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Improving Capabilities of Broadband Differential Satellite Navigation Systems via Radio Occultation Technology

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Abstract—The existent satellite system for radio occultation monitoring the Earth's neutral atmosphere and ionosphere (COSMIC) provides data to consumers in the regions with limited possibilities of constructing dense measurement networks (e.g., in the World Ocean area). A forthcoming increase of LEO small spacecrafts and the deployment of new satellite radio navigation systems will result in a pronounced increase in the efficiency of radio occultation method and its space resolution. As a result, the Space-Based Augmentation Systems (SBAS) broadband differential system will become global, or the quality of corrections delivered to single-frequency consumers of individual systems, e.g., the Augmentation and Monitoring System, will be improved. Therefore, the methods for processing and analyzing obtained radio occultation data should be improved. A simple method to reconstruct the electron density profile at radio occultation points, based on the total electron content measurement on the satellite–satellite path and the IRI-type ionospheric model has been proposed. The method needs initial information, it does not require refraction measurements, and it is free of the assumption that the ionosphere is spherically stratified in the occultation region. Verification of the proposed method based on data for 121 radio occultation cases across Europe in May 2013 demonstrated good agreement with the vertical sounding data.

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1. INTRODUCTION

The COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) program, which was started in 2006 and uses radio occultation technology (Hajj et al., 2000), performs ~2000 atmospheric and ionospheric soundings per day, arbitrarily distributed over the globe. The measurements of ionospheric electron density profiles substantially complete the data of other ionospheric monitoring methods and can become decisive methods for solving problems that require the ionospheric support in individual regions, e.g., above the World Ocean area. The proposed development of the COSMIC program, which consists of an increase in the number of LEO (Low Earth Orbiting) spacecrafts in orbits with ~800 km altitude and the application of other (in addition to GPS) satellite navigation systems (SNSs), i.e., GLONASS, Galileo, etc., will make it possible to pronouncedly improve the space/time resolution of the atmospheric and ionospheric structure, trace the dynamics of processes proceeding in these regions. Additionally the COSMIC program makes it possible to solve problems in solar–terrestrial physics and space weather and increase the accuracy and effectiveness of the communication, location, and navigation systems.

We propose here a method for reconstructing ionospheric profiles based on radio occultation data and consider the possibility of using these data in order to calculate corrections, which are delivered from SBAS (Space-Based Augmentation Systems) to single-frequency consumers in regions where information about the ionospheric state is insufficient or absent.

2. METHOD FOR RECONSTRUCTING RADIO OCCULTATION PROFILES OF ELECTRON DENSITY USING THE IONOSPHERIC MODEL

The methods for reconstructing the $Ne(h)$ profile during the period when LEO moves from the zenith beyond the limb have been described in detail (see., e.g., (Hajj and Romans, 1998; Stankov and Jakowski, 2006; Krankowski et al., 2011)). Unfortunately, the methods according to which the refraction angle or total electron content (TEC) are measured on the LEO–GPS line have one general disadvantage: it is assumed that the ionosphere is spherically stratified in the occultation region, i.e., horizontally homogeneous, which is quite non-realistic. However, numerous verifications, which consist of comparing radio occultation (RO) profiles (Ne_{RO}) with vertical sounding (VS) (Ne_{VS}) and incoherent scatter (IS) station data, indicated that the results are in a good agreement, even though the occultation region is sometimes located at a large distance from VS and IS stations. According to GPS/MET experimental data (1995–1997) (Hajj and Romans, 1998) including ~40000 occultations, the difference between occultation *foF*2 and *foF*2 obtained from ionograms is ~10–20%, sometimes reaching 50%. Andreeva and Lokota (2014) illustrated the verification of the COSMIC system RO data based on the ionosonde measurements in different regions during 2006–2008. They indicated that the difference in *Ne*(*h*) profiles increases with increasing geomagnetic disturbances. In this case the critical frequencies according to the ionospheric VS data are as a rule higher than *foF*2 according to the RO data. These researchers also state that ionospheric models (e.g., NeQuick) adequately reproduce RO electron density values near the *F*2 layer maximum. Krankowski et al. (2011) illustrates a comparison of VS *NmF*2 with the occultation data of the COSMIC experiment over Europe in 2008 (the total number of the selected profiles was ~750), which indicated that the difference δ is about 8–9%. Parameter δ is calculated using the following formula

$$\delta = \frac{|NmF2_{RO} - NmF2_{VS}|}{NmF2_{VS}} \times 100\%,$$

where $NmF2_{RO}$ is the electron density near the *F*2 layer maximum according to the RO data, and $NmF2_{VS}$ is the electron density near the *F*2 layer maximum according to the VS station data.

