



EGNOS 对流层延迟改正模型及其精度分析

刘靖晔, 宋元明, 胡加星

(桂林理工大学 土木与建筑工程学院, 广西 桂林 541004)

摘要: 对流层延迟是 GPS 定位中一个主要的误差源, 目前处理对流层延迟的主要方法是通过模型法、差分法等; 当基线的距离较短时, 基线两端气象条件基本相同差分法可以很好地修正对流层延迟误差, 当基线的距离很长时, 由于基线两端的气象参数差别较大差分法不能很好地消除对流层误差, 模型法却能很好地消除对流层误差。对 EGNOS 模型进行了详细的介绍, 并通过 MATLAB 编写程序; 利用 IGS 跟踪站的数据进行计算分析比较, 结果表明 EGNOS 对流层改正模型在高程上介于 Saastamoinen 模型和 Hopfield 模型之间, 在 x, y 方向上精度相当。

关键词: GPS; 对流层; EGNOS; 精度分析

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对流层紧邻地表, 大气稠密, 其高度为 40 km 以下的大气底层; 由于折射率的变化, GPS 信号穿过对流层时路径会发生弯曲, 因此对 GPS 定位产生了偏差。天顶方向上的延迟可达 2.3 m, 天顶距离 $z=80^\circ$ 时对流层延迟将增加至约 13 m^[2]。有关对流层延迟的改正方法, 国内外的学者作了大量的研究, 并提出了很多方法, 如模型改正法、差分法、参数估计法等。在 GPS 的各种定位中应用比较广泛的对流层改正模型有 Hopfield 模型、Saastamoinen 模型、Black 模型等。而投影函数有 Marini (1972), Chao (1974), Davis (1985) 及 Niell (1996) 等模型, 其中 Niell 模型是目前高精度 GPS 定位中经常采用的一种投影函数^[2]。在 GPS 数据处理中, 对流层改正量总是与其他改正参数一起平差求得。实际证明, 利用模型改正实测到的对流层天顶延迟信息精密、可靠, 精度可达 1-2 cm^[5]。本文详细介绍了 EGNOS 对流层延迟改正模型, 并与其他几种常用模型进行分析比较。

1 EGNOS 天顶延迟改正模型及映射函数^{[3-5] [15]}

EGNOS 模型是欧盟的 EGNOS (the European Geostationary Navigation Overlay System) 所采用的对流层天顶延迟改正模型。EGNOS 模型最大的好处就是计算天顶延迟时不需要实测的气象数据。该模型是基于接收机高度和 5 个气象参数 (气压、温度、水蒸气、温度下降率、水蒸气温度下降率)。这些参数利用多年的季节和时间数据的平均值, 这些数值还与接收机所处的经纬度和时间有关系。

EGNOS 模型也是分为干延迟和湿延迟两部分, 任意方向上的对流层延迟可以用下式表示^[6-7]:

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$$d_{trop} = d_{dry} \cdot m_{dry} + d_{wet} \cdot m_{wet} \quad (1)$$

式中, d_{trop} 为对流层总的延迟量; d_{dry} 为对流层天顶方向的干延迟; d_{wet} 为对流层天顶方向的湿延迟; m_{dry} 为对流层干延迟的映射函数; m_{wet} 为对流层湿延迟的映射函数。

EGNOS 模型的数学模型如下:

由平均海平面的天顶延迟计算接收机处的天顶延迟:

$$\begin{cases} d_{dry} = z_{dry} \left(1 - \frac{\beta H}{T}\right)^{\frac{g}{R_d \beta}} \\ d_{wet} = z_{wet} \left(1 - \frac{\beta H}{T}\right)^{\frac{(\lambda+1)T}{R_v \beta}} \end{cases} \quad (2)$$

