynamic Data Of Turkey Based On The User Preferences

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A geospatial data infrastructure comprises geospatial databases and data handling facilities, also data producer and consumer interactions. Geospatial data’s being produced, managed and served globally is depend on the technical policies, standards, human resources, and technology.
The aim of the study is to propose a Geospatial Data Infrastructure to make geodetic and geodynamic data of Turkey manageable and analyzable on web. Proposed Geospatial Data Infrastructure has a multi-tier architecture which is compliant with INSPIRE, including data layer, service layer and application layer. Data layer consists of records, data and metadata about user generated and GNSS related data. For this purpose, PostgreSQL object-relational database is used, and PostGIS is also used to extend PostgreSQL capabilities to store, manage and serve geospatial data on online platforms.
Service layer follows the principles of Service Oriented Architecture (SOA) to build Network Service Architecture. SOA consists of different services with different purposes, and these services work with harmonization and exchange data easily. Interoperability and continuity of these services can be achieved by Extended Markup Language (XML) based Open Geospatial Consortium (OGC) Standard Services; such as Web Map Service (WMS), Web Feature Services (WFS), Web Processing Service (WPS), Web Coordinate Transform Service (WCTS), Web Map Tile Service (WMTS). In SOA architecture data transfer in between client and server is provided by Representational State Transfer (REST) which is proxy independent and uses Hyper Text transfer Protocol (HTTP) Methods. GeoServer is being employed to interpret and to respond user requests, as a web map server.
Application layer offers two main and many other sub-functionalities that only main functionalities are emphasized here; collecting user request and user data, and visualizing response which is interpreted with respect to user preference.

Keywords: GNSS/GPS, Geospatial Data, Web Based System Architecture, OGC web services

GNSS可降水量とMSMを用いた水蒸気ラマンライダーの校正
Calibration technique for water vapor Raman lidar using GNSS PWV and meso-scale model

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豪雨などの局所的な大気現象の理解や、気象予報精度の向上のためには、高い時空間分解能での水蒸気の定量計測が欠かせない。光を使ったリモートセンシング手法であるラマンライダーは、水蒸気の鉛直分布計測に適している。ラマン散乱信号から水蒸気量を推定するには、窒素分子や水蒸気分子のラマン散乱波長の受光効率等に関係した校正係数を定める必要がある。一般的には、ラジオゾンデのような水蒸気混合比を観測する別の手法と比較することにより校正係数を決定している。そのため、ラジオゾンデ観測ができないような場所においては、ラマンライダーによる高精度の水蒸気計測を行うことが難しい。

本研究では、全地球航法衛星システム(GNSS)を用いて推定される可降水量と気象庁メソスケールモデル(MSM)を利用した水蒸気ラマンライダーの校正手法を提案する。本手法ではMSMとラマンライダー観測を統合して得られる水蒸気混合比の鉛直分布積算量が、GNSS可降水量と一致するようにして校正係数を決定する。この手法は、観測可能な高度の制約があるライダー信号においても適用できるという特徴がある。例えば、紫外線C(UV-C)領域のレーザーを使用したラマンライダーは、昼間の太陽背景光の影響を受けないという利点を有するが、UV-C領域におけるオゾンの強力な吸収効果により観測可能高度は1～3km以下となる。また、雲があるときは、ライダー信号の減衰により雲高度以上の解析ができなくなるが、本手法では雲底下までの水蒸気分布を用いて校正係数が導出できる。本稿では、提案する校正手法の校正係数推定精度に関して、シミュレーション研究に基づき説明する。

キーワード：水蒸気、ライダー、GNSS、MSM
Keywords: water vapor, lidar, GNSS, MSM

次世代放射計KUMODeSによる冬季水蒸気量観測
Long-term monitoring of water vapor by using a next generation microwave radiometer “KUMODeS”

