Low-cost multi-constellation GNSS receivers for Earth observation

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Low-cost, multi-constellation GNSS receivers that output raw data (i.e. at least code pseudorange and carrier phase observations) have been introduced on the market in the last three years, enabling several advanced applications in the field of Earth observation, including atmospheric measurements, in a cost-effective way. Such receivers, in fact, combine the benefits of using low-cost hardware with those of multi-constellation receivers. The former include, for example, the possibility to make the densification of existing GNSS networks more practical in terms of cost, or to deploy receivers in hazardous locations that might put at risk the integrity of the hardware itself. The latter are at least twofold:

· the increased redundancy provided by satellites belonging to constellations other than GPS makes the estimation process more robust, and increases the available slant measurement directions at any given epoch;

· new signals can be exploited that may prove beneficial for specific applications.

As regards the first point, the number of available multi-GNSS satellites can already be increased to about 2-3 times that of GPS satellites alone, depending on the region of observation, only considering those already in orbit and functioning. This number is going to be further increased when taking into account the new launches scheduled for the next few years.

The second point includes new signals, on frequencies other than L1 or L2, which could be used to obtain more precise measurements (e.g. by the precise code of the Galileo E5 signals) or to provide a second frequency at affordable cost (e.g. exploiting the L2C or L5 signals).

As an example, the advantage of using a cost-effective dual-frequency receiver could be significant for GNSS/MET analyses. In fact, GNSS-based tropospheric estimation and water vapor retrieval are typically performed by using high-grade dual-frequency GPS receivers. A densification of existing GNSS networks is beneficial for precipitable water vapor (PWV) monitoring at a local scale, which is expected to be useful to improve the nowcasting and forecasting of localized heavy rain. However, such a densification would have a high economic impact when standard dual-frequency receivers are involved. On the other hand, when dealing with single-frequency receivers one has to take into account the ionospheric delay, which has to be removed in order to retrieve the tropospheric delay (and consequently the PWV). A second frequency onboard a low-cost GNSS receiver would allow to compensate the ionospheric delay by linear combination of the two frequencies, excluding the need of performing complex interpolations from available dual-frequency stations surrounding the single-frequency receiver.

In general, all the applications requiring the processing of GNSS observations by PPP (precise point positioning), or by relative positioning over long baselines, would benefit from the availability of cost-effective dual-frequency receivers.

This presentation will give an overview of the current status of low-cost receivers and multi-GNSS, describing experiments and test cases related to the combination of the two technologies. Details about the feasibility of designing cost-effective dual-frequency receivers will also be investigated and reported.

Keywords: GNSS, low-cost, multi-GNSS
Impact of advanced ZTD estimate method - Separation from site coordinates estimation

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In this paper we introduce the new procedure to estimate ZTD to obtain GPS PWV for numerical weather models. In general the major systematic error source of the ZTD estimation is the trade-off between the ZTD and the coordinate solutions usually simultaneously estimated in the GNSS analysis. In the analysis of the ZTD estimation, we fix the accurate site coordinates and exclude the trade-off systematic errors.

In the first step of the procedure, we estimate site coordinates as well as hourly ZTD, every four-hourly atmospheric gradient, and ambiguities of all of the GEONET 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 of the GEONET sites, estimating from the recent 30-days site coordinates solutions time series 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 and every four-hourly gradients of the GEONET sites fixing the site coordinates obtained in the second step.

