ISSN 0010-9525, Cosmic Research, 2018, Vol. 56, No. 2, pp. 115–122. © Pleiades Publishing, Ltd., 2018.
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On the Accuracy of the Conjugation of High-Orbit Satellites with Small-Scale Regions in the Ionosphere

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Received October 8, 2016

Abstract—The degree of uncertainty that arises when mapping high-orbit satellites of the *Cluster* type into the ionosphere using three geomagnetic field models (T89, T98, and T01) has been estimated. Studies have shown that uncertainty is minimal in situations when a satellite in the daytime is above the equatorial plane of the magnetosphere at the distance of no more than 5 R_E from the Earth's surface and is projected into the ionosphere of the northern hemisphere. In this case, the dimensions of the uncertainty region are about 50 km, and the arbitrariness of the choice of the model for projecting does not play a decisive role in organizing satellite support based on optical observations when studying such large-scale phenomena as, e.g., WTS, as well as heating experiments at the EISCAT heating facility for the artificial modification of the ionosphere and the generation of artificial fluctuations in the VLF band. In all other cases, the uncertainty in determining the position of the base of the field line on which the satellite is located is large, and additional information is required to correctly compare the satellite with the object in the ionosphere.

DOI: 10.1134/S0010952518020089

1. INTRODUCTION

In connection with the active use of the near-Earth space for both scientific and practical purposes, there is an increasing need for the terrestrial support of satellite observations. Namely, in the comparison of dynamic processes in the magnetosphere with phenomena in the magnetic conjugated ionosphere region and vice versa. It is widely believed that the magnetospheric-ionospheric interaction is largely realized through the geomagnetic field lines, i.e., through field-aligned currents, precipitating particles, and Alfven waves. Therefore, here and below, *magnetic conjugation* refers to finding conjugate objects on the same geomagnetic field line.

It is not difficult to compare satellite and terrestrial (more precisely, ionospheric) data if one considers low-orbit satellites like *DMSP* and *FAST*, the orbits of which are a short distance from the Earth's surface ranging from several hundred to 1000 km. At these distances, the main contribution to the geomagnetic field introduces the own Earth's field, so that the shape of the field line is weakly affected here by magnetospheric currents, and the International Geomagnetic Reference Field (IGRF) model is quite suitable for its analytical description. The problems of mapping (projecting) a satellite into the ionosphere using the IGRF model were successfully solved, e.g., in [1, 2] and contributed to the progress in understanding the nature of poorly studied phenomena as the auroras in the cusp and the diffuse auroras of the auroral zone, respectively. The importance of the correct conjugation of the *FAST* satellite with the region of modulated ionospheric heating above the EISCAT heating facility was clearly demonstrated in [3], where it was shown that the satellite is projected at the heating spot, rather than away from it, as was initially assumed in rough estimates. In this paper, it was noted that the use of the IGRF model to determine the base of the field line on which the satellite is located is permissible up to an orbit altitude of not more than 1 R_E. In [4], the *Cluster* satellites were located at a relatively small distance from the ionosphere (3–5 R_E), and the authors considered it possible to take into account only the own Earth's field taking as the basis the IGRF model. In this case, the error when projecting the satellite reached 400 km, which is about an order of magnitude greater than the width of the auroral structures in the ionospheric region conjugated with the satellites. Therefore, when projecting high-orbit satellites into the ionosphere, it is necessary to use the detailed semi-empirical Tsyganenko model, which is unique for today, in various modifications.

In situations when the accuracy of conjugation is not of principal importance, the projecting method does not raise questions. For example, in [5], it was sufficient to show that the source of the auroral arc lies deep in the magnetosphere and, therefore, cannot be associated with the Kelvin–Helmholtz instability on the magnetopause. In [6], it was enough to verify that both *Themis* satellites are projected into the region occupied by the active forms of auroras. The question of association of satellite measurements with any particular auroral structure did not stand. In [7], the data from the twenty ground-based optical observation stations of the *Themis* project were used to determine the time of substorm onset during the period of conjugation of the *Themis* satellites with these observatories. In [8], the *Geotail* satellite was projected from the plasma sheet into the ionosphere, where images of auroras from the *Polar* satellite were also projected. The question of precisely comparing the data from both of these satellites did not stand because, as noted by the authors, the application of the statistical Tsyganenko model in a concrete situation can lead to appreciable errors. In the study, it was sufficient to qualitatively estimate where *Geotail* satellites were found relative to the auroral convexity.