式中, $g=9.80665\text{m/s}^2$; H 是对海平面接收机高度 (m); T 是对海平面的温度值 (K); β 是温度下降率 (K/m); $R_d=287.054\text{J}/(\text{kg}\cdot\text{K})$; λ 水蒸气湿度下降率; Z_{dry} 是对海平面的“干”空气的延迟; Z_{wet} 是对海平面的“湿”空气的延迟。

$$Z_{dry} = \frac{10^{-6} k_1 R_d P}{g_m} \quad (3)$$

式中, $k_1=77.604\text{K}/\text{mbar}$; P 海平面气压 (mbar); $g_m=9.784\text{m/s}^2$ 。

$$Z_{wet} = \frac{10^{-6} k_2 R_d}{g_m (\lambda + 1) - \beta R_d} \times \frac{e}{T} \quad (4)$$

式中, $k_2=382000\text{K}^2/\text{mbar}$; e 是水蒸气气压 (mbar)。

平均海平面的气象参数 P 、 T 、 e 、 β 、 λ 的计算公式如下:

$$\xi(\phi, D) = \xi_0(\phi) - \Delta\xi(\phi) \times \cos\left(\frac{2\Pi(D - D_{min})}{365.25}\right) \quad (5)$$

其中, $\xi(\phi, D)$ 为 5 个气象参数, 它仅与接收机的纬度 ϕ 和观测的日期 D (年积日) 有关; $\xi_0(\phi)$ 为个气象参数的年平均值; $\xi(\phi)$ 为个气象参数的季节变化

值； D_{\min} 为个气象参数的年变化的最小指的日期（北半球 $D_{\min}=28$ ，南半球 $D_{\min}=211$ ）。

$\xi_0(\varphi)$ 和 $\xi(\varphi)$ 可由在纬度范围 $(\varphi+\varphi, \varphi-\varphi)$ 内的全球（或某区域）平均海平面的各气象参数拟合求得。表 1、表 2 分别列出了不同纬度圈 5 个气象参数的年平均值和季节变化值。

表 1 EGNOS 模型中的 5 个气象参数的年平均值

Latitude/°	P/mbar	T ₀ /K	E ₀	β_0	λ_0
15	1 013.25	299.65	26.31	6.30e-3	2.77
30	1 017.25	294.15	21.79	6.05e-3	3.15
45	1 015.75	283.15	11.68	5.58e-3	2.57
60	1 011.75	272.15	6.78	5.39e-3	1.81
75	1 013.00	263.65	4.11	4.53e-3	1.55

表 2 EGNOS 模型中的 5 个气象参数的季节变化值

Latitude/°	P/mbar	T ₀ /K	E ₀	β_0	λ_0
15	0.00	0.00	0.00	0.00e-3	0.00
30	-3.75	7.00	8.85	0.25e-3	0.33
45	-2.25	11.00	7.24	0.32e-3	0.46
60	-1.75	15.00	5.36	0.81e-3	0.74
75	-0.50	14.50	3.39	0.62e-3	0.30

其映射函数可以用下式表示：

$$MF(E) = \frac{1.001}{\sqrt{0.002001 + \sin^2(e)}} \quad (6)$$

如果高度角低于 5° 时，这个映射函数就不再适用了^[4]。

2 常用的几种对流层延迟模型及映射函数

霍普菲尔德（Hopfield）模型^{[6] [9-11]}

$$d_{trop} = \frac{155.2 \cdot 10^{-7} \frac{P_s}{T_s} * (h_d - h_s)}{\sin(E^2 + 6.25)^{\frac{1}{2}}} + \frac{155.2 \cdot 10^{-7} * 4810 * \frac{e_s}{T_s} (h_w - h_s)}{\sin(E^2 + 2.25)^{\frac{1}{2}}} \quad (7)$$

式中， $h_d = 40 136 + 148.72(T_s - 273.16)$ ； $h_w = 11 000$ 。

萨斯塔莫宁（Saastamoinen）模型^{[6] [9-11]}

该模型的天顶方向的干湿延迟为：

$$\begin{cases} \Delta z, d = \frac{0.002277 P_s}{f(B, H)} \\ \Delta z, w = \frac{e_s}{f(B, H)} \left(\frac{0.2789}{T_s} + 0.05 \right) \end{cases} \quad (8)$$

