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METHODOLOGICAL STEPS OF GNSS METEOROLOGY

This paper highlights the gradual steps of GNSS meteorology realization. The structure of GNSS meteorology is represented in the introduction in general. The main feature of it is that the neutral atmosphere delays the passage of GNSS signal, causing the error in the measured distance is called tropospheric delay. If in geodesy a lot of efforts have been put to reduce this error to a desired level, then for meteorology this error was used as an important source of information about the state of moisture accumulation in atmosphere and its dynamics in space and time. The next sections describe the basic equation of code pseudo-distance with the transition to the value of tropospheric delay. Then using a mapping function the transition from GPS tropospheric delay to its zenith value is shown. As well as there are given the calculation formulas of zenith tropospheric delay both by integration of vertical profiles of basic meteorological parameters and using the surface atmospheric pressure only. Further a transition from GPS tropospheric delay to its zenith value with use a mapping function is shown. A procedure for obtaining of the wet component of zenith tropospheric delay from GPS observations and formulas for the determining of average temperature of weighted water vapor and integrated as well as precipitable water vapor are described.

Key words: GNSS meteorology, zenith tropospheric delay, hydrostatic and wet components, mean temperature, water vapor.

1. Introduction

Twenty years ago, the fundamental work [*Bevis et al.*, 1992] gave the beginning of a new scientific direction "GPS meteorology" (today it is called "GNSS meteorology"), where was shown how using the data of GNSS observations can determine the content of water vapor in the troposphere. This is possible on condition if a value of tropospheric delay is being determined from the results of GNSS observations.

This delay in surveying (in achieving of an accurate measurement result) is a noise component, that is an impediment, and it should be eliminated or corrected. Hence the first approach, as in ionospheric delay is impossible, the second one remains i.e. to correct the tropospheric delay, that is to reduce it to the minimum that will satisfy the required accuracy. In this regard, a number of analytical models designed to solve this problem have been developed.

However, as is known, the desired result was not achieved due to the significant spatial and temporal variability of contents and distribution of water vapor in the atmosphere, and accordingly of wet component of tropospheric delay.

For meteorology, in contrast to surveying, the delay contains important information about the total mass of water vapor along the signal path. The delay caused by the neutral atmosphere, is estimated by the processing of GNSS data, inserting the GNSS observation data to a model that includes the tropospheric delay with other delays (errors) to be evaluated simultaneously [*Seeber*, 2003].

As a result, GNSS observation data is a valuable source of information about the number of the precipitable water vapor for weather forecasting. However problematic issue arises in this case: GNSS meteorology evaluates the content of water vapor in the atmosphere, and hence of precipitable water content, but do not provide an information about this whether the content of water is released in the form of rain reaching the earth's surface.

It should be noted that this problem is solved in part using the method radio occultation (GNSS-RO, Global Navigation Satellite System-Radio Occultation) in the transmission of GPS signals to the low Earth orbiter satellite system "FORMOSAT-3" (COSMIC). Today it is successfully realized via the CICERO project [*McCornic et al.*, 2007]. The similar "RADIOMET-SMKA" system which registers the signals both from the GPS satellites and the GLONASS ones was developed in Russia [*Vishnyakov et al.,* 2010].

2. The basic equation of GNSS observations

The basic equation for code pseudoranges from GNSS observations has the form [*Seeber,* 2003]:

$$P_r^s = \rho_r^s + c\cdot\delta t_r + c\cdot dt_{r,syst} - c\cdot\delta t^s - \\ - c\cdot dt^s_{syst} + d_{trop} + d_{ion} + \delta\rho_{rel} + \delta\rho_{mul} + \ldots + \Delta, \tag{1}$$

where P_r^s is code pseudorange between satellite and receiver;

ρ_r^s is geometric distance between satellite and receiver;
c is speed of light in vacuum;
δt_r is clock correction of station;
$dt_{r,syst}$ are delays in receiver and its antenna;
δt^s is clock correction of satellite;
dt^s_{syst} are delays in satellite and its antenna;
d_{trop} is total tropospheric delay;
d_{ion} is ionospheric delay;
$\delta\rho_{rel}$ is correction for relativistic effects;
$\delta\rho_{mul}$ is correction for multipath effect;
Δ is measurement error.