To evaluate the advanced ZTD estimation, we compare the PWV values calculated from the three kind of ZTDs obtained by three different analysis procedures. We assimilate the PWVs to the CReSS numerical weather model, and examine the impact of the PWVs in the heavy rain in the Southern Gifu Prefecture, Central Japan, on July 15 2010. The ZTDs are estimated by the following three procedures; (a) in the near real-time analysis applying the GAMIT program and estimating site coordinates, hourly ZTDs, four-hourly atmospheric gradient, and ambiguities simultaneously using IGS ultra-rapid orbit, (b) in the post-processing analysis applying the Bernese software and estimating site coordinates, three-hourly ZTDs, atmospheric gradient, and ambiguities simultaneously using IGS final orbit calculated by GSI (F3 solution), (c) in the post-processing analysis and applying the procedure mentioned above in this study (advanced ZTDs) using IGS final orbit. Examining the wide area distribution of water vapor in the objective analysis, (a) and (b) indicate the almost same distribution and (c) only shows the sharp contrast of the mixing ratio, dry in the north-western area in contrast with wet in the south-western area, in Central and Western Japan. The heavy rain phenomena calculated using (c) only significantly coincides with the observation.

We also introduce the impact of the heavy rains applying PWVs obtained by the advanced ZTDs in the cases of the heavy rain in the Niigata Prefecture, Central Japan, in July 2011, and the thunderstorm in the Tokyo metropolis on July 15 2006.

Keywords: Zenith Total Delay, GNSS precipitable water, GEONET, Numerical weather model, CReSS model
Preliminary studies on the integration of GPS and ECMWF to derive high spatial and temporal resolution water vapor maps

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The development of Global Navigation Satellite Systems (GNSS), since middle 1980s, has led to a significant change in the life of world’s community. One of their most important and known application for the mass market is navigation systems for automobiles but also for aircrafts and ships. They play an important role also in several technical and scientific activities such as surveying, mapping and geographic information systems (GIS). In geophysics, the high precision measurements of multiple stations can be used to find strain and ground movement. Actually the most common system, operational and globally available, is the US Global Positioning System (GPS).

Recently studies are in place to evaluate GPS application for meteorology. The atmosphere affects the GPS radio signals transmissions from space since the index of refraction is variable along the ray path. This index is a function of pressure, temperature, and moisture so GPS can be directly used for sensing properties of the atmosphere. Water vapor, located in the lowest layers of the atmosphere, significantly affects the GPS signal propagation velocity and, at the same time, plays an important role in atmospheric processes, from global climate change to micrometeorology. The information derived from GPS, which allows to quantify water vapor, is the Zenith Total Delay (ZTD) that summarizes the increase of the optical path length between GPS satellites and receiver. It has two components: the Zenith Hydrostatic Delay (ZHD), primarily affected by hydrostatic gasses, and the Zenith Wet Delay (ZWD), directly related to water vapor. While the ZHD can be modeled with high accuracy, the ZWD has a large temporal and spatial variability so it is rather difficult to model and predict.

The comparison between water vapor estimated from GPS ZTD and the results obtained from other well-known technics (radio-sounding with water vapor radiometers, ground or space-based, or Numerical Weather Models) has shown the reliability of GPS data for the estimation of this atmospheric parameter.

This work describes the results of preliminary studies on the integration between GPS and European Centre for Medium-Range Weather Forecasting (ECMWF) data to derive high spatial and temporal resolution water vapor maps. The data from ECMWF, characterized by high spatial resolution but low temporal resolution (3 hours), can be used to calculate the covariance function, which quantify their spatial variability. Knowing this function, ZTD values obtained from GPS, which have a low spatial resolution but high temporal resolution (15 minutes) could be regionalized and high resolution water vapor maps, almost in real time, could be obtained.

The work has been developed in the contest of a three year international program between Italy and Argentina (2011-2013). In the first two years, different analysis have been conducted, focused on the assessment of the capabilities of the SIRGAS permanent network, which is the densification of the International Reference Frame (ITRF) in South America and Antarctic continent. The ZTD derived by the SIRGAS permanent network has been compared with those obtained from the International GNSS Service (IGS) products and from the radiometer on Jason-1 altimeter satellite. The results showed the reliability of SIRGAS permanent network. The accuracy of SIRGAS ZTD values was analyzed also in terms of consistency with ZTD values obtained from the ECMWF ERA-Interim database. ERA-Interim is an “interim” reanalysis to the period 1979-present of all the data stored in the ECMWF database.