式中， $f(B, H) = 1 - 0.002 66 \cos 2B - 0.000 28H$ ；B 测站纬度和测站 H (km) 高程。

公式 (7) (8) 中的可用下式计算^[12]：

$$e_s = RH * \exp(-37.246 5 + 0.213 166 * T_s - 0.000 256 908 T_s^2)$$

Niell 映射函数模型^{[1] [13]}

Niell 干延迟映射函数模型为：

$$m_{hyd} = \frac{1 + \frac{a_{hyd}}{b_{hyd}}}{1 + \frac{c_{hyd}}{1 + \frac{a_{hyd}}{b_{hyd}}}} + \frac{\sin(E) + \frac{a_{hyd}}{\sin(E) + \frac{b_{hyd}}{1 + \frac{c_{hyd}}{1 + \frac{a_{hyd}}{b_{hyd}}}}}}{\sin(E) + \frac{b_{hyd}}{1 + \frac{c_{hyd}}{1 + \frac{a_{hyd}}{b_{hyd}}}}}} \left(\frac{1}{\sin(E)} - \frac{1 + \frac{a_{hgt}}{b_{hgt}}}{1 + \frac{c_{hgt}}{1 + \frac{a_{hgt}}{b_{hgt}}}} \right) \cdot \frac{H}{1000} \quad (9)$$

式中，E 为卫星高度角；H 为测站高程 (m)； $a_{hgt}=2.53 \cdot 10^{-5}$ ， $b_{hgt}=5.49 \cdot 10^{-3}$ ， $c_{hgt}=1.14 \cdot 10^{-3}$ ；测站处的 3 个干延迟映射系数 a_{hyd} ， b_{hyd} ， c_{hyd} 可采用下式内插得到^[13]。

$$\begin{cases} \xi(\phi, t) = \xi_{avg}(\phi_i) + [\xi_{avg}(\phi_{i+1}) - \xi_{avg}(\phi_i)] \cdot \frac{\phi - \phi_i}{\phi_{i+1} - \phi_i} - \left\{ \xi_{amp}(\phi_i) + [\xi_{amp}(\phi_{i+1}) - \xi_{amp}(\phi_i)] \cdot \frac{\phi - \phi_i}{\phi_{i+1} - \phi_i} \right\} \cdot \cos\left(\frac{2\pi(t-28)}{365.25}\right), 15^\circ < |\phi| < 75^\circ \\ \xi(\phi, t) = \xi_{avg}(\phi_i) - \xi_{amp}(\phi_i) \cdot \cos\left(\frac{2\pi(t-28)}{365.25}\right), |\phi| \leq 15^\circ \text{ 和 } |\phi| \geq 75^\circ \end{cases} \quad (10)$$

式中， φ 为用户测站的大地纬度，t 为年积日， ξ 代表各参数的内插值。

Niell 湿延迟映射函数模型为：

$$m_{wet} = \frac{1 + \frac{a_{wet}}{b_{wet}}}{1 + \frac{c_{wet}}{1 + \frac{a_{wet}}{b_{wet}}}} \frac{\sin(E) + \frac{a_{wet}}{\sin(E) + \frac{b_{wet}}{1 + \frac{c_{wet}}{1 + \frac{a_{wet}}{b_{wet}}}}}}{\sin(E) + \frac{b_{wet}}{1 + \frac{c_{wet}}{1 + \frac{a_{wet}}{b_{wet}}}}} \quad (11)$$

式中，E 为卫星高度角； a_{wet} ， b_{wet} ， c_{wet} 根据 Niell 湿延迟映射模型系数格网值内插得到。湿延迟模型不考虑时间因素，所以内插公式只与纬度相关，与年积日无关，得到内插公式为：

$$\begin{cases} \xi(\phi, t) = \xi_{avg}(\phi_i) + [\xi_{avg}(\phi_{i+1}) - \xi_{avg}(\phi_i)] \cdot \frac{\phi - \phi_i}{\phi_{i+1} - \phi_i}, 15^\circ < |\phi| < 75^\circ \\ \xi(\phi, t) = \xi_{avg}(\phi_i), |\phi| \leq 15^\circ \text{ 和 } |\phi| \geq 75^\circ \end{cases} \quad (12)$$