However, we should note that the data from the midlatitude region at low solar activity were compared. That's why the errors are small, whereas the VS and RO data were selected very thoroughly. Below we present a method for determining Ne_{RO} profiles based on the TEC_{RO} measurements that are contained in the file podTec_C001.2013.121.20.00.0033.G08.01_2013.3520_nc (http://tacc.cwb.gov.tw/en), neglecting refraction but also without assumption that the ionosphere is stratified in the occultation region.

The idea of the method is that the ionospheric model, corrected by the ionospheric solar activity index (ISAI), which is determined based on the TEC_{RO} measurements (as was made in (Troitsky et al., 2007) based on the TEC maps or in (Bakurskii et al., 2014) based on data on the SBAS system delays), is used to calculate the *Ne*(*h*) profile. For instance, the IRI-*Plas* (Gulyaeva et al., 2002) or NeQuick (http://www.itu.int/dms_pub/itu-r/oth/0A/04/R0A040000180001ZIPE.zip) models are used to calculate $TEC_{IRI\text{-}Plas}$ on the LEO–GPS path, and the difference between $TEC_{IRI\text{-}Plas}$ and TEC_{RO} is minimized by varying the input index (SSN). The optimal SSN index replaces ISAI for a given session and is used to calculate the *Ne*(*h*) profile, together with RO (e.g., tangential) point coordinates.

The objective function, is the sum of squared deviations of the measured TEC_{RO} values from their calculated values ($TEC_{IRI\text{-}Plas}$) obtained from the IRI-*Plas* model. ISAI is calculated at the process of the objective function optimization. The input governing parameter of the SSN model or the Wolf number is used as an optimization parameter.

Thus, the functional to be minimized has the form

$$\sum_{i=1}^{N} (TEC^{i}_{RO} - TEC^{i}_{IRI\text{-}Plas}(W))^2 \to \min, \qquad (1)$$

where *N* is the number of TEC measurements taken from the formed files of the type ionPrf_C001.2013.121.20.32.G08_2013.2640_nc, TEC_{RO} is the TEC value measured by the RO method; $TEC_{IRI\text{-}Plas}$ is the TEC value obtained from the IRI-*Plas* model; and *W* is the Wolf number.

In addition to TEC measurements, the coordinates of the corresponding LEO and GPS satellites at specified instants are used to form the objective functional.

A specific feature of the procedure proposed is that the occultation onset (long intervals with small TEC values) and offset parts. When LEO goes beyond the Earth's surface limb and errors can be caused by diffraction and other effects affecting TEC determination accuracy, are rejected from the measured TEC values.

The calculated (model) TEC values at the instants of measurements are formed as an integral over the LEO–GPS straight line segment joining points with $P_{LEO}(X_{LEO}, Y_{LEO}, Z_{LEO})$ and $P_{GPS}(X_{GPS}, Y_{GPS}, Z_{GPS})$ satellite coordinates. The known relationships are used to find coordinates of points of division *P*(*X*, *Y*, *Z*):

$$X = \frac{X_{LEO} + \lambda X_{GPS}}{1+\lambda},$$

$$Y = \frac{Y_{LEO} + \lambda Y_{GPS}}{1+\lambda},$$

$$Z = \frac{Z_{LEO} + \lambda Z_{GPS}}{1+\lambda},$$

where λ is the number characterizing the m/n, ratio, in which point *P* divides the LEO–GPS straight line; $m/n = \overline{P_{LEO}P}/\overline{PP_{GPS}} = \lambda$. Changing this relationship, we form the integral for determining TEC on the oriented straight line joining the satellites. An analysis of the performed calculations indicates that the division (integration) step, which makes it possible to calculate the TEC values on the LEO–GPS path up to the third sign, ranges from 10 to 30 km depending on the time of a day and solar activity during the considered period.

The uniform empirical method (Panteleev and Legova, 2002) for the function of one variable was used as a functional (1) optimization method. In this case we selected the empirical method, because it was necessary to reject gradient procedures with the numerical determination of partial derivatives for non-

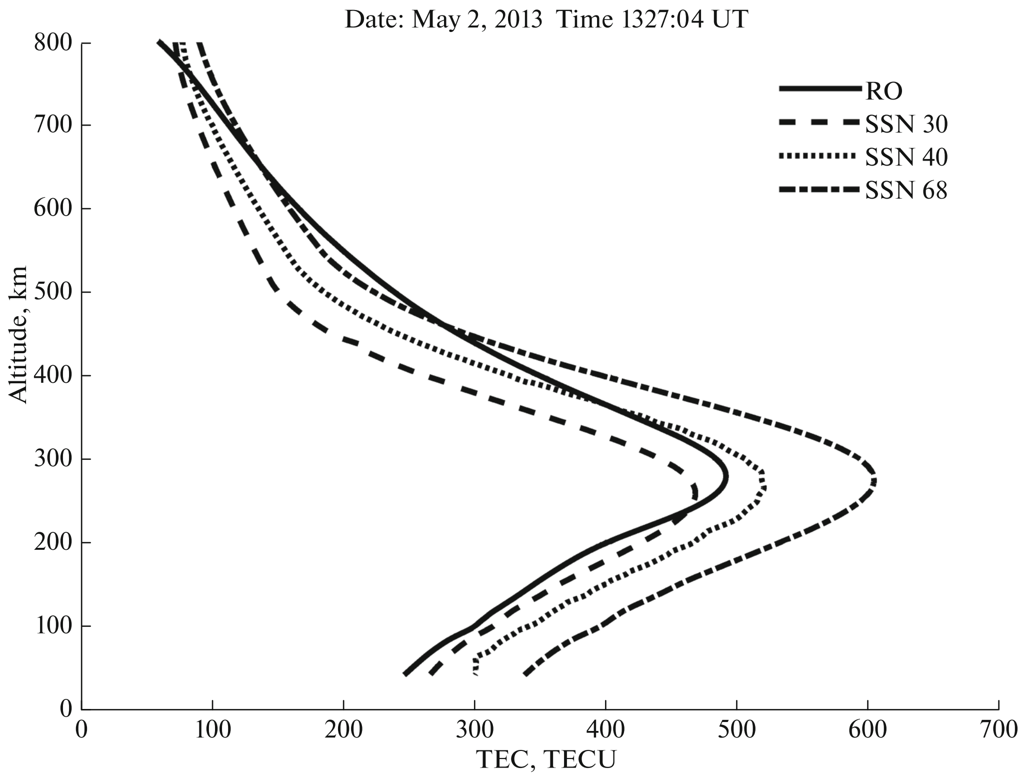

Fig. 1. TEC distributions on the LEO–GPS path obtained from the COSMIC system data and calculated in the IRI-*Plas* model for different values of the solar activity index at 13:27:04 UT on May 2, 2013.

linear functional (1), since we should know the increment for the parameter to be found in this case. Since the generalized function is complex, the increment value can disagree with the function topology, which results in a substantial increase in the minimum search time.

Figure 1 demonstrates the dependence of TEC_{RO} on the session onset (a solid curve) during the occultation over Europe on May 2, 2013 (the session started at 13:27:04 UT). Dotted curves show the variants of $TEC_{IRI\text{-}Plas}$(RO) calculations according to the IRI-*Plas* model with different SSN values. It is evident that the maximal approximation of $TEC_{IRI\text{-}Plas}$ to TEC is reached at SSN ≈ 36, and it is precisely this value that characterizes the ISAI of a given session with occultation point coordinates, which can be used to obtain the electron density profile according to the model.

It is evident that the method does not use an ionosphere spherical stratification approximation in the RO region and can therefore operate in the presence of horizontal ionospheric gradients. The method can be applied when TEC_{RO} measurements are discontinuous (during processing, it became clear that we can take only several TEC_{RO} values near maximums of the curves similar to those shown in Fig. 1). In addition, according to this method, we should not measure refraction angles, specify boundary conditions for Abelian transforms, etc. The fact that it is impossible to register such phenomena as sporadic layers in the ionospheric *E* region can be considered among the method's disadvantages.

3. COMPARING CALCULATIONS BASED ON RADIO OCCULTATION DATA WITH *foF*2 CRITICAL FREQUENCIES AT VS STATIONS

To verify the results obtained, we used *foF*2 data in the databases of the VS stations (www.iono.noa.gr/DIAS) located in Europe and the results of RO monitoring at Taiwan Analysis Center for COSMIC on the site (http://tacc.cwb.gov.tw/en/) and at COSMIC Data Analysis and Archive Center on the site (http://www.cosmic.ucar.edu/cdaac/).

Occultations were selected in the region with coordinates [20° N, 90° N; 60° W, 60° E] (Europe), where the first and second two values are latitude and longitude, respectively. The number of occultations during a day varies from 120 to 200 in this region.

In this sum the number of occultations with coordinates within 5° from the VS stations varies from 3 to 12 during a day.

The solid curve in Fig. 2 shows the *foF*2 daily variations obtained from the data of the VS stations, the

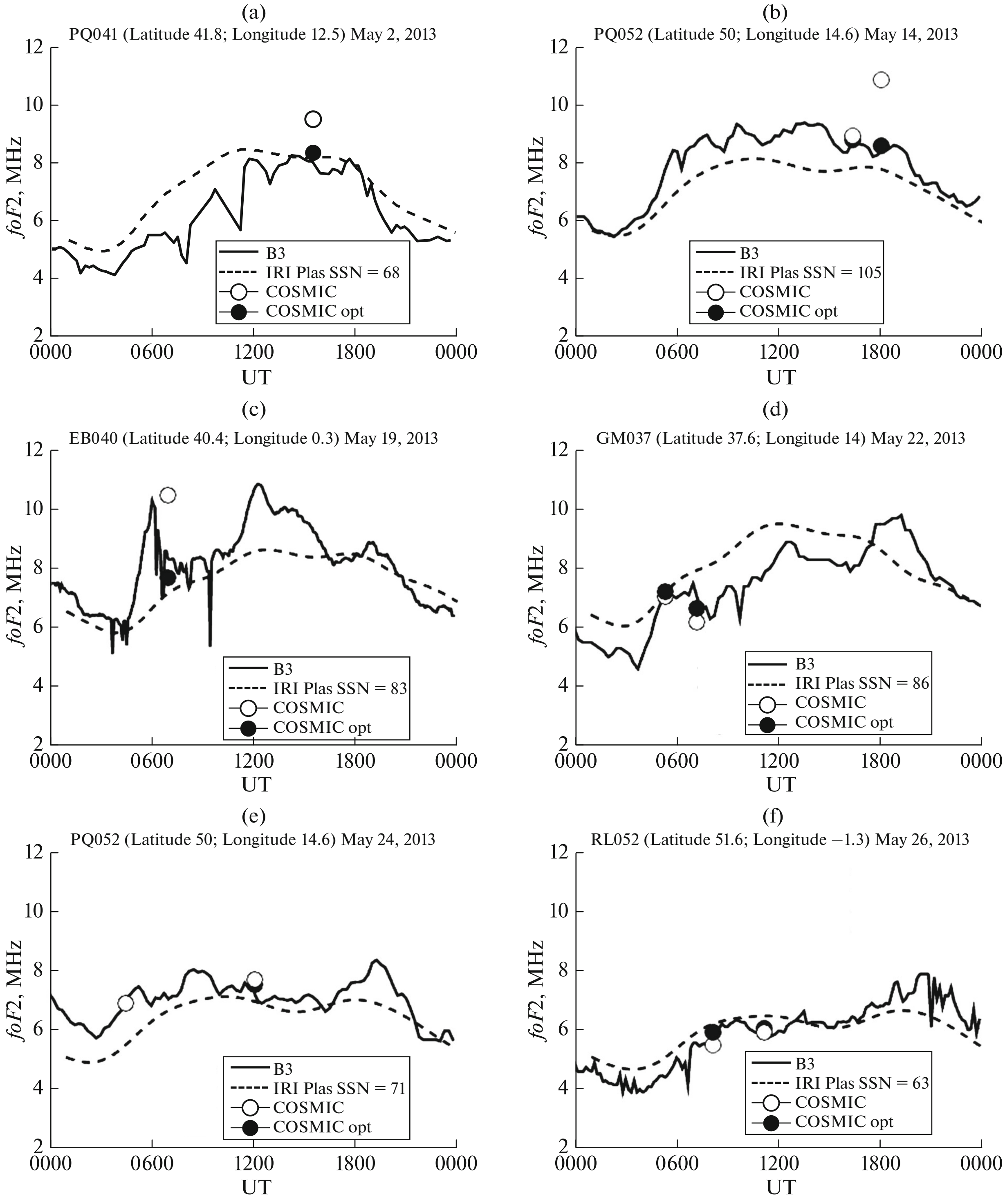

Fig. 2. Comparison of the *F*2 layer critical frequencies for the ionospheric VS stations: (a) RO041 with coordinates (41.8° N; 12.5° E), (b) and (e) PQ052 (50.0° N; 14.6° E), (c) EB040 (40.4° N; 0.3° E), (d) GM037 (37.6° N; 14.0° E), and (f) RL052 (51.6° N; 1.3° W).

codes and coordinates of which are shown in Fig. 2 for arbitrarily selected dates in May 2013; the dotted curve shows *foF*2 obtained by the IRI-*Plas* at predicted SSN according to the National Geophysical Data Center (USA) data (http://spidr.ngdc.noaa.gov).

The *foF*2 values obtained based on the described method (COSMIC opt) and RO data (COSMIC) are marked by filled and open circles, respectively. We selected the occultation sessions with coordinates in the same 5° cell as the VS stations.

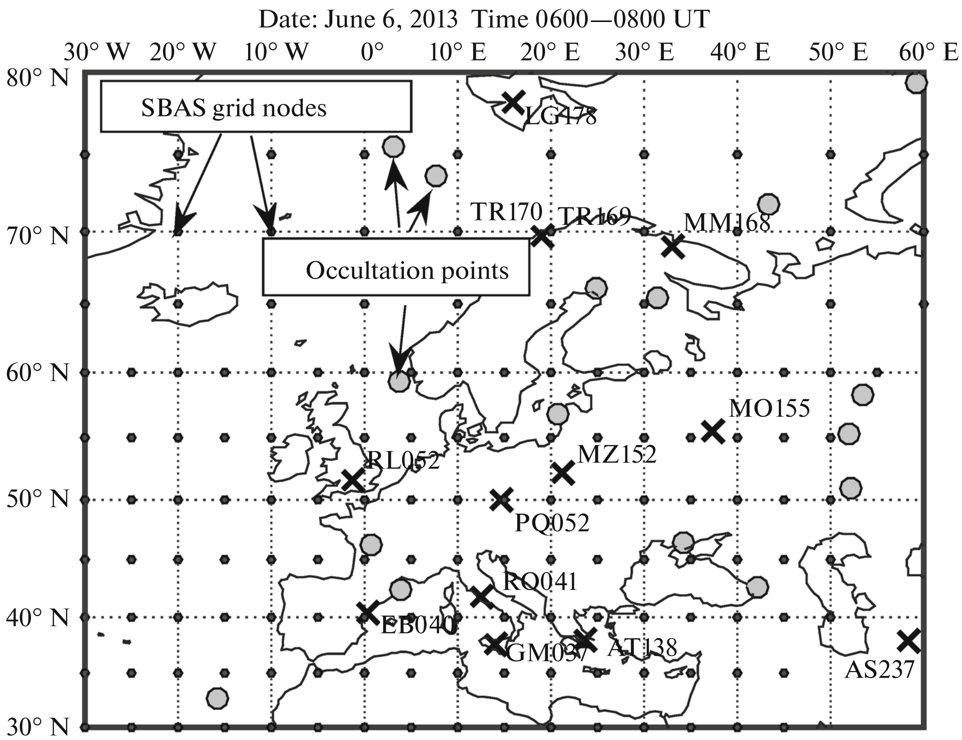

Fig. 3. The EGNOS system area of responsibility with RO points for 06:00–08:00 UT on June 26, 2013, and the location of the ionospheric VS stations in Europe.