The Tsyganenko model represents a statistical generalization of measurements of the geomagnetic field vector on satellites. In this case, the data of the last satellite projects, *Cluster* and *Themis,* are not included in the early modifications of Tsyganenko models, which may be one reason for the poor fit of the model to real measurements on these satellites. An estimation of the error in the application of the Tsyganenko model for conjugation of remote satellites like *Themis* with ground-based observatories was carried out in [9]. The authors compared the real position of the boundary of isotropic precipitation determined using the data of low-orbit satellites with a theoretical proposition calculated according the three Tsyganenko models. Note that the evaluation results are applicable to the near-midnight sector (0 ± 2 h MLT). Using the *Cluster* data to the verification of the Tsyganenko models revealed in [10], a discrepancy of approximately 70 nT in the region of the ring current (at a distance of 4–5 R_E).

Comparison of the results of projection performed using a statistical model with the results of specific measurements can lead to incorrect interpretation of observations. For example, in [11], the T96 Tsyganenko model gave the position of the boundary between the closed and open field lines in the projection into the ionosphere in the premidday sector at 200–300 km to the south than was determined by the *Polar* satellite data. According to the results of studies in [12], for a satellite flying at an altitude of about 4 R_E, the use of various versions of the Tsyganenko model introduced in to calculate the position of the base of the geomagnetic field line the uncertainty of about 100 km. In this case, depending on the model, the satellite was projected either into different auroral forms (pulsating patches) or between them. According to the SI12 camera onboard the *Image* satellite, it was shown that under disturbed conditions the T01 model does not adequately reflect the degree of elongation of the magnetic field lines at large distances from the Earth [13]; therefore, the results of conjugation of the phenomena in the ionospheres of the northern and southern hemispheres (see, e.g., [14]) should be treated with caution.

To apply the model to the analysis of a specific situation, in some cases, a model correction based on additional and a priori information is possible. In [15], the method of adjusting the Tsyganenko model for the correct modeling of the magnetospheric tail is discussed using additional data on the position of the boundary of isotropic precipitations and the angle of inclination of the magnetic dipole. In [16], the T89 Tsyganenko model was used for the projection of the *Cluster* satellites flying at the altitude of 22000 km (~4.4 R_E) over the northern part of the Scandinavian Peninsula. Within a few minutes, the satellites crossed two arcs. In order to achieve better correspondence with the satellite data at the intersection of the second arc, the authors had to change the initial model parameter (to increase the value of the K_p index from 3 to 5), arguing that the second arc appeared as a result of the pseudo-breakup development. In [17], devoted to the same case, the projection was carried out according to the T89 model for constant $K_p = 3$. As a result of a joint analysis of terrestrial radar and satellite data, a shift was detected in the boundary between the closed and open field lines relative to the convection circulation region. In light of the above, it is not clear whether the shift was real or a consequence of an incorrect description of the situation by the T89 model.

The most sensitive to the choice of the Tsyganenko model can be the problems of conjugation of high-orbit satellites with small regions in the high-latitude ionosphere or on the Earth's surface. Such areas at the altitude of the *E* sheet of the ionosphere can be, e.g., auroral arcs (arc width about of 10 km or less) or luminous spots propagating along them; the region of the modified ionosphere above the heating facility in the experiments for modulating the auroral electrojet arising in the *E* region (the diameter is about 20 km with the width of heating beam of 11.8°) and the cross section of the beam of the EISCAT radar (the diameter is ~1 km with the width of beam of 0.5°).

At the high latitudes where the auroras are recorded, the EISCAT radar and heating facilities are operated, the geomagnetic field lines along which conjugation is performed are strongly deformed by the currents of the plasma sheet, and their shape depends on local time and geomagnetic latitude. Therefore, the uncertainty in the conjugation of ionospheric regions with satellites flying near the equatorial plane of the magnetosphere, e.g., *Themis* satellites, is greater here than for satellites flying far from the equatorial plane and at a relatively short distance from the Earth's surface, e.g., *Cluster* satellites.

Based on the foregoing, the aim of this paper is formulated as follows. Using the example of the high-orbit *Cluster* satellite, it is necessary to estimate the uncertainty, which arises in the choice of a given Tsyganenko model for conjugating the satellite with the optical equipment and the low-frequency transmitter in the central part of the Kola Peninsula (the geomagnetic latitude is ~64.2°) with the radar, and the EISCAT heating bench in the northern part of Scandinavian Peninsula (the geomagnetic latitude is ~66.6°), as well as with optical equipment, the ESR radar (the EISCAT Svalbard radar), and the SPEAR heating bench on the Spitsbergen archipelago (the geomagnetic latitude is ~75.1°).