The work done consists in a detailed study of the consistence of the results (in terms of ZTD) obtained from ECMWF and GPS, considering two small areas of South America. The areas chosen were characterized by different features (e.g. orography) in order to better understand their influence on the spatial variation of ZTD. A procedure is also proposed to optimize the management of data.

Keywords: GPS meteorology, high resolution water vapor maps, ECMWF
GNSS 视线延迟数据捕获的樱岛火山喷发柱的移流扩散
Advection diffusion of eruption column captured by GNSS slant path delay in Sakurajima volcano

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We assess the ability of GPS data to detect volcanic plumes at Minami-dake of Sakurajima Volcano. In this study, we describe the July 24, 2012 activity at Minami-dake of Sakurajima Volcano. We analyzed the data from more than 20 continuous GPS stations, which located on the volcano flanks, and neighboring region. We used GIPSY-OASIS II version 6.3 software. We extracted the post-fit phase residual in the ionosphere-free linear combination for each pair of GPS satellites and ground stations for the detection of eruption column. The wet zenith tropospheric delays and its gradient at all the GPS sites were estimated at all processing epochs (30 seconds). Firstly, we analyze the all of the GPS data in July 23, 2012 for the reference. Obtained post-fit phase residual of the reference days showed the noise-level for the path delay effects caused by the volcanic plume. This reference post-fit phase residual contained many noise sources such as multipath effects. The noise level of the post-fit phase residual strongly depends on the each GPS satellite and ground station pair. Finally, we analyzed the data of the July 24, 2012. The post-fit phase residual clearly shows large disturbance just after the eruption. For example, the phase residual between SVN34 satellite and GEONET 0720, which located in the east coast of Sakurajima, suddenly increased just after the eruption. The obtained residual amount reached 80mm. It is clearly larger than the noise level measured on the reference days. Furthermore, other GPS satellite and ground station pairs also clearly showed significant amounts of disturbance. These results suggest that the eruption column moved to the westward by the wind after the eruptive event.

キーワード: GNSS
Keywords: GNSS
直接波と反射波の干渉を利用したGNSS積雪計：2014年2月の山梨豪雪の観測

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GNSS の「マルチパス」を利用した観測によってアンテナ周辺の積雪深度を求めた事例について報告する。GNSS 衛星からの直接波と地面等で反射した電波の干渉によって生じる様々な現象を総称してマルチパスと呼ぶ。衛星の公転周期である恒星日に同期した繰り返し測位誤差などが良く知られるが、昨今では、マルチパスを積極的に利用して、土壤水分、植生、海面等のアンテナ周辺の様々な状況を推定する手法が開拓されつつある。Larson et al. (2009) は、GNSS 受信信号の SN 比の変動から、積雪に伴う見かけ上のアンテナ高の変動を求める手法を提唱した。一方 Ozeki & Heki (2012) は、L1 と L2 の搬送波位相の差 (L4) の振動からも同様に積雪深度を推定できることを示した。Ozeki & Heki (2012) は、国土地理院の連続観測網 GEONET の北海道新篠津村の GNSS 点のデータを用いて、L4 と SN 比の双方を用いて求めた積雪深度を近傍のアメダス積雪計と比較することにより、それぞれ約 6 cm および約 4 cm の確度があることを示した。

本研究では山梨県北杜市小淵沢町にある GEONET 点 950263 の 2014 年一月から三月にかけてのデータを用い、複数の衛星が協共の地平線に沈む真前の SN 比のマルチパスによる変動を解析した。北杜市では 2014 年二月の大雪で交通の遮断等による物資や農業施設への被害等が発生している。同観測点は小学校校庭の南西側に設置され、東北方向は平坦なグランドであるため、直接波と反射波の干渉の観測に条件が良い。衛星は GPS 衛星の 12, 20, 32 の三衛星を用い、それぞれが北西に沈む前夜二時間の SN 比データを用いた。観測時間帯は毎日約 4 分ずつ早くして、衛星の方向を毎日同じに保った。無積雪時のマルチパスによる GPS 12 番衛星の L2 の SN 比変化の周波数は 4.6 mHz 程度であるが、これが本年の GNSS アンテナの高さである約 6 m に相当する。その間波数は雪が深くなるに従って高くなり、1 m 程度の積雪で L2 の SN 比変動周波数のピークは約 0.75 mHz 下方にシフトする。様々なアンテナ高で理論的に予測される SN 比変化の周波数を計算してあらかじめ校正曲線を作っておき、日々の周波数ピークト値から積雪深度の推移を求めた。

