# GPS-based monitoring and modeling of the ionosphere and its applications for high accuracy correction in China

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**Abstract** The main research conducted previously on GPS ionosphere in China is first introduced. Besides, the current investigations include as follows: (1) GPS-based spatial environmental, especially the ionosphere, monitoring, modeling and analysis, including ground/space-based GPS ionosphere electron density (IED) through occultation/ tomography technologies with GPS data from global/regional network, development of a GNSS-based platform for imaging ionosphere and atmosphere (GPFIIA), and preliminary test results through performing the first 3D imaging for the IED over China, (2) The atmospheric and ionospheric modeling for GPS-based surveying, navigation and orbit determination, involving high precisely ionospheric TEC modeling for phase-based long/median range network RTK system for achieving CM-level real time positioning, next generation GNSS broadcast ionospheric time-delay algorithm required for higher correction accuracy, and orbit determination for Low-Earth-orbiter satellites using single frequency GPS receivers, and (3) Research products in applications for national significant projects: GPS-based ionospheric effects modeling for precise positioning and orbit determination applied to China's manned space-engineering, including spatial robot navigation and control and international space station intersection and docking required for related national significant projects.

**Keywords:** GPS/GNSS, atmosphere, ionosphere, electron density, ionospheric delay, spatial environment, navigation, positioning, orbit determination, grid ionospheric model (GIM), absolute plus relative scheme (APRS),ionospheric Eclipse Factor Method (IEFM), auto-covariance estimation of variable samples (ACEVS), different area for different stations (DADS), network RTK, China's manned space- engineering, international space station (ISS), intersection and docking, spatial robot

## 1. Introduction

According to requirements for some important GPS research projects in the fields of Geodesy, Geophysics, Space-Physics and navigation in China, research on how to monitor/model/correct the effects of the ionosphere on GPS were conducted systematically with high precision/accuracy[1~28]. Of these, they focused mainly on: improvement of GPS positioning/surveying by reducing ionospheric delay for dual/single frequency kinematic/static users, high accuracy correction of ionospheric delay for ground /spatial single/dual frequency GPS users, China WAAS ionospheric modelling, and the theory and method for monitoring of ionosphere using GPS. They include the following aspects:

① A static real-time calibration scheme of instrumental bias of GPS observation[1]; ②A ionospheric model based on a generalized trigonometric series function (GTSF)[2,5]; ③ The different area for different stations (DADS) [ 7], a method of constructing large range (regional and global) high accuracy grid ionospheric model; ④ The absolute plus relative scheme

(APRS) [3], a method of efficiently correcting ionosphere effects for WAAS's users and low earth orbit spacecraft under typical adverse conditions; ⑤ The auto-covariance estimation of variable samples (ACEVS) [4], a general theory of using GPS time series data to monitor random ionospheric disturbances and an ACEVS based general scheme of monitoring random ionosphere; ⑥ The ionospheric eclipse factor method (IEFM) [11,16], an approach to fit ionospheric delay using GPS data.

On the other hand, currently, GPS ionosphere subjects involved in some national significant scientific or engineering projects of China have been studied, including China's Manned Aerospace engineering, pre-investigation of Chinese next generation GNSS. They involve the following aspects: ① GPS-based spatial environmental, especially the ionosphere, monitoring, modeling and analysis. ②The atmospheric and ionospheric modeling for GPS-based surveying, navigation and orbit determination; ③ GPS-based ionospheric effects modeling for achieving precise positioning and orbit determination applied to China's manned space-engineering

## 2. Conducted research on GPS ionosphere monitoring/modeling/correcting [6]

### 2.1 A static scheme on calibration of instrumental biases in GPS observation[1]

For a GPS-based Wide Area Augmentation System (WAAS), a key issue in determining ionospheric delay is to precisely calibrate satellite and receiver bias since these instrumental biases (IB) may introduce a several-meter systematic error for ionospheric delay measurement and an error of the order of meters for positioning. For these purpose, an improved algorithm about static real time determination of ionospheric delay is presented. This scheme can decrease the number of unknown parameters, can reduce the effect from instrumental bias, and can be applied to directly and precisely extract ionospheric delay from dual-frequency data.. It is an available scheme to determine ionospheric delays for a WAAS and many other large range GPS application systems.