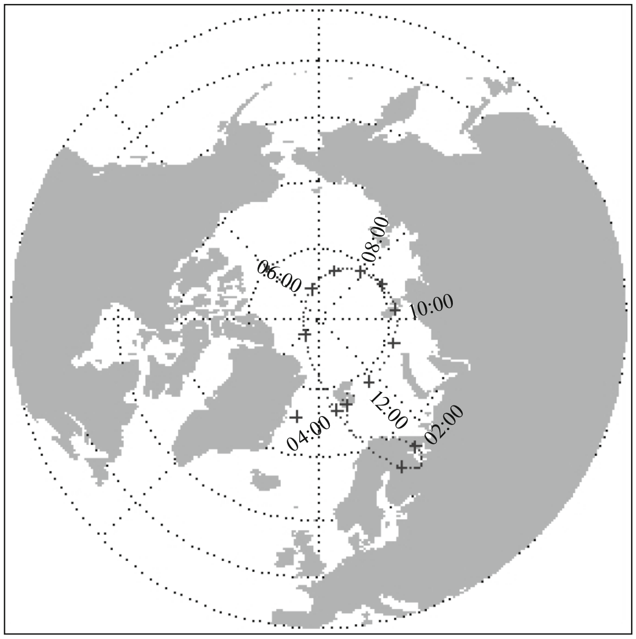
2. PROCEDURE

The selection of events took place in two stages. At the first stage, the date and time of the probable conjugation of the *Cluster* satellite with one of the above items was determined using the data of the Cluster Data Center website, which gives a very approximate representation where one of the *Cluster* quartet satellites was projected (http://www.cluster.rl.ac.uk/csdsweb-cgi/csdsweb_pick). An example of projecting is shown in Fig. 1, where it can be seen that, during the day, the satellite could potentially be conjugated with objects on both the Kola Peninsula and in Northern Scandinavia as well as on the Spitsbergen archipelago. Here, the trajectory of the satellite in the projection into the ionosphere is shown by dashed line, the crosses indicate the position of the satellite every hour of flight.

At the second stage, the projection of the satellite was determined more precisely using the Orbit Visualization Tool program developed specifically for this purpose by one of the participants of the *Cluster* project, the Swedish Institute of Space Physics (http://ovt.irfu.se). The program makes it possible for the given position of the satellite to calculate the shape of the magnetic field line on which it is located and the coordinates of its base at an altitude of 100 km for different models of the geomagnetic field. The field is assumed to be the sum of the own Earth's field (dipole or IGRF) and the field created by external sources. The latter is calculated using the T89, T98, or T01 Tsyganenko models. The input parameters are the date and time, as well as K_p and D_{st} indices, the values of the interplanetary magnetic field components (B_x, B_y, and B_z) and the dynamic solar wind pressure (*SWP*), the coefficients G1 and G2 (for the T01 model) [18]. These parameters were taken from the Virtual Radiation Belt Observatory (VIRBO) website (http://virbo.org) for the relatively quiet day of May 4, 2004 and were $[B_x\ B_y\ B_z]$ GSM = [1 –0.9 –4.0] nT, $SWP = 1.2$ nPa, $K_p = 2$, $D_{st} = -7.0$ nT, [G1 G2] = [2.4 6.4].

To estimate the uncertainty, events were selected during which one of the *Cluster* quartet satellites was projected according to the T89 model into the region of ~100 × 100 km centered at either the Lovozero observatory on the Kola Peninsula or at Tromso in northern Norway, which were located near the EISCAT facility, or in the Henriksen observatory near the Longyearbyen village at Spitsbergen. Then, for this satellite, the projections using the T98 and T01 models, the mean latitude and longitude of the projection (note that they are not true coordinates of the base of the field line), and the error of relative mean value were calculated. In fact, the error represents the characteristic dimensions of the region in which the satellite is projected by a given model of the geomagnetic field. Below, for brevity, this region will be called the *region of uncertainty.*

Cluster Reference Spacecraft



17 Dec. 2002

Fig. 1. Projecting the trajectory of the *Cluster* satellite on the Earth's surface according to the website http://www.cluster.rl.ac.uk/csdsweb-cgi/csdsweb_pick.

3. RESULTS

For the period of January 2001 to June 2004, we revealed 49 cases of the conjugation of one of the *Cluster* satellites with the above objects. Note that, in a number of cases, the satellites followed one after another at intervals of several dozen minutes and were projected into the same region from almost the same part of the magnetosphere. In these situations, we limited ourselves to project only one satellite. As a result, the studies covered various MLT sectors and, in this case, the satellites were located at different distances from the Earth's surface. In addition, during the interval, the program of the cluster operation changed, as a result of which the orbits of the satellites changed. The use of real situations in studies allowed us not only to significantly simplify the implementation of the conceived, but also gave statistical significance to the results despite a relatively small sample, because when

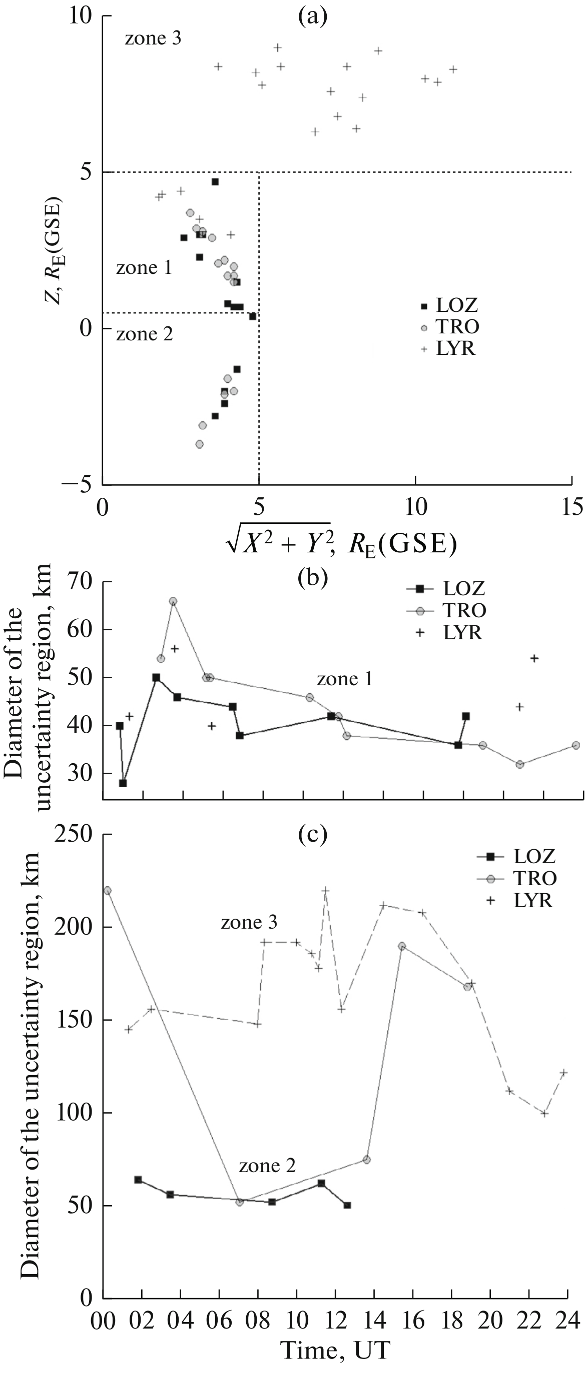


Fig. 2. (a) Distribution of the satellite position in the magnetosphere using three spatial zones; (b) dimensions of the uncertainty region as a function of time when projecting satellites into the ionosphere from zone 1; (c) dimensions of the uncertainty region as a function of time when projecting satellites into the ionosphere from zones 2 and 3. Local noon at LOZ, TRO, and LYR stations is 08–09 UT.

using this procedure, the distribution of points in the magnetosphere, from which the projection was carried out, can be considered close to stochastic.