本研究の結果、小淵沢 GNSS 点で二月の七日と十四日の二回にわたる大雪で積雪深度が約 1 m に達したこと、その後徐々に融雪により深度がゆっくり小さくなる様子が現れてきた。大雪直後は時折データの乱れが見られるが、現地は誰も自由に出歩くできる学校の構内であり、電波が反射する部分の雪面がしばしば人為的に乱されるだろう。積雪が 1 m を超えた時からは、人為的な擾乱が無くなったためデータは雑騒になる。アメダスには、例年積雪がありない地点では積雪計が装備されていないことが多いが、GEONET 点を利用することで、それらを補完する積雪データが得られることが期待される。

文献

キーワード: GNSS, GPS, 積雪深度, マルチパス, 干渉, 2014 山梨豪雪
Keywords: GNSS, GPS, snow depth, multipath, interference, 2014 Yamanashi heavy snowfall
For past two decades, U.S. Global Positioning System (GPS) has been almost sole reliable operational system for space based Position, Navigation and Timing. Recently, other countries, Russia, China, EU, India and Japan, are competing in the efforts to establish their own Global Navigation Satellite System (GNSS) or Regional one in order to seek secure and effective social infrastructure, and economical growth.

In present, two GNSS, U.S. GPS and Russian Glonass, are operated and China is pushing their national program strongly, BeiDou has started regional service with 14 satellites in Asia pacific region since December 2012. European Galileo is progressing to launch its initial service in 2015-16, though their latest two Full Operational Capability (FOC) satellites could not reach planned orbit slots due to the upper stage failure of launch vehicle, unfortunately. India has just started their regional satellite navigation system, IRNSS, three satellites has been launched already. As for Japanese QZSS, adding QZS-1 orbiting since 2010 to three additional satellites, Japan will provide GPS interoperable signal for Eastern Asia and Oceania region as well as augmentation service for Japan in 2018.

Forecasting the situation in 2020, more than 120 navigation satellites will orbiting around the Earth and more than 30 satellites are to be available to use even in town in this coming multi-GNSS era. The utilization of multiple GNSS constellation is expected to resolve one of the drawbacks of satellite navigation which is difficult to use in dense urban area. Especially, carrier phase positioning in urban canyon is still big challenge, since surrounding building can easily block satellite signals, cycle slip and signal loss occur frequently. However, multi-GNSS signals can facilitate to get positioning solution even in such severe condition. In addition, use of multiple system contributes to more dense atmospheric delay measurement such like Slant Tropospheric Delay (STD) which is useful to monitor the distribution of precipitable water rather than conventional ZTD estimation with only GPS observation.

Toward the future multiple GNSS environment, Multi-GNSS Advanced Demonstration Tool for Orbit and Clock Analysis (MADOCA) has been developed by Japan Aerospace Exploration Agency (JAXA) which supports all usable GNSS constellations. The current version of MADOCA can estimate precise orbit and clock offset for GPS, GLONASS, Galileo and QZSS. The final product for GPS and GLONASS generated by post processing analysis with more than 80 observation at Multi-GNSS Monitoring Network (MGM-Net) and IGS sites is comparable to IGS final product within a couple of centimeters. Supporting BeiDou will come in near future update in 2015. In parallel with MADOCA development, the development of its applications on Precise Point Positioning (PPP), which we call “MADOCA-PPP” are being conducted. The first satellite of QZSS, Michibiki, has an experimental signal (LEX) which can transmit 2000 bps data stream on 1278.75 MHz with BPSK(5) radio signal. JAXA is routinely generating error correction message for MADOCA-PPP, broadcasting it via LEX signal and evaluating its performance. Current performance of MADOCA-PPP is sub-decimeter accuracy (RMS) for both horizontal and vertical direction in real time processing.