### 2.2 A generalized ionospheric model based on a set of trigonometric series functions [2,5]

On the basis of ionospheric diurnal variation with an approximate period of 24 hours under normal conditions, a generalized ionospheric model, call the GTSF model, has been constructed which consists of a set of trigonometric series functions. This model not only can fit diurnal variation properties of normal ionosphere very well but also has good monitoring ability to ionosphere. It may be applied to correct efficiently the effects of ionospheric delay on single frequency GPS uses serviced by DGPS and improves modeling ability to local ionosphere.

### 2.3 A method of constructing large range (regional and global) high accuracy grid ionospheric model—the Different Area for Different Stations (DADS) [7]

Establishing a large range and high precision GIM is a critical step for investigating the ionosphere using a GPS network. However, in majority of the methods used currently, the parameters of an ionospheric model are usually determined by fitting all data from large area covered by the model. It has a limitation to model determination precision due to neglecting local characteristics of ionosphere and is also disadvantageous to analysis of the effects of the fitting method on the estimation precision of the model parameters. The Different Areas for Different Stations (DADS) is investigated which is advantageous for avoidance of the shortcomings of the current methods and improvement of the estimation precision of the model parameters. For the whole area of China, the correction precision of the DADS-based grid ionospheric model obviously is better than that of a parameterized model, and it has been applied to establish a real time grid ionospheric correction model of China.

### 2.4 A method for correcting ionospheric delays for WAAS's users under typical adverse conditions—the Absolute Plus Relative Scheme (APR-I) [3]

It is difficult to account precisely for the ionospheric delays for single frequency GPS receivers. In general, the ionospheric correction model broadcast with the GPS signals is inadequate for many GPS users, and its effectiveness will be less under abnormal ionospheric conditions. The WAAS with a grid ionospheric model is one of the most effective methods for modelling ionospheric delays for single frequency users. It is particularly needed when differential ionospheric delay corrections cannot be broadcast, when users cannot receive them, or when there are ionospheric anomalies. For single frequency GPS users, an ionospheric delay correction scheme, called the

APR-I scheme, is proposed which can address well the above problems. The APR-I scheme not only retains the high accuracy of the DIDC from a WAAS under normal conditions, but also has relatively better correction effectiveness under different abnormal conditions. In addition, its implementation need not change the present basic ionospheric delay correction algorithm of the WAAS, and the APR-I does not impose any new demand on receiver hardware and only makes a few improvements to receiver software.It can be easily applied to single frequency GPS users.

### 2.5 A new theory of monitoring random signal and its application for monitoring random ionosphere using GPS—the Auto-Covariance Estimation of Variable Samples(ACEVS) [4]

Ionospheric disturbance monitoring is required for many GPS applications. From a general mathematical aspect, a method for monitoring ionospheric variations is presented based on both the characteristics of a time series of GPS observations and an investigation of the statistical properties of the estimated auto-covariance of the random ionospheric delay when the number of samples is changed in the time series. An approach to monitoring ionospheric delays is found, and then a ACEVS-based framework scheme for monitoring disturbed ionospheric delay is established. The framework scheme can be applied to design various types of practical schemes on monitoring ionopheric random variations using a single (static or kinematic) dual frequency GPS reciever.

### 2.6 An approach to determine ionospheric delay using GPS—the Ionospheric Eclipse Factor Method (IEFM) [11,16] .

For GPS-based precise ionospheric delay modeling, a critical factor is to exactly distinguish ionospheric daytime and nighttime and reasonably represent the variation characteristics of ionospheric TEC associated with different periods at IPP. The local time of IPP is usually applied to construct the mathematical expressions of ionospheric TEC, directly or indirectly. It is difficult and even almost impossible in most cases to use the local time only to exactly distinguish the ionospheric daytime and nighttime of IPP. An important way to improve computation efficiency of GPS-derived ionospheric delay is to more reasonably represent differential periods of daytime and nighttime and to model the ionospheric variations with differential seasons at IPP, and then develop a method for modeling the ionospheric effects. The ionospheric Eclipse Factor Method (IEFM) is therefore investigated, and the IEFM may further improve determination efficiency of ionospheric delay, which is closer to that achieved by dual frequency users.

## 3. Progress in research on GPS ionosphere monitoring /modeling/ correcting

### 3.1 GPS-based spatial environmental, especially the ionosphere, monitoring, modeling and analysis[26].

A GNSS-based platform for imaging ionosphere and atmosphere (GPFIIA) is being developed at the institute of geodesy and geophysics. The GPFIIA will be an important part of a scientific software platform for processing and analyzing a large amount of different types of data associated with ever increasing number of GNSS and low-orbit earth observation satellites. At present, GPFIIA can combine a voxel-based ionosphere tomographic technique with ground-based and space-based GPS data to image the ionospheric electron density (IED), to study the vertical structures and related properties of the ionosphere, and to improve the correction accuracy of ionospheric delay. Dual frequency GPS data selected from the Crustal Movement Observation Network of China (CMONC) and some simulated GPS/MET data can be applied to invert a time series of the IED profiles over China using tomographic algorithms. The reconstructed IED profiles can be partially validated with those obtained using the IRI2001 model. The inverted results may illustrate the characteristics of the IED to some extent. There are two typical application scenarios as follows[27,28]:

(1) Study the effect of strong magnetic storm on the ionosphere over China region. The ionospheric strom evolution process was monitored during the 18 August 2003 magnetic strom over China, through inversion of the ionospheric electron density from GPS observations. The temporal and spatial variations of the ionosphere were analysed as a time series of ionospheric electron density profiles. Results illustrate that the main ionospheric effects of the storm over China under consideration are: the positive storm phase effect usually happens in the low latitudinal ionospheric; the negative storm phase effect occurs in the middle latitude, and the equatorial anomaly structure can be found as well.

(2) Inversion of the Equatorial Ionospheric Anomaly Using Ground- and Space- Based GPS Data. A method is presented to estimate the Ionospheric Electron Content (IEC) above the Low Earth Orbit (LEO) satellite using GPS data onboard CHAMP. On the basis of CHAMP GPS data and IONEX data supplied by the Center for Orbit Determination in Europe (CODE), three kinds of different ionospheric states during the process of the equatorial ionospheric anomaly evolution are demonstrated in terms of qualitative analysis, namely the preliminary stage, the developing stage and the forming stage.

### 3.2 The atmospheric and ionospheric modeling for GPS-based surveying, navigation and orbit determination.

These involve high precisely ionospheric TEC modeling for phase-based long/median range network RTK system for CM-level real time positioning, next generation GNSS broadcast ionospheric time-delay model or algorithm required for higher correction accuracy, and orbit determination for Low-Earth-orbiter satellites using single frequency GPS receivers. In this aspect, both the wavelet and the fractal geometry theories will be applied to open a new approach to achieve CM-level real time positioning under GPS-alone or a combined multi-GNSS system. Meanwhile, a new GNSS Broadcast ionospheric time delay correction model is being developed, called the IGGSH model.

### 3.3 Research products related to GPS ionosphere in applications for national significant projects.

These involve GPS-based spatial environmental and ionospheric effects modeling for achieving precise positioning and orbit determination applied for China's manned space-engineering, including spatial robot navigation and control and international space station intersection and docking required by some national significant projects. Currently, some important investigations/developments on the Kalman Filtering theory are being applied to this area [29~32]

## 4. Summaries

In all the above work, fortunately, the first author is the person solely responsible for related ionosphere research and its implementation in practice. Currently, we focus on development of a new broadcast ionospheric delay correction models/ algorithms required for next generation GNSS, especially for Chinese new generation system, research on GPS ionosphere involved in China's manned aerospace engineering and national CORS system, and ionospheric electron density inversion using GPS/GNSS satellite geodetic data.


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