The geometrical distance between satellite and receiver is given by formula:

$$\rho_r^s = \sqrt{(X^s - X_r)^2 + (Y^s - Y_r)^2 + (Z^s - Z_r)^2}\ , \quad (2),$$

where X^s, Y^s, Z^s are triaxial rectangular coordinates of a satellite, X_r, Y_r, Z_r are triaxial rectangular coordinates of a receiver (station).

3. Tropospheric delay from GNSS observations

The tropospheric delay, according to equation (1), is defined as follows. First of all, the terms of the right-hand side are stipulated by one or another factor that expresses a correction, delay or error namely:

– the correction $c\cdot(\delta t_r - \delta t^s)$ together with the delay $c\cdot(dt_{r,syst} - dt^s_{syst})$, caused by non synchronous of the satellite and receiver clocks, is determined from the solution of combinations of single and double differences;

– ionospheric delay d_{ion} is eliminated using the dual-frequency GNSS receivers;

– correction of relativistic effects $\delta\rho_{rel}$ is determined from modeling;

– eliminating of effects caused by signal multipath $\delta\rho_{mul}$ is made by the application of an special technology at a station;

– measurement error, Δ, in the averaged results is small relatively and is usually neglected.

The $P_r'^s$ pseudorange, corrected in this way, has the form:

$$P_r'^s = \rho_r^s + d_{trop}, \tag{3}$$

hence a tropospheric delay will be:

$$d_{trop} = P_r'^s - \rho_r^s. \tag{4}$$

It should be noted that the geometric distance can be determined accurately if satellite coordinates and GNSS station position are known very precisely.

3.1. Hydrostatic and wet components of zenith tropospheric delay of GNSS observations

The total tropospheric delay, obtained from the formula (4), refers usually to non-zenith directions ($z \neq 0^\circ$) or to the directions of elevation angles $90^\circ \succ \varepsilon \succ 0^\circ$. The value d_{trop} is reduced to the zenith direction by using the dependence:

$$d^z_{trop} = \frac{d_{trop}}{m(\varepsilon)}. \tag{5}$$

It is known that the value includes zenith hydrostatic component and zenith wet one:

$$d^Z_{trop} = d^Z_h + d^Z_w. \tag{6}$$

Zenith hydrostatic and wet components had been proposed to determine by equation [*Davis et al.,*1985]:

$$d^Z_{trop} = d^Z_h + d^Z_w = 10^{-6} K_1\cdot R_d \int_{H_s}^{H_a} \rho\cdot dH + \\ + 10^{-6}\int_{H_s}^{H_a}\left(K_2'\frac{e}{T} + K_3\frac{e}{T^2}\right) Z_w^{-1}\cdot dH, \tag{7}$$

where K_1, K_2 and K_3 are empirical coefficients of a refractivity; R_d = 287,06 *J/(kg·K)* is specific gas constant for dry air; H_s is height of station (level of receiver antenna); H_a is top boundary of atmosphere; ρ is density of moist air; e is partial pressure of water vapor; T is the Kelvin air temperature; Z_w^{-1} is the compressibility factor for water vapor. Coefficient K_2' is determined from the relation:

$$K_2' = K_2 - K_1 \frac{R_d}{R_w} = \\ = K_2 - K_1 \frac{M_w}{M_d} = K_2 - K_1 \cdot 0.622, \qquad (8)$$

here R_w=461,525 *J*/(*kg*·*K*) is specific gas constant of water vapor; M_w, M_d is molecular weights of water vapor and dry air.

So the first term in equation (7) is called zenith hydrostatic component of tropospheric delay, and the second one is zenith wet component. It should be noted that this formula is widely used recently.

We notice, the expression (7) requires of the integration in height of the main meteorological parameters along the whole neutral atmosphere for any point (station) and at any time that is impossible practically. Because, taking into account the main equation of atmosphere statics [*Matveev,* 1984], the integral expression of the first term of the equation (7) obtains the next form:

$$\int_{H_s}^{H_a} \rho \cdot dH = \int_{H_s}^{H_a} \frac{dP}{g} dH = \frac{P_s}{g_m}, \qquad (9)$$

where P_s is surface pressure of moist air (on the level of receiver antenna); g_m is acceleration due to gravity at the center of mass of the vertical column of air.

The g_m value is calculated by equation:

$$g_m = 9.784(1 - 0.0026\cos 2\varphi - 28 \cdot 10^{-6} H_s), \quad (10)$$

where φ is latitude of a station.

So zenith hydrostatic component of tropospheric delay will seem finally:

$$d_h^z = 10^{-6} K_1 R_d \frac{P_s}{g_m}. \qquad (11)$$

Thus, zenith hydrostatic component can be determined only by the surface atmospheric pressure measured at the antenna height of GNSS receiver, using the formula (11) or by formula [*Saastamoinen*, 1973]:

$$d_h^Z = \frac{0.002277 \cdot P_S}{(1 - 0.0026\cos 2\varphi - 28 \cdot 10^{-8} H_S)}, \qquad (12)$$

or by improved *Saastamoinen* formula [*Davis* et al., 1985]:

$$d_h^Z = \frac{0.0022768 \cdot P_S}{(1 - 0.0026\cos 2\varphi - 28 \cdot 10^{-8} H_S)}. \qquad (13)$$

Having the d_h^z value, zenith wet component of tropospheric delay is determined from the equation (6):

$$d_w^z = d_{trop}^z - d_h^z. \qquad (14)$$

If vertical profiles of the basic meteorological parameters are known for a given station at a given time (or an observation period) by the data, for example, of numerical weather prediction [*Vedel et al.,* 2010], or of the radio occultation method [*McCornic et al.,* 2007; *Vishnyakov et al.,* 2010], or from some other sources then you can calculate not only the zenith wet component but zenith hydrostatic one using the formula (7).

Since the hydrostatic component is calculated in this formula through the density of moist air, which is not measured directly, but is determined by the equation of state of gases, then we use a formula for the determining of zenith hydrostatic component, which expresses an air density due to pressure of moist air, temperature of air and partial pressure of water vapor, and has the form [*Zablotskyy,* 2000]:

$$d_h^z = 10^{-6} K_1 \int_{H_s}^{H_a} \frac{P}{T} \left(1 - 0.378 \frac{e}{P}\right) \cdot dH. \qquad (15)$$

4. Mean temperature and integrated precipitable water vapor

The mean temperature of the weighted water vapor of an atmosphere column is calculated as:

$$T_m = \frac{\int_{H_s}^{H_a} \frac{e}{T} Z_w^{-1} dH}{\int_{H_s}^{H_a} \frac{e}{T^2} Z_w^{-1} dH}. \qquad (16)$$

Taking into account the expression (16) the second term of the equation (7), the zenith wet component of tropospheric delay, can be written as follows:

$$d_w^Z = 10^{-6} \left[K_2' + \frac{K_3}{T_m} \right] \cdot \int_{H_s}^{H_a} \frac{e}{T} Z_w^{-1} dH. \qquad (17)$$

Using the state equation of water vapor, we obtain finally:

$$d_w^Z = 10^{-6} R_w \left[K_2' + \frac{K_3}{T_m} \right] \cdot \int_{H_s}^{H_a} \rho_w dH. \qquad (18)$$

The integral of equation (18) is the integrated water vapor (*IWV*), defined as the total mass of water vapor in a column of air with cross section of 1 m^2 extending from the surface to the top of the atmosphere, that is usually given in units of kg/m^2:

$$IWV = \int_{H_s}^{H_a} \rho_w dH . \qquad (19)$$

This quantity can be easily converted to length units by dividing on the density of liquid water ($\rho_{H_2O} = 10^3 kg/m^3$) and can be interpreted as the height of an equivalent column of liquid water on condition that the water vapor would condensed. In this case, it is the integrated precipitable water vapor (*IPWV*) or precipitable water (*PW*):

$$PW = \frac{1}{\rho_{H_2O}} \int_{H_s}^{H_a} \rho_w dH . \qquad (20)$$

Substituting the equation (19) into (18), we get:

$$d_w^Z = \xi \cdot IWV, \qquad (21)$$

where ξ is a constant of proportionality:

$$\xi = 10^{-6} R_w \left[K_2' + \frac{K_3}{T_m} \right]. \qquad (22)$$

The mean temperature T_m is the only unknown in formula (22) and its estimation plays an important role in the conversion from zenith wet delay to precipitable water vapor. Due to its dependence on the water vapor profile, the value T_m is variable in space and time.

The well-known model of mean temperature (*MB* model) based on the analysis of 9,000 radiosonde profiles approximately from sites in the United States in the range of latitudes from 27° N to 65° N and in the range of heights from 0 to 1.6 km for the period of 2 years [*Bevis et al.*, 1992]:

$$T_m = a + b \cdot T_S , \qquad (23)$$

where *a* and *b* are linear approximation coefficients which equal, respectively, 70.2 and 0.72.

At present, a number of such models have been developed for other regions of the Earth. In particular, the following coefficients were determined by the radiosounding data at the Uzhgorod station: *a* = -6.8; *b* = 1.04, and by the conformable data for Kyiv station were obtained: *a* = 55.5 and *b* = 0.78 [*Kablak*, 2011]. For the northwestern part of Russia (St. Petersburg) the following coefficients: *a* = 65.5 and *b* = 0.73 had been derived [*Chukin*, 2010]. According to the analysis performed by *Chukin*, the use of approximations gives the relative error of definition of integrated water vapor content not exceeding 1% and using *a* and *b* coefficients adapted to the region does not improve an accuracy significantly.

5. Conclusions and outlook

By the materials of this paper can be formulated as follows:

1. The main methodological steps of GNSS meteorology include

– obtaining of total tropospheric delay on basic of the main equation of code pseudo-distance;

– determination of hydrostatic and wet components of zenith troposphere delay from GNSS observations;

– definition of integrated precipitable water vapor from the wet component of zenith tropospheric delay.

2. In our opinion, it should be carefully evaluate the accuracy of zenith troposphere delay, which is defined by the formula (4), based on an analysis of residual errors of members of the right-hand side of equation (1).

REFERENCES

Zablotskyy F.D. *Do vyznachennja zenitnoji troposfernoji zatrymky v GPS vymirakh* [To the determination of zenith tropospheric delay in GPS measurements]. *Mizhvid. nauk.-tekhn. zb. "Geodesija, Kartografija i Aerofotoznimannyja".* [Interdepartmental scientific-technical collected articles "Geodesia, Kartografia i Aerofotoznimannya"]. Lviv, Publishing House of Lviv Polytechnic National University, 2000, issue 60, pp. 33-38.

Kablak N.I. *Dystancijne zonduvannja vodyanoji pary v atmosferi z dopomohjyu dystancijnykh suputnykovykh system* [Remote sounding of water vapor by means of remote satellite systems]. *Mizhwid. nauk.-tekhn. zb. "Geodesija, Kartografija i Aerofotoznimannja"* [Interdepartmental scientific-technical collected articles "Geodesia, Kartografia i Aerofotoznimannya"]. Lviv, Publishing House of Lviv Polytechnic National University, 2011, issue 75, pp. 31-35.

Vishnyakov V.M., Vinogradov A.A., Pavelev A.G., Yakovlev O.I., Matyugov S.S. *Kosmicheskaya sistema na osnove swerchmalych sputnikov «Радиомет-СМКА» dlya radiozatmennogo monitoringa atmosfery i ionosfery signalami GNSS GLONASS i GPS* [The space system on basis of the “RADIOMET-SMKA” very-small satellites for the radio occultation monitoring of atmosphere and ionosphere by the GLONASS and GPS signals]. 8^{th} *Wserossijskaya konferenciya “Sowremennye problemy distancionnogo zondirowaniya Zemli iz kosmosa”,* Moskow, IKI RAN, November, 15-19, 2010. - File acces mode: http://d33. infospace. ru/d33_conf/ 2010_conf_pdf/ atmos/vishniakov.pdf

Matveev L.T. *Kurs obschey meteorologii (Fizika atmosfery): uchebnik.* Leningrad: Gidrometeoizdat, 1984, 751 p.

Chukin V.V. *Monitoring soderzhaniya wlazhnosti w atmosphere pri pomoschi system GLONASS /GPS* [Monitoring of moisture content in the atmosphere by the GLONASS and GPS systems]. *Uchenye zapiski RGGMU*, Leningrad, 2010, no.12, pp. 51-60.

Bevis, M., S. Businger, T.A. Herring, C. Rocken, R.A. Anthes, and R.H. Ware (1992). GPS meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System/ Journal of Geophysical Research, Vol. 97, No. Dl4, pp.15,787-15,801.

Davis J.L., T.A. Herring, I.I. Shapiro, A.E.E. Rogers, and G. Elgered (1985). Geodesy by radio interferometry: Effects of atmospheric modeling errors on estimates of baseline length / Radio Science, Vol. 20, no. 6, pp. 1593-1607.

McCormick, C., C. Lenz, and D. Smith (2007). Community Initiative for Continuing Earth Radio Occultation CICERO. - File acces mode: http://digitalcommons. usu.edu/cgi/viewcontent.cgi? article=1437&context= smallsat&sei-redir=1&referer

Mendes,V.B. (1999). Modeling the neutral-atmosphere propagation delay in radiometric space techniques // Ph.D. dissertation, Department of Geodesy and Geomatics Engineering Technical Report no. 199, University of New Brunwick, Fredericton, New Brunswick, Canada, 353 pp.

Saastamoinen, J. (1973). Contributions to the theory of atmospheric refraction. In three parts. Bulletin Geodesique, No. 105, pp. 279-298; No. 106, pp. 383-397; No. 107, pp. 13-34.

Seeber, G. (2003). Satellite Geodesy//2^{nd} Edition.-Walter de Gruyter.-Berlin.-New York.-589 pp.

Vedel H., S. de Haan, and J. Jones. E-GVAP and the use of ground based GNSS data in meteorology. File acces mode: http://www.igs.org/event/newcastle 2010/ assets/pdf

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МЕТОДОЛОГІЧНІ ЕТАПИ ГНСС-МЕТЕОРОЛОГІЇ

Запропонована стаття висвітлює поступові кроки реалізації ГНСС-метеорології. У вступі змальовується сама структура ГНСС-метеорології, основна особливість якої полягає у тому, що нейтральна атмосфера затримує проходження ГНСС-радіохвилі, викликаючи похибку у виміряній відстані, що називається тропосферною затримкою. І якщо в геодезії прикладають масу зусиль, щоб звести цю похибку до бажаного мінімуму, то в метеорології цю похибку почали використовувати як важливе інформаційне джерело про стан атмосферного вологонасичення та його динаміку як у просторі, так і в часі. У подальших розділах висвітлюється основне рівняння кодової псевдовідстані з переходом до величини тропосферної затримки. Далі, використовуючи функцію відображення, показують перехід отриманої із GPS-спостережень тропосферної затримки до її зенітного значення. Також наводяться формули обчислення зенітної тропосферної затримки як інтегруванням вертикальних профілів основних метеорологічних параметрів, так і з використанням лише приземного атмосферного тиску. Описано процедуру отримання вологої складової зенітної тропосферної затримки із GPS-спостережень, а також формули визначення середньої температури завислої водяної пари та інтегрованої й осаджуваної водяної пари.

Ключові слова: метеорологія ГНСС, зеніт затримки в тропосфері, гідростатичні і вологі компоненти, середня температура, водяна пара.

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МЕТОДОЛОГИЧЕСКИЕ ЭТАПЫ ГНСС-МЕТЕОРОЛОГИИ

Предлагаемая статья освещает постепенные шаги реализации ГНСС-метеорологии. Во введении в общем описывается сама структура ГНСС-метеорологии, основная особенность которой состоит в том, что нейтральная атмосфера задерживает прохождение ГНСС-радиоволны, вызывая погрешность в измеренном расстоянии, что называется тропосферной задержкой. И если в геодезии прикладывают массу усилий, чтобы привести эту погрешность к желаемому минимуму, то в метеорологии её начали использовать как важный информационный источник о состоянии атмосферного влагонасыщения и его динамике как в пространстве, так и во времени. В дальнейших разделах освещается основное уравнение кодового псевдорасстояния с переходом к величине тропосферной задержки. Далее, используя функцию отображения, показывается переход от полученной из GPS-наблюдений тропосферной задержки к её зенитному значению. Также приводятся формулы вычисления зенитной тропосферной задержки как путем интегрирования вертикальных профилей основных метеорологических параметров, так и с использованием только приземного атмосферного давления. Описываются процедура получения влажной составляющей зенитной тропосферной задержки из GPS- наблюдений, а также формулы определения средней температуры взвешенного водяного пара, а также интегрованного и осаждаемого водяного пара.

Ключевые слова: метеорология ГНСС, зенит задержки в тропосфере, гидростатические и влажные компоненты, средняя температура, водяной пар.

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