The latest status of the MADOCA and MADOCA-PPP development is described with performance test results. In addition, current technical challenges are introduced and how to resolve them are also discussed in the presentation.

**Keywords:** Multi-GNSS, Precise Orbit and Clock estimation, Quasi-Zenith Satellite System, MADOCA, PPP/PPP-AR
GNSS ionospheric anomalies following recent big earthquakes: Results and statistical analysis

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Up to now, it is still difficult to well understand and predict Earthquake from traditional seismometer and space geodetic deformation measurements. Ionospheric disturbances following the earthquake may provide new insights. In this paper, GNSS seismo-ionospheric anomalies are presented following recent bigger earthquakes, e.g., 2008 Mw 8.0 Wenchuan (China) earthquake, 2011 Mw 9.1 Tohoku (Japan) Earthquake and 2011 Mw 7.2 Van (Turkey) earthquake. Significant pre-seismic, co-seismic and post-seismic ionospheric disturbances are observed with about 0.2—0.5TECU from continuous GPS measurements. Furthermore, different seismo-ionospheric behaviors and patterns are presented and discussed as well as statistic analysis.

Keywords: Seismo-ionosphere, TEC, Earthquake, GNSS
An observational study on the time and spatial variations of the localized ionospheric delays with a dense GNSS receiver

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The integrated amount of water vapor along the zenith angle, or PWV (Precipitable Water Vapor) can be estimated by GPS (GNSS) meteorology, which is a method to compute atmospheric parameters from troposphere-induced delays in signals of GPS (GNSS). We deployed a dual-frequency (DF) GNSS network around Uji campus of Kyoto University, Japan, with inter-station distances of few kilometers. By using this dense network, we built a basic system to observe PWV fluctuations occurring within a small horizontal scale (less than 10 km), which were then analyzed to identify possible precursors of local torrential rain.

To utilize this network as a practical heavy rain early warning system for urban area, using inexpensive single-frequency (SF) receivers would be better for economic reasons. However, using SF receivers occurs error in computing PWV because we cannot eliminate the ionospheric delay by using SF receivers. So we investigate and estimate ionospheric delay within this dense network system in many cases. From this investigate, we aim to find the appropriate method to correct the effect of ionospheric delays on SF observations in this dense GNSS network system.

Keywords: GPS, GNSS, ionosphere, dense network
Development of GNSS tomography for ionospheric electron density and tropospheric water vapor distribution

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The GNSS signal contains the information on electron density distribution of water vapor along the line of sight. Therefore, it is possible to develop the electron density tomography and the water vapor tomography to visualize the 3D structures in time and space. For this aim, we use the algorithm of residual minimization learning neural network (RMTNN) without any models (Ma et al., 2006; Hirooka et al., 2011). Tomographic algorithms have a tendency to fall into ill-posed problems. Therefore, in general a regularization is required. In this study, we use the data observed by Ionosonde and AMeDAS to restrict data for electron density and water vapor reconstruction, respectively. We performed the numerical simulation to investigate the ability of the developed RMTNN algorithm and carried out the practical application for actual data.

The results provide following capacities of the RMTNN algorithm: (1) for the electron density visualization, transient disturbances can be reconstructed successfully without any model assumptions, (2) the reliability of the lower edge of the ionosphere is a little bit weak, and (3) for the water vapor, if adequately restricted data are given, the water vapor disturbance can be reconstructed successfully. These facts show that the developed RMTNN tomography algorithm on GNSS/GPS data for electron density and tropospheric water vapor has the capacity to reconstruct disturbance without any model dependence.

Keywords: GNSS tomography, ionospheric electron density, tropospheric water vapor distribution, RMTNN
Chiba University Microsatellite for Ionospheric Monitoring
Chiba University Microsatellite for Ionospheric Monitoring

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Chiba University develops two microsatellites called GAIA-I (50 kg class) and GAIA-II (100 kg class). GAIA-I payload is GNSS Radio Occultation (RO) sensor and Electron Density - Temperature Probe (EDTP) for Ionosphere monitoring, and GAIA-II payload is Circularly Polarized Synthetic Aperture Radar (CP-SAR, Patent Pending 2014-214905) for global land deformation monitoring. In the near future, we will employ these microsatellites to investigate relationship of total electron content (TEC), electron density and temperature, and global land deformation to observe precursor of earthquake. This paper focuses to discuss the development progress of GAIA-I microsatellite.

Keywords: Ionospheric Monitoring, GNSS-RO, EDTP, Microsatellite

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キーワード: Ionospheric Monitoring, GNSS-RO, EDTP, Microsatellite
Keywords: Ionospheric Monitoring, GNSS-RO, EDTP, Microsatellite
Proposal of GNSS Buoy Array in the Ocean for a Synthetic Disaster Mitigation

KOSHIKA, Naokiyo

Keywords: GNSS, GNSS buoy, tsunami, ocean bottom crustal movement, meteorology, ionosphere
GPS³: 革新的衛星技術実証プログラムへの提案
GNSS occultation & Plasma Small Satellite Systems (GPS³)

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平成27年度より実施される革新的衛星技術実証プログラムに提案した掩蔽観測小型衛星構想について発表する。

キーワード: GNSS 掩蔽観測, 数値気象予測, 国際標準電離層, 地震前電離層変動, 宇宙天気, 宇宙状況認識
Keywords: GNSS-RO, Numerical Weather Prediction, International Reference Ionosphere, Seismo-Ionospheric Precursor, Space Weather, Space Situational Awareness
GPS/GNSS 気象学 -概要と将来展望-
GPS/GNSS Meteorology in JAPAN - Overview and future scope -

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日本におけるGPS/GNSS 気象学をレビューし、将来を展望する。

水蒸気はGPS（Global Positioning System：全地球測位システム）測位には誤差をもたらすノイズだが、天気予報にとっては精度向上をもたらす重要なシグナルである。1997-2001年度に取り組まれた科学技術庁科学技術振興調整費「GPS気象学：GPS水蒸気情報システムの構築と気象学・水文学への応用（以下「GPS気象学」と記す）」は、この「水蒸気」をキーワードに、測地研究者と気象研究者が、GPSという研究資源を介して学際協力を行い、相互の発展を図ることを基本概念として実施された。

「GPS気象学」プロジェクトは、世界に類を見ない精密な国土地理院のGPS観測網GEONET（GPS Earth Observation NETWORK）から得られる水蒸気情報を天気予報の根幹である数値気象予報に活用すること、および数値予報データを用いた測位精度の向上という2つの目標を掲げ、測地研究者と気象研究者が参加する学際的なプロジェクトであった。1996年の実現可能性を問う予備研究（Feasibility Study: FS）を経て、GEONETから解析された可降水量（PWV）の精度検証、数値予報へのデータ同化実験、観測情報への処理の一部。3次元水蒸気の非一様性に関する研究等が取り組まれた。2000年、2001年にはつくば市周辺20km四方の領域に37箇所のGPS観測点を設置する世界初の精密観測実験が実施され、積乱雲の発達に伴う水蒸気の3次元構造とその変動を捕えることに成功した。この観測結果を基に、高精度到達電波の利用の可能性を検討した。さらに、天気予報の精度向上のための気象情報の活用は、気象情報学の重要な課題である。

このGPS/GNSS気象学の将来展望に向けた研究が進んでいる。