3 计算及结果分析

为了分析 EGNOS 模型在 GPS 定位中的精度，本文将 EGNOS 模型与目前精度比较高并广泛采用的 Hopfield 模型、Saas_Niell 模型（Saastamoinen 天顶延迟模型和 Niell 映射函数的组合）在 GPS 普通单点定位中进行精度的分析比较。

为了实现各个模型的精度分析比较，本文采用了在 MATLAB 7.1 里面编写程序，实现了普通单点定位的模块；Hopfield 模型、Saas_Niell 模型、EGNOS 模型等 3 个对流层模块。在普通单点定位的模块中采取 C/A 码伪距、广播星历的 Klobuchar 模型进行电离层延迟改正，用多项式拟合卫星钟差。试验选取 BJFS（北京房山）和 WUHN（武汉）两个 IGS 跟踪站的 2009 年第

90 天和第 155 天的观测数据，并用拉格朗日插值法求出相应的卫星坐标，用于单点定位的计算。各个模型间的 3 个方向的偏差如表 3、表 4 所示，表中 Saas-Hop 表示 Saas_Niell 模型与 Hopfield 模型之差；Eg-Hop 表示 EGNOS 模型与 Hopfield 模型之差；Eg-Saas 表示 EGNOS 模型与 Saas_Niell 模型之差。

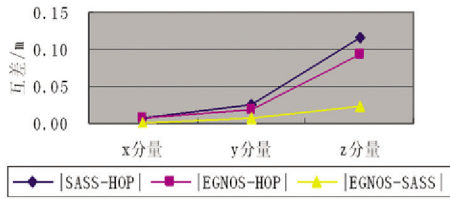


图 1 各个模型在 BJFS 站 155 d 平面坐标互差图

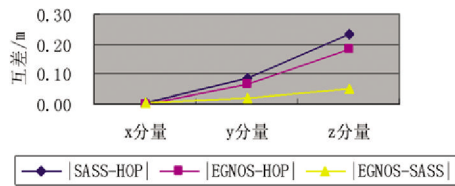


图 2 各个模型在 BJFS 站 90 d 平面坐标互差图

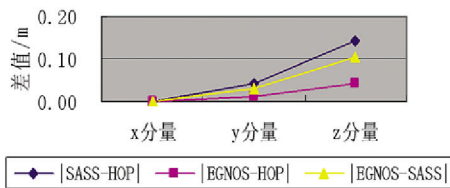


图 3 各个模型在 WUHN 站 155 d 平面坐标互差图

由图 1-图 3 分析数据可看出各对流层改正模型在平面 x 方向的偏差约为 1 cm，在平面 y 方向约为 3 cm，在高程 H 方面偏差约为 20 cm。还可以反映出 EGNOS 对流层延迟改正模型与 Saas_Niell 模型和 EGNOS 模型相比在 x，y 方向上的修正相当，在高程上介于 Saastamoinen 模型和 Hopfield 模型之间。分析影响各个模型精度的因素，都与气象参数密切相关；当测站处的气象参数未知时，都是用标准气象元素计算测站的气象元素。不同的算法直接影响到测站气象元素的精度，EGNOS 模型则是利用全球（或某区域）平均海平面的各气象参数拟合求得，图 1-图 3 的结果也说明 EGNOS 模型比 Saastamoinen 模型和 Hopfield 模型更能实际反映出测站气象元素。

4 结 语

EGNOS 模型是欧盟的 EGNOS 所采用的对流层天顶延迟改正模型。本文是在某一的气象条件下分析 EGNOS 模型、Saastamoinen 模型和 Hopfield 模型对 GPS 定位精度的影响。利用 IGS 跟踪站数据多次计算分析得到，EGNOS 对流层延迟改正模型与 Saas_Niell 模型和 EGNOS 模型相比在 x，y 方向上的修正相当，在高程上介于 Saastamoinen 模型和 Hopfield 模型之间。EGNOS 模型采用全球（或某区域）平均海平面的各气象参数拟合测站实际的气象元素更于实际符合。

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第一作者简介：刘靖晔，硕士，主要从事 GPS 技术与应用方面的研究。

NETRS receiver, multipath and noise levels of L2C code was significantly higher than C/A code, contrary to expectations.