The distribution of points in the magnetosphere, from which the projection was carried out, is represented by the diagram in Fig. 2a. Here, the values of the radius vector of the projection of the satellite on the equatorial plane of the magnetosphere are plotted on the horizontal axis, Z is the coordinate along the z axis in the GSE coordinate system. The cloud of points is divided into three zones. The most numerous zone 1 includes 24 points, projections of which were performed in the vicinity of both Lovozero (LOZ) and Tromso (TRO), as well as in Longyearbyen (LYR). Points are located in the region of positive values of Z with R not more than 5 R_E. The most remote point (along the magnetic field line) from the Earth's surface is at the distance of 0.8 R_E from the equatorial plane. In zone 2, there are points at which the radius vector R also does not exceed 5 R_E, but almost all of them lie below the equatorial plane, in the region of negative Z. Points of zone 2 are projected into LOZ and TRO. The distance (along the magnetic field line) of the points of zone 2 to these objects is greater than for the points of zone 1. At night, the equatorial part of the field line along which the points from zone 2 are projected can be distorted by the current of the plasma sheet. All points of zone 3 are projected into LYR, and the shape of the field lines on which they are located differs markedly from that of points in zones 1 and 2 due to the influence of the solar wind on these parts of the magnetosphere. Thus, it is reasonable to expect the least uncertainty in projection using different models of the geomagnetic field for points of zone 1, where the distortions of field lines introduced by external sources should not be so great.

The results of the satellite projection from zones 1, 2, and 3 are presented in Tables 1, 2, and 3, respectively. Here, the second column indicates the number of the *Cluster* satellite, the third and fourth columns indicate the date and time of conjugation of the satellite with one of the observatories, while the fifth and sixth columns contain the coordinates of the satellite in the GSE coordinate system (R is the radius vector of the projection of the satellite on the equatorial plane, Z is the coordinate along the z axis). The last column gives the diameter of the uncertainty region, which is calculated as twice the absolute error of projection using three different models of the geomagnetic field.

The cases of conjugation are ordered in tables according to increasing time UT. Note that the difference between universal and local time in Lovozero, Tromso, and Longyearbyen is insignificant and lies in the interval of 2–3 h. According to the data from the fourth and seventh columns, the graphical time dependence of the diameter of the uncertainty region for each of the zones is presented (Figs. 2b, 2c). As expected, the dimensions of the uncertainty region are small when projecting a satellite into Lovozero or Tromso during daylight hours and are ~40 km for satellites from zone 1 and 50–60 km for satellites from zone 2, i.e., located below the equatorial plane. When projecting a satellite into Lovozero and Tromso from

Table 1. Coordinates of satellites in zone 1 and dimensions of the uncertainty region when they are projected into the ionosphere using various models of the geomagnetic field

No.	C	Date	Time, UT	R, R_E	Z, R_E	D, km
1	2	3	4	5	6	7
Lovozero [67.97° 35.08°]						
1	1	Jan. 18, 2002	00.50	4.4	0.7	40
2	2	Jan. 7, 2001	01.00	4.0	0.8	28
3	1	Dec. 18, 2001	02.40	4.3	1.5	50
4	3	Nov. 16, 2002	03.44	3.6	4.7	46
5	3	Oct. 17, 2001	06.30	3.2	3.0	44
6	3	Oct. 16, 2002	06.50	3.1	3.0	38
7	3	Aug. 4, 2001	11.24	4.2	0.7	42
8	1	Apr. 29, 2004	17.45	2.6	3.1	36
9	1	Apr. 21, 2001	18.08	3.1	2.3	42
Tromso [69.66° 18.94°]						
10	1	Dec. 18, 2001	02.54	4.2	2.0	54
11	3	Dec. 17, 2002	03.30	3.7	2.1	66
12	3	Nov. 17, 2001	05.09	3.2	3.1	50
13	3	Nov. 16, 2002	05.20	3.0	3.2	50
14	3	Sept. 4, 2001	10.20	3.9	2.2	46
15	3	Aug. 4, 2001	11.46	4.2	1.7	42
16	3	Aug. 14, 2003	12.10	4.2	1.5	38
17	1	Apr. 20, 2002	18.59	2.8	3.7	36
18	1	Apr. 20, 2002	20.50	3.5	2.9	32
19	1	Feb. 6, 2001	23.38	4.0	1.7	36
Longyearbyen [78.20° 15.82°]						
20	4	Jan. 18, 2002	01.20	4.1	3.0	42
21	4	Dec. 17, 2002	03.35	3.1	3.5	56
22	4	Nov. 16, 2002	05.26	1.9	4.3	40
23	3	Mar. 31, 2003	20.50	1.8	4.2	44
24	1	Mar. 20, 2002	21.34	2.5	4.4	54

Table 2. Coordinates of the satellites in zone 2 and dimensions of the uncertainty region when they are projected into the ionosphