How the Ionosphere Affects Positioning Solution Using Terrestrial and Satellite Navigation Systems?

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Abstract. The Earth's ionosphere, a dispersive medium, is an atmospheric layer that lies typically between 50 and 1,000 km of altitude. The physical parameters of ionosphere have a direct influence on propagation delay (Satellite Navigation Systems – SNS) and on a radio waves propagation (Terrestrial Radionavigation Systems – TRNS), that both cause significant user's position error and additionally in the case of TRNS the lack of the position sometimes. The most frequently used solutions to this problem, as the dual–frequency receivers which permit the calculation of ionosphere-free pseudorange, model of the ionosphere with eight coefficients transmitted in navigation message or differential mode with pseudorange corrections (SNS) and different corrections to the measurements as SWC and ASF in Loran C system (TRNS) are described in this paper. The detailed relations and equations concerning ionospheric delay are presented also.

Keywords: ionosphere, ionospheric refraction, ionospheric delays, ionospheric scintillations, satellite navigation systems.

1 Introduction

Telematics can be defined as any integrated use of telecommunications and informatics. Hence the application of telematics is with among other things any of the following:

- the technology of sending, receiving and storing information via telecommunication devices in conjunction with affecting control on remote objects.
- telematics includes but is not limited to satellite navigation systems (SNS) as GPS or GLONASS technology integrated with computers and mobile communications technology in automotive navigation system.

Telecommunication is the transmission of information over significant distances to communicate. Nowadays telecommunications include the use of the orbiting satellites. That's why telematics involves the impact of the ionosphere on the terrestrial and satellite signals propagation and the determination of the user's position.

J. Mikulski (Ed.): TST 2012, CCIS 329, pp. 249–257, 2012.

2 Ionosphere

The structure of the Earth's atmosphere can be described, for most practical purposes, as asset of concentric spherical shells with different physical and chemical properties. Various subdivisions are possible, but with respect to signal propagation a subdivision into ionosphere and troposphere is advisable. The ionosphere, is the region of Earth's atmosphere of ionised gases (free electrons and ions). The upper limit of the inospheric region is not clearly defined [1 - 5]. The ionisation is caused by the Sun's radiation, and the state of the ionosphere is determined primarily by the intensity of the solar activity [4]. The height of the lower and upper part of Earth's ionosphere can be different, e.g. 75 km and 500 km [6] or 70 km and 1000 km [1, 7], respectively.

Ionospheric region is divided into subregions, or layers (D, E, F1 and F2), according to the electron density. The heights of these layers and the electron density of ionized particles are not constant, both change with the time of the year, seasons, and time of day. Generally, the region between 250 and 400 kilometers above the Earth's surface, known as the F–region, contains the greatest concentration of free electrons. This region affects the satellite signals propagation considerably.

3 Effects of Ionosphere on Terrestrial Radionavigation Systems

The signals transmitted by the stations of terrestrial radionavigation systems (TRNS) can arrive at user's receiver as groundwave or skywave or both groundwave and skywave. It depends on the frequency carrier, radio range, daytime, propagation conditions etc. The user's position with the lowest error can be obtained if the signals arrive directly from all used stations as groundwave without any refraction. If at least from one station signals arrive as skywave it means that:

- in TRNS based on phase or difference phases measurements the user's position cannot be determined. That's why at nighttime both the range of the station and total coverage area of every chain of this system are less than during daytime considerably,
- in TRNS based on time or difference time measurements the user's position can be obtained only if the special corrections were used, e.g. SWC (Sky Wave Correction) in Loran C system. The station range on skywave is greater than on groundwave, e.g. in Loran C it is 2300 Nm or more and 1200 Nm respectively, but position's accuracy is in the first case less considerably.

As the refraction index of the ionosphere depends on the varying electron and ion concentrations, although distinct boundaries do not exist, reflection and refraction take place in a more or less layered medium. Thus signals at a low frequency are reflected at low altitudes, while high-frequency signals are only refracted, but they may develop an increased angle of incidence so that they are reflected at higher layer [8]. Frequencies below about 500 kHz (among them once Decca Navigator system and since 1977 Loran C system) are reflected in the D layer, 0.5 – 2 MHz in the E layer and 5 – 30 MHz in the F layer, whereas frequencies above 30 MHz are not reflected in the ionosphere.

4 Effects of Ionosphere on Satellite Navigation Systems

As Medium Earth Orbits (MEO) with height about 20000 km are used for constellations of navigation satellites such as GPS, GLONASS, Galileo, Compass, the signal transmitted from satellite passes through the ionosphere.

4.1 Ionospheric Refraction

As ionised gas is a dispersive medium for radio waves the ionosphere affects the propagation of satellite signals. The speed of these signals depends upon the number of free electrons in the path of a signal, defined as the TEC (Total Electron Content), i.e. the number of electrons in a tube of 1 m^2 cross section extending from the user's receiver to the satellite. TEC is measured in units of TEC Units – TECU, defined as 10^{16} electrons/m^2. As the path length through the ionosphere is shortest in the zenith direction, TEC in the vertical direction (TECV) is the lowest. TECV typically varies between 1 and 150 TECU [4] or between 1 and 1000 [1]. The state of the ionosphere is described by the electron density N_e with the unit [number of electrons/m^3] or [number of electrons/cm^3]. For a given place and time, vertical TEC can vary 20–25% from its monthly average [1].

The main contribution of the inospheric refraction corresponds to the first order ionospheric term, which is inversely proportional to the square of the frequency. That's why the refraction coefficient describing the propagation of phase n_p and coefficient of the group delay n_g can be expressed by the approximate relations [7]:

$$n_p = 1 - \frac{40.3N_e}{f^2} \qquad n_g = 1 + \frac{40.3N_e}{f^2} \tag{1}$$

If N_e is the number of electrons per cubic meter, numerator 40.3 N_e is expressed in Hz^2, f is frequency carrier. In ionosphere, a dispersive medium, the carrier and the modulation travel at different speeds, respectively with phase velocity v_p and group velocity v_g. These velocities can be defined as follows:

$$v_p = \frac{c}{1 - \frac{40.3N_e}{f^2}} \qquad v_g = \frac{c}{1 + \frac{40.3N_e}{f^2}} \tag{2}$$

where c is the speed of light in vacuum.

As a consequence of the different velocities, a phase advance and group delay occur. Therefore SNS carrier phases are advanced and ranging codes are delayed. That's why the measured carrier phase pseudoranges are too short and the measured code pseudoranges are too long compared to the geometric range between the satellite and user's receiver. The amount of the difference is the same in both cases.

The ionospheric group delay for different frequencies carrier and the number TEC if the satellite elevation angle is 90^{O} is presented in the table 1, for different angles and different heights of the ionosphere with maximal electron density if frequency carrier is equal 1.6 GHz and 1.2 GHz in the table 2. The difference Δ_{iono} between measured and geometric range called ionospheric refraction for a phase Δ_{ionop} and group delay Δ_{ionog} can be written as

$$\Delta_{ionop} = -\frac{40.3TEC}{\sqrt{1-\frac{R_z\cos(h_t)}{R_z+h_{j\max}}}}\cdot\frac{1}{f^2} \qquad \Delta_{ionog} = \frac{40.3TEC}{\sqrt{1-\frac{R_z\cos(h_t)}{R_z+h_{j\max}}}}\cdot\frac{1}{f^2} \tag{3}$$

where R_z is radius of the Earth, h_t satellite elevation, h_{jmax} the height of the ionosphere with maximal electron density.

Table 1. Ionospheric group delay [m] for different frequencies and TEC, elevation angle 90O

Frequency carrier	TEC [el/m^2] 10^{16}	10^{18}	$5 \cdot 10^{18}$	10^{19}
150 MHz	17.9	1 790	8 950	17 900
400 MHz	2.52	252	1 260	2 520
1.2 GHz	0.28	28	140	280
1.6 GHz	0.16	15.8	79	158
10 GHz	0.004	0.4	2	4

Table 2. Ionospheric group delay [m], for different satellite elevation ht, for different frequencies carrier L and different heights of the ionosphere with maximal electron density hmax, TEC = 1018

L [GHz]	h_{max} [km]	Satellite elevation h_t [^{O}] 0	5	10	15	20	25	30	45	60	75	90
1.6	250	81.0	77.3	68.8	59.3	50.9	44.0	38.6	27.8	21.9	18.2	15.8
	300	74.2	71.4	64.5	56.5	49.2	42.9	37.9	27.6	21.8	18.2	
	350	69.0	66.7	61.1	54.2	47.6	41.9	37.2	27.4	21.7	18.1	
	400	64.8	62.9	58.1	52.1	46.3	41.0	36.6	27.2	21.6	18.1	
1.2	250	144.0	137.4	122.3	105.4	90.5	78.2	68.6	49.4	38.9	32.4	28
	300	131.9	126.9	114.7	100.5	87.5	76.3	67.4	49.1	38.8	32.4	
	350	122.7	118.6	108.6	96.4	84.6	74.5	66.1	48.7	38.6	32.3	
	400	115.2	111.9	103.4	92.7	82.3	72.9	65.1	48.4	38.5	32.3	

4.2 Corrections of Ionospheric Delays

As at given moment the values of TEC and h_{jmax} are for almost all users, except for the scientific centres, known, but with too low accuracy or, in major cases, completely unknown, four different methods of the corrections of ionospheric delays were defined. These methods can be used in particular by the users determining own positions in real time.

The most frequently used solutions to this problem are: differential mode with pseudorange correction, satellite based augmentation system with geostationary satellites, the dual–frequency receivers which permit the calculation of ionosphere-free pseudorange, model of the ionosphere with eight coefficients transmitted in navigation message used in single-frequency receivers.

Differential Mode. The fundamental principle of differential mode of SNS is the comparison of the accurately measured position of a fixed point, referred to as the terrestrial reference station, with position obtained from a stand-alone SNS receiver (without any corrections) at that point. By comparison of measured and calculated results at this position, corrections, called Pseudo Range Corrections (PRC), are produce for distribution to all users within the coverage area. This technique can be used and works well only if an essential portion of the measurement errors is caused by factor outside the receiver which at the same time are correlated in the area. The four most important of these errors are the following:

- ionospherical delays of the signals,
- tropospheric time delays,
- ephemeris errors,
- satellite clock errors.

As the ionospheric group delay, the tropospheric delay and both last errors are always positive, PRC is always negative, and its value depends on satellite elevation and daytime among other things. For signal arriving at vertical incidence (90^O) PRC ranges from about 3 m at night to as much as 15 m during the day. At low satellite viewing angles (less than 10 degrees) PRC can range from 9 m at night up to 150 m during the day [7]. Actual values of PRC for all satellites used for the positioning are signalised by receiver.

The number of beacons (stations) transmitting DGPS corrections has been increased in 10 last years considerably. In 2002 there were in the world 162 stations with status operational, 62 with status on trial and 20 planned, in 2006 these numbers were 235, 57 and 11 respectively. At present (2012) 281 operational stations are localized in 37 countries, the greatest numbers of these stations are in USA (38), Japan (27), China (21) and India (19). In Poland there are two stations, Dziwnow and Rozewie. Since few years there are two operational stations, both in Ukraine (Yenikal'skiy Lt and Zmeiniy Lt), transmitting DGLONASS corrections (in RTCM protocol 6 message types, numbers 31–36) also. At present in Russia 4 DGPS/DGLONASS stations (1 Baltic Sea, 3 Black Sea) have the status on trial, next 12 (4 Arctic Coast, 8 Pacific Coast) are planned [9].

The user must be in coverage of least one reference station and must be equipped with DGPS receiver; the signals arrive from GPS satellites and from PRC station.

The Satellite Based Augmentation Systems (SBAS). The Satellite Based Augmentation Systems (SBAS) use a network of terrestrial monitoring stations to perform SNS ranging measurements. SBAS provides integrity data and correction parameters for the satellite orbits, the satellite clocks, and the ionosphere influence using geostationary satellites (GEO) as the communication path. SBAS message differentiates between 64 types, type 18 provides ionosphere grid point masks, type 26 the L1–only user with vertical ionospheric delay values over a grid of locations with predefined latitude and longitude values [7]. The words L1–only user mean that this ionospheric corrections only apply for single-frequency SNS receivers, at the time of this writing (2012), GPS receivers only.

The SBAS models the vertical delays of the ionosphere at the inospheric grid points (IGP), which commonly span a regular raster of 5^O x 5^O. The user's receiver estimates the ionospheric delays for every satellite in four step process.

Actually some SBAS are fully operational (WAAS within the United States and Canada, EGNOS within Europe, MSAS within Japan and Southeast Asia), some are under construction (GAGAN within India, SDCM within Russia).

The user must be in coverage of least one SBAS GEO satellite and must be equipped with GPS/SBAS receiver; the signal from GPS satellites and correction parameters from GEO satellite.

Single-Frequency Receiver Model of the Ionosphere. In most commercial SNS receivers only one frequency (L1 in the case GPS system) is available. That's why the pseurorange measurements on two frequencies cannot be made. Consequently, models of the ionosphere are employed to correct for the ionopsheric delay. One important example is the Klobuchar model, which assumes that the vertical ionospheric delay can be approximate by half a cosine function of the local time during daytime and by a constant level during nightime. In the case of GPS system the ionospheric data collected from subframe 4 of navigation message NAV can be used to reduce the ionospheric effect. In page 18 of this subframe there are eight ionospheric data: α_0 (69 – 76), α_1 (77 – 84), α_2 (91 – 98), α_3 (99 – 106), β_0 (107 – 114), β_1 (121 – 128), β_2 (129 – 136), β_3 (137 – 144). These eight coefficients are computed from a global, empirical model and updated every 10 days (every 5 days if the Sun is particularly active). In order to use this model the user's single-frequency receiver has to compute the obliqueness of the signal from the satellite, i.e. the position where the signal path intersects the average ionosphere altitude. This altitude has been set to 350 km. In addition, the receiver has to compute his own geomagnetic latitude (as the ionosphere is a function of the geomagnetic latitude). Using this model one can reduce the user root mean square (rms) position error caused by ionosphere effect at least by 50% percent [7, 10] or 55 – 60% [8].

Dual-Frequency Receiver. The difference between the refraction index (i.e. the phase velocity) in a vacuum and in the ionosphere is consequently inversely proportional to the square of the frequency. That's why the satellites of all SNS transmit the signals on at least two frequencies, which makes it possible to determine the constant of proportionality and, consequently, remove the influence of the ionosphere to a large extent. Differencing pseudorange measurements ρ_1 and ρ_2 made on f_1 and f_2 frequencies, respectively, enables the estimation of both the N_1 and N_2 delays, respectively, neglecting multipath and receiver noise errors. Delay N_1 becomes

$$N_1 = (\rho_2 - \rho_1) \cdot \frac{f_2^2}{f_1^2 - f_2^2} \tag{3}$$

therefore the estimate of ionosphere-free pseudorange measurement at f_1 ρ_{1F} can be presented as

$$\rho_{1F} = \frac{f_1^2}{f_1^2 - f_2^2} \cdot \rho_1 - \frac{f_2^2}{f_1^2 - f_2^2} \cdot \rho_2 = a \cdot \rho_1 - b \cdot \rho_2 \tag{4}$$

where a and b are coefficients which depend on carrier frequencies f_1 and f_2 only. The values of these coefficients for all possible combinations of two frequencies of GPS and Galileo systems are presented in the table 3.

Table 3. Dual frequency measurements, estimation of ionosphere-free pseudorange measurements, coefficient values for GPS system and Galileo system

System	Frequency carrier [MHz]		Coefficient	
	f_1	f_2	a	b
GPS, Galileo	1 575.42	1 176.45	2.261	1.261
GPS	1 575.42	1 227.60	2.546	1.546
	1 227.60	1 176.45	12.26	11.26
Galileo	1 575.42	1 278.75	2.931	1.931
	1 575.42	1 207.14	2.422	1.422
	1 278.75	1 207.14	9.186	8.186
	1 278.75	1 176.45	6.527	5.527
	1 207.14	1 176.45	19.920	18.920

The ionospheric group delay is in direct proportion to TEC along the propagation path of a satellite signal and in inverse proportion to frequency carrier. That's why the stand-alone SNS receiver one frequency uses always the highest frequency of given SNS, e.g. 1575.42 MHz in the case of GPS system and Galileo system.

Ionospheric Scintillations. At times, the mentioned above F–region of the ionosphere, becomes disturbed, and small-scale irregularities develop. When sufficiently intense, these irregularities scatter radio waves and generate rapid fluctuations, called scintillations, in the amplitude and phase of radio signals. Scintillation activity varies with operating frequency, geographic location, latitude in particular, local time, season, magnetic activity, and 11–year solar cycle. Scintillation may accompany ionospheric behaviour that causes changes in the measured range between the user's receiver and the satellite. Its activity is most severe and frequent in around the equatorial regions, particularly in the hours just after sunset. In high latitude regions, scintillation is frequent but less severe in magnitude than that of the low latitude. In the mid-latitude regions (Europe) scintillation is rarely experienced [7, 11].

5 Conclusion

- the increasing use of satellite navigation systems for precise position measurements has provoked an increased interest in ionosphere behaviour, particularly propagation properties as functions of time
- the atmosphere around the Earth, ionosphere in particular, affects the travelling speed of the SNS signals and causes measurement error
- to eliminate ionospheric error single frequency SNS receivers apply SBAS ionospheric corrections, while dual frequency SNS receivers use the measurements on two transmitted satellite frequencies
- for precise local differential positioning PRC can be used if the distance between the user and reference station is less than 10 km, if this distance is greater dual frequency receiver is required
- ionospheric refraction affects the stability of satellite clocks using satellite navigation system time transfer
- ionospheric scintillation, the rapid fluctuations in the amplitude and phase of radio signals caused by small-scale irregularities in the ionosphere, is one of the most potentially significant threats for all SNS and SBAS. This phenomenon can lead to a receiver being unable to track one or more visible satellites for short periods of time

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