Key words GPS modernization ,L2C code ,SNR ,multipath effect (Page:75)

Landscape Pattern Analysis Based on High-resolution Remote Sensing Image by CHEN Zhiyun

Abstract On the basis of landscape ecology theory, using high resolution remote sensing data as sources, using RS and GIS techniques, the planning area of Meizhou City was divided into 9 land use types, including cultivated land, forest, grassland, urban land and highway land, lake, river, bare land and beaches. The basic structure of the landscape, the fragmentation and diversity of landscape-level and the spatial pattern characteristics of different landscape patches were studied and analyzed. At last, some recommendations were proposed to rational planning land development and utilization of the study area.

Key words high-resolution remote sensing image ,landscape pattern ,landscape indexes ,planning area of Meizhou City (Page:78)

Application of GPS Close-range Photogrammetry Crossing Location Technique in Surveying and Mapping on Island and Reef by LUO Liang

Abstract Surveying and mapping engineering on island and reef is one of five important items during 11th five-year planning in State Bureau of Surveying and Mapping. GPS close-range photogrammetry crossing location module is part of the quickly positioning information collection system. This technology can be completed on island and reef of the special terrain mapping mission. Particularly it can provide a new method to map difficulties coastline.

Key words island and reef, close-range photogrammetry crossing location, resection, forward intersection (Page:81)

Design and Realization of Query System of Geographic Information Based on ArcIMS by YANG Guofei

Abstract WebGIS, based on the Internet and the Web, is the main trend of the development of GIS currently. And one of the most popular platform for realizing it is ArcIMS. We summarized the characteristics and the system structure of the ArcIMS, then described the idea of designing and developing the query system of geographic information by using ArcIMS. At last we made geographic information released online and queried in multiple forms, managed and shared in network by users.

Key words Query of geographic information, ArcIMS, WebGIS (Page:84)

Design and Implementation of Campus Information Service Platform Based on Object by MAO Yanqing

Abstract Open and flexible campus services platform is the key to promoting campus information technology, the difficulty is the describing ,organizing and sharing of information and data. This article investigated the object-oriented spatial data model on the basis of proposing object-oriented method and process of information organization on campus , as well as the ways of designing the services platform. Focus on object-based information organization on campus and campus information management platform framework. To achieve a set of "people", "capital equipment", "geospatial information" resource management platform for the integration of campus information services, information service system for the construction of the campus and campus information sharing to provide new methods and ideas.

Key words GIS, object-oriented, campus information, service platform (Page:87)

Design of Provincial Land Resource Electronic Government Information System Based on ArcGIS by PENG Jianbin

Abstract This article researched on the design of the provincial land resource E-Government system, proposed the overall goals and framework of the system, particularly described the function modules of the system based on the soft platform of ArcGIS, finally discussed the key techniques and system features related with the system, formed a unified technical framework, operating environment and normative standards, achieved the integration management of land resource information.

Key Words land and resource ,E-government ,ArcGIS (Page:90)

Study of Land Quality Assessment Based on GIS by ZHOU Dan

Abstract The authors established the system of land quality assessment and evaluated the land quality of Shuangqiao in Dongxing district of Neijiang city based on the Analytical Hierarchy Process and graphic overlay methods, made the evaluation results map of the region, the region was divided into five types, the excellent or better quality land area was 699.45 km², in possession of 72.87% of the whole region; the moderate quality land area was 184.43km², which was in possession of 19.2% ; the land of lower or poor quality area was 76.4km², in possession of 7.96%,according to the location and the modes of fanning of the region , the whole land quality of Shuangqiao in Dongxing district of Neijiang city was in good condition.