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　大雨や積乱雲下で生じる竜巻・大雪などの局所的・突発的自然災害による被害を最小化するには、気象事象の早期予測が重要である。その実現に向けて、大気の熱力学場を高頻度・高精度に観測する手段と、その他の予報・ナウキャスト情報を用いた解析が求められている。
　次世代放射計”KUMODeS(クモデス)”は地上設置型のマイクロ波帯放射計であり、大気中に存在する水分子から放射される輝線 (20 - 30 GHz 帯)ならびに酸素分子からの輝線 (50 - 60 GHz 帯) をマルチバンド受信する。前者の帯域には冷却受信機を採用し、高感度(低雑音)な観測を実現する。加えて、冷凍機の余剰冷却能力を用いて５０Kに冷却した温度較正源を搭載しており、機械的な駆動によって２周波数帯を同時較正する機能を有する。これにより、気温変動等を補正した高精度な屋外観測を実現している。感度向上は大気の熱力学場、雲物理量の推定を短時間で広域観測を実現し、熱力学場の急激な不安定化や、雲物理量の変化の察知に役立つ。現在、試作機を用いて２０１６年度冬季の長期観測をつくば市にて実施している。
　本講演では、システムの概要ならびに大気観測の結果を報告する。また小型・低電力化を目指した二号機の開発状況も報告する。なお、本研究は文部科学省・大学発新産業創出拠点プロジェクト「START」(http://www.jst.go.jp/start/) に平成２６年度より採択され、その援助のもとに開発を行った。

キーワード：大気水蒸気量、放射系、大気熱力学場
Keywords: atmospheric water vapor, radiometer, thermodynamic environment

A comparison of precipitable water vapor retrieved with novel ground-based microwave radiometer, GPS and analysis data in Tsukuba during a cold front passage

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We have developed a state-of-the-art microwave radiometer named KUMODeS (KEK Universal Moisture and Oxygen Detection System) using the technology of millimeter-wave spectroscopy for the high-resolution and high-precision monitoring of water vapor behavior. We have carried out comparative measurements of precipitable water vapor (PWV) in order to investigate the potential of KUMODeS/PWV measurements.

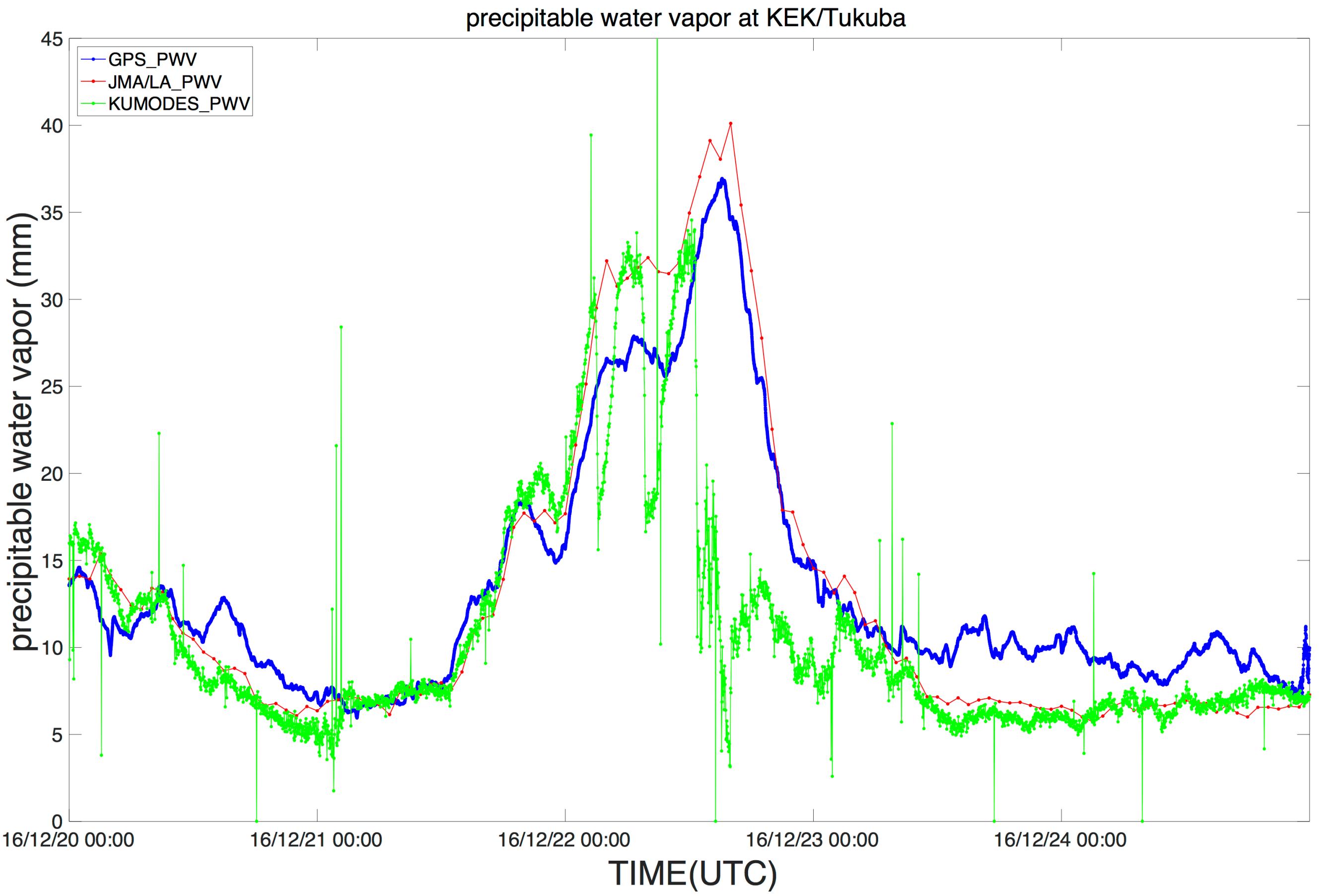
KUMODeS measures spectra using two receivers with frequency bands of 20–30 GHz and 50–60 GHz. The low-noise amplifier of the first receiver and a cold calibration source are implemented in a cryostat, which is maintained at 10 K in order to improve the sensitivity in the detection of the characteristic broad peak of water vapor at around 22 GHz. The second receiver is used to measure the absorption peaks of oxygen (~60 GHz).

The GPS-based PWV is estimated reliably with 1–2 mm accuracy according to previous studies. The GPS PWV values are retrieved from zenith wet delays (ZWDs), which are computed by subtracting the zenith hydrostatic delays (ZHDs) from GPS-based zenith total delays (ZTDs). In this procedure, the ZHDs are obtained from the surface pressure and temperature.

We analyzed the PWV variation in Tsukuba, Japan, derived from three techniques, i.e., using KUMODeS, GPS and JMA operational local analysis (LA), during a cold front passage. The PWV measurements derived from GPS and KUMODeS have temporal resolutions of 30 s and about 2 min, respectively. The estimates from the LA have a temporal resolution of 1 h. A comparison of time series shows good agreement between the PWV measurements retrieved from KUMODeS, GPS and the LA between 20 and 22 December 2016. On the other hand, some differences between them appeared after the heavy rainfall of 22 December.

Although further investigation is required to evaluate the performance of KUMODeS, the preliminary result of the comparison implies the consistency and potential of KUMODeS measurements.

キーワード：マイクロ波放射計、可降水量、衛星測位システム
Keywords: microwave radiometer, precipitable water vapor, GNSS


precipitable water vapor at KEK/Tukuba
GPS_PWV
JMA/LA_PWV
KUMODES_PWV
precipitable water vapor (mm)
45
40
35
30
25
20
15
10
5
0
16/12/20 00:00
16/12/21 00:00
16/12/22 00:00
16/12/23 00:00
16/12/24 00:00
TIME(UTC)

過去20年間の可降水量の長期変動と大気遅延勾配の地域性

Long-term behavior of precipitable water vapor over the last 20 years and regionality of atmospheric delay gradient

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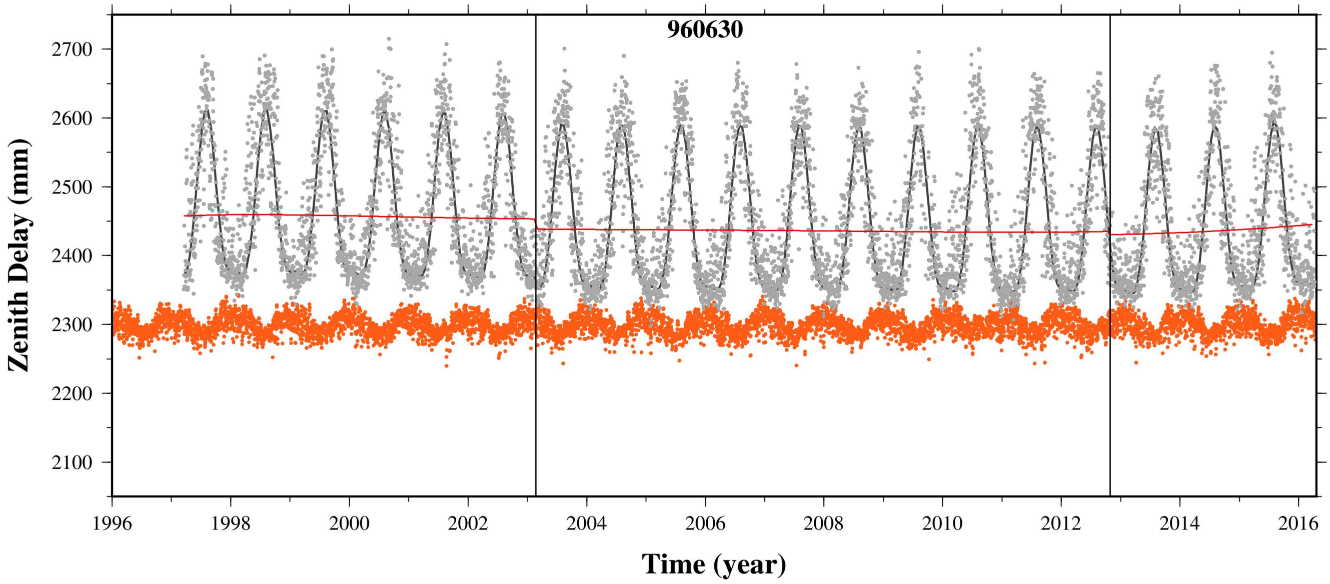
Recent increase of extreme climate events has been a focus of debate all over the world, and they believe that global warming is responsible for the increase. IPCC AR5 (Intergovernmental Panel on Climate Change Fifth Assessment Report) suggested that the average temperature on Earth increased by 0.85℃ from 1880 to 2012 and the average temperature over the last 30 years is higher than any decadal averages since 1850. There is little doubt concerning the reality of the on-going global warming.
It is an important meteorological issue to understand how the changes of atmospheric water vapor influence global warming. By observing the distribution and dynamics of atmospheric water vapor, we can understand its link to the climate change. It will also contribute to improve the accuracy of forecasting precipitation. Precise knowledge of the long-term behavior of water vapor would enable us to predict future climate changes over centuries.
Microwave signals from GNSS satellites experience delays when they propagate the neutral atmosphere. We can infer the amount of wet atmospheric delay (delay caused by water vapor) by subtracting the hydrostatic delay (delay caused by dry atmosphere) from the total delay. In this research, I estimated changes of atmospheric water vapor from 1996 to 2016 by combining the atmospheric delays from the Japanese dense GNSS array GEONET (GNSS Earth Observation NETwork) with the surface atmospheric pressure data from the Japan Meteorological Agency. I then found that the atmospheric water vapor shows complicated inter-annual variations rather than simple monotonous increase. By comparing the behaviors of the atmospheric delays at various points in Japan, I found that multiple factors, e.g. latitude and height, influence the amount of delay.
Atmospheric delay gradient is an important factor to reduce positioning errors when atmospheric delays are not in azimuthal symmetry. In the early days of positioning with GNSS, they assumed that the atmospheric delay depends only on the elevation angle. Now it became standard to model its azimuthal dependence by introducing the atmospheric delay gradient as a new parameter. Estimating the gradients all over the Japanese Islands also made it possible to assess the non-uniform distribution of water vapor not canceled by taking long-term averages. I found several general tendencies in the time-averaged atmospheric delay gradient vectors, e.g. they often show significant southward components, and they are often perpendicular to the coastline and tend from ocean to land.

キーワード：GNSS、可降水量、長期変動
Keywords: GNSS, PWV, Long term variation


960630
Zenith Delay (mm)
2700
2600
2500
2400
2300
2200
2100
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
Time (year)

Relationships among Rainfall Distribution, Surface Wind, and Precipitable Water Vapor derived from GNSS during Localized Heavy Rainfall in Tokyo in Summer

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In recent years, short-term heavy-rainfall events that have caused various damages such as flooding have frequently occurred in the Tokyo Metropolitan area in summer. This study aims to clarify the evolutionary process of short-term heavy rainfall as a contribution to short-range forecasting of heavy rainfall that occurs locally.

The relationships between the occurrence of intense rainfall and the convergence of surface winds and water vapor concentration for typical heavy-rainfall cases were examined using data from July to August in 2011–2013 obtained from high-density meteorological observations in Tokyo, Japan. Additionally, the differences in the temporal variations in wind convergence and water vapor between days with and without heavy rainfall events were compared.

Corresponding to the heavy-rainfall area, the convergence of surface winds tended to increase for several tens of minutes prior to the heavy rainfall. The peak of convergence was observed 10–30 min before the heavy-rainfall occurrence, and increasing of convergence continued for approximately 30 min until the convergence peak time. Around the heavy-rainfall area, the increase in the water vapor concentration index was observed coincide with the increasing of convergence. From these results, by monitoring the temporal variations and distributions of these parameters using a high-density observation network, it should be possible to predict the occurrence of heavy rainfall rapidly and accurately.

This study is supported by the S-8 Project, Comprehensive Research on Climate Change Impact Assessment and Adaptation Policies, implemented by the Environment Research and Technology Development Fund of the Ministry of the Environment, Japan and Tokyo Metropolitan Area Convection Study for Extreme Weather Resilient Cities (TOMACS) under the Funds for Integrated Promotion of Social System Reform and Research and Development by the Ministry of Education, Culture, Sports, Science and Technology, Japan.

キーワード：短時間強雨、地上風収束、水蒸気量、高密度観測網
Keywords: localized heavy rainfall, wind convergence, water vapor, high-density observation network

船舶搭載GNSS水蒸気観測への反射波の影響
The Multi-path Effect on PWV Retrieved from Shipborne GNSS Measurements

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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 observation system of water vapor over the ocean using GNSS receivers equipped on top of floating buoys and vessels (Shoji et al. 2016). 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).

In year 2015, we conducted observations using four shipborne GNSS receivers on three research vessels and one passenger ferry to assess the real-time practicality of measuring GNSS-derived precipitable water vapor (PWV) over the ocean. All antennas were equipped on the upper-most deck of each vessel. A kinematic precise point positioning strategy was used for the GNSS analysis with a real-time GNSS satellite ephemerides (orbit and clock information).

The analyzed time series of PWV was contaminated with unrealistic sharp variations that occasionally occurred. Periodic occurrence of a spiky variation with a cycle of one sidereal day, along with post-fit phase residuals averaged at each elevation and azimuth, indicated that one of the causes of the unrealistically large time variation was interference of reflected signals (multi-path).

A simple quality control (QC) procedure based on the amount of PWV time variation was proposed. After the QC was applied, the retrieved PWVs had 3.4 –5.4mm root mean square (RMS) differences against radiosonde observations, and 2.3 –3.7mm RMS against those retrieved at nearby ground GNSS stations. The proposed QC procedure rejected more than 60 percent of retrieved PWV on research vessels and 6 –11 percent on a passenger ferry. The results demonstrate the great potential of the real-time ephemerides and the necessity for careful consideration of the observation environment.

On 20 October 2016, we introduced an additional GNSS antenna on top of the mast of a vessel and conducted campaign observation till March 2017. Comparison with PWVs analyzed at nearby GEONET stations resulted that both antennas (mast top and deck) show about 2 mm RMS. In the case of the mast

top observation, about 1 percent of retrieved PWV were rejected while more than 30 percent were rejected in the case of the deck observation.

キーワード：水蒸気、GNSS、キネマティック
Keywords: Watervapor, GNSS, Kinematic