Figures 2a–2f indicate that the method for reconstructing the electron density (proposed in the present work) in the region of the ionospheric $F2$ layer maximum based on the TEC values measured by the RO method is comparable with the method applied in the COSMIC project with respect to the accuracy.

This conclusion is confirmed by the processing of 121 occultation sessions in Europe. The method sometimes yields the best result during sunrise–sunset periods, which is possibly caused by the fact that the horizontal *Ne* gradients in the terminator region are taken into account (via the model).

If several (n) RO sessions take place in a certain time interval in an arbitrary region (e.g., over Europe), we can determine the n ISAI values and construct the regional ISAI map and, consequently, the $foF2$ map.

Bakurskii et al. (2014) indicated that the average ISAI value in Europe varies insignificantly during the day. Therefore, we select the occultation sessions in a 2-h interval. We determine the ISAI values for each session and construct the map. Then, having calculated $foF2$ at the ionosonde sites, we compare these values with the VS data for the middle of the selected time interval using the expressions:

$$\Delta f = \left| foF2_{\mathrm{RO}} - foF2_{\mathrm{VS}} \right|,$$

$$\delta = \frac{\left| foF2_{\mathrm{RO}} - foF2_{\mathrm{VS}} \right|}{foF2_{\mathrm{VS}}} \times 100\%,$$

where $foF2_{\mathrm{RO}}$ and $foF2_{\mathrm{VS}}$ are the critical frequencies according to the RO and VS station data, respectively.

Table illustrates a comparison of the data for eight VS stations for June 6, 8, and 26, 2013, at 06:00–08:00 UT.

Table indicates that the critical frequency of the ionospheric $F2$ layer is reconstructed very accurately almost without exception. Pronounced differences in δ (~12–13%) and Δf ~ 1 MHz, are possibly caused by the fact that the ionosondes are located at the edge of the ISAI map where interpolation errors increase.

Figure 3 shows the location of the ionosondes (crosses) and the occultation region (filled circles) from 06:00 to 08:00 UT on June 26, 2013.

If the ISAI map, which makes it possible to determine the ionospheric parameter at any point of the mapped region from a model (e.g., IRI-*Plas*), is available, it becomes possible to construct the regional TEC map and, consequently, to calculate the vertical corrections for distance at frequency $L1$ at SBAS grid nodes in the region. We performed such a calculation based on the RO data from 06:00 to 08:00 UT on June 26, 2013, over Europe (35°–65° N; 0°–50° W) and compared the results with the corrections that are delivered from the EGNOS system (*Current* ..., 2010) to single-frequency consumers.

Figure 4 shows the correction numerical values (in meters) according to the RO data (left of the bar) and the values calculated using the EGNOS data (right of

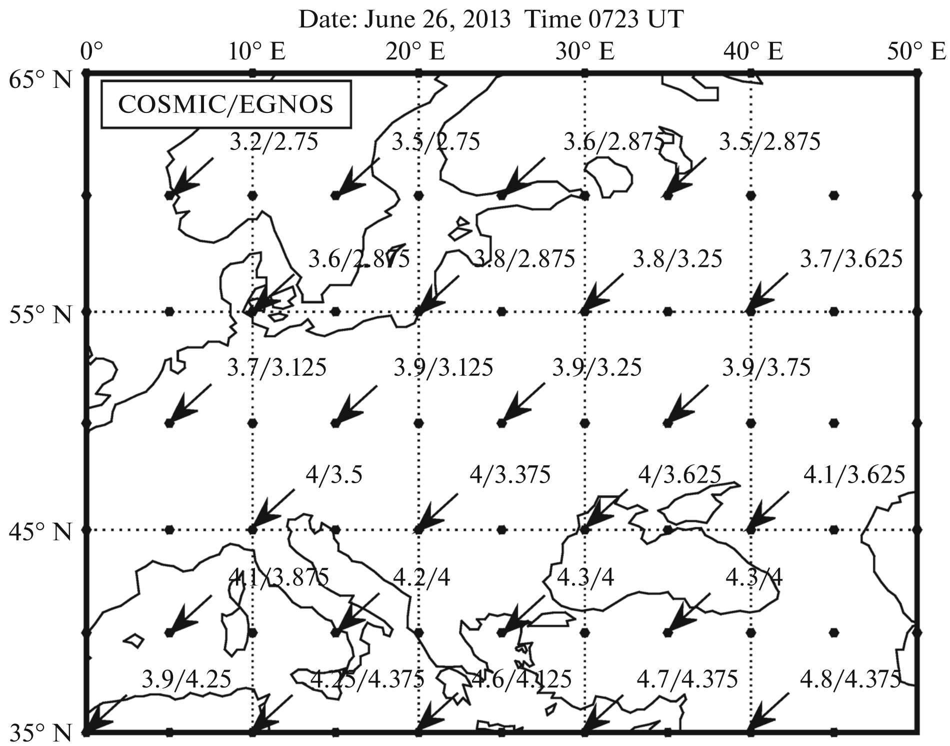

Fig. 4. Vertical delays at the SBAS grid nodes according to the COSMIC program and EGNOS system data for 07:23:00 UT on June 26, 2013.

the bar). It is evident that the difference is equal to several decimeters. We performed a similar procedure for June 6 and 8, 2013.

It turned out that the difference is not more than 15%. Note that the TEC measurement errors in the SBAS systems also result in correction errors of several decimeters.

4. CONCLUSIONS

We proposed the method for reconstructing the electron density in the ionosphere based on the TEC measurements on satellite–satellite paths during ROs in the scope of the FORMOSAT-3/COSMIC project. The electron density is calculated according to the ionospheric model (e.g., IRI-*Plas*) corrected by ISAI,

Comparison of VS station data at 06:00–08:00 UT on June 6, 8, and 26, 2013

Ord. no.	Designation	Latitude, deg	Longitude, deg	June 6, 2013		June 8, 2013		June 26, 2013	
				Δf, MHz	δ, %	Δf, MHz	δ, %	Δf, MHz	δ, %
1	RL052	51.6 N	1.3 E	0.14	2.15	0.40	7.03	0.004	0.006
2	TR169	69.7 N	19.0 W	0.47	8.5	0.32	6.15	0.23	3.79
3	TR170	69.7 N	19.0 W	0.37	6.59	0.37	7.23	0.19	3.14
4	PQ052	50.0 N	14.6 E	0.39	5.26	0.49	7.86	0.37	5.33
5	RO041	41.8 N	12.5 E	0.34	4.04	0.41	5.35	0.94	12.66
6	EB040	40.0 N	0.3 E	0.008	0.10	0.35	4.76	0.26	3.51
7	GM037	37.6 N	14.0 E	0.41	4.87	1.18	13.45	0.15	1.91
8	AT138	38.0 N	23.6 E	0.06	0.68	1.12	12.04	0.14	1.92

which is determined from primary data on TEC from the site (http://tacc.cwb.gov.tw/en).

Based on processing 121 RO cases in May 2013 in Europe, we compared the *foF*2 critical frequencies based on the VS and *foF*2 data, which were reconstructed from COSMIC system occultations by the method described in the work.

We concluded that the accuracy of the proposed method (which is undoubtedly more efficient than other methods, is independent of the assumption that the ionosphere is spherically stratified, and is free of the possible refraction measurement errors) is not lower than the *foF*2 determination accuracy of the method used in the COSMIC project.

The RO method for monitoring the ionosphere is less effective than the WAAS or EGNOS systems; however, the RO method for diagnosing the ionosphere can become useful in hard-to-access regions and in the World Ocean area with increasing number of LEO satellites. This method can be used to maintain the ionospheric systems of communication, location, and navigation, e.g., in order to increase the possibilities of broadband differential systems.

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