Key words GIS ,land quality assessment ,Neijiang (Page:93)

Delay Model and Accuracy Analysis of EGNOS Tropospheric

by LIU Jingye

Abstract Tropospheric delay in GPS positioning is a major source of error in the handling of the main methods of tropospheric delay correction through model difference method, etc, weakening or elimination of tropospheric delay error. When the distance is short baseline, baseline ends meteorological conditions are basically the same ,difference method can be very good correction troposphere delay error, when the baseline, due to the long distance between the meteorological data at baseline large , difference method can't eliminate the troposphere error well, but model can be a very good method to eliminate the troposphere error. In this paper, EGNOS model was introduced in detail, and through MATLAB programming. IGS tracking station data used to calculate statistical analysis, results showed that the EGNOS tropospheric correction model in elevation on the Saastamoinen model and the Hopfield model range, between the x, y direction precision.

Key words GPS , tropospheric model ,EGNOS , accuracy analysis (Page:96)

Measuring Method of Unified Annual Output Value Standard of Land Expropriation Based on GIS Technology by FU Weijia

Abstract Reasonable measuring method of unified annual output value standard of land expropriation is the basis and guarantee to improve the land expropriation compensation mechanism and protect farmers' rights of land. In this paper, revision and related measurements had been optimized with selecting the representative revision factors and building GIS spatial clustering model. At the same time, it used data organization method which integrated maps, data and database based on GIS. Finally, it achieved the measuring method of unified annual output value standard of land expropriation. Measuring results not only to present the spatial distribution of land expropriation compensation and the difference rule, but also to provide a new way to measure.

Key words Unified Annual Output Value Standard of Land Expropriation , GIS , Gongcheng County ,revision ,spatial clustering ,compensation standard (Page:99)

Building and Application of Remote Sensing Image Interpretation Signs of Eco-environmental in Four Rivers Valley of Tibet by GUAN Lei

Abstract In fully grasp the characters of natural geography and with the region of the TM images and related data contrast, we builded remote sensing image interpretation signs of Eco-environmental by using the classification system in Four Rivers Valley of Tibet. This work provided basis for Eco-environment or land resource remote sensing survey in south-east Tibet.

Key words remote sensing, interpretation signs , Four Rivers Valley , Tibet (Page:103)

Rendering Method Over 3D Vector Data in EV-Globe

by WANG Haitao

Abstract The paper, which based on the 3D plat roof of EV-Globe, analysed advantages and disadvantages of 3D vector-data, raster-data and mixed modals, realized symbolization and LOD display of vector data in 3D GIS. The method satisfied the rendering request of vector data in 3D GIS.

Key words 3D vector data modal, 3D vector data modal, modal based on feature, symbolization, LOD (Page:106)

Gray Model and Intelligent Algorithm Combined Model in Deformation Prediction by ZHANG Yutang

Abstract Because of various parameters have great uncertainty, deformation monitor project is a complicated integrated system . At present deformation prediction and analysis using a single forecasting methods ,but each method has their own application scope. Sometimes a single forecasting method made it difficult to determine the nature of projects .This paper introduced the idea of combination forecasting based on the gray GM (1,1) model ,Construction of the gray + GA + BP neural networks combination models ,explored the time series of data processing and prediction problems. Calculation and analysis by example proved that the combined model met the engineering needs and had a certain value .

Key words deformation monitor, combination model, gray prediction model, genetic algorithm , BP network (Page:109)

Control Surveying of the Combined Highway and Railway Yangtze Bridge of Tongling by ZHOU Ruixiang

Abstract This article brought forward and expatiated a method using GPS, electronic level and techniques of river-crossing leveling to fulfill the precision measurement task. The results not only verified the accuracy of this method, as well as provided references for other similar projects.

Key words bridge engineering ,construction control network ,GPS ,river-crossing leveling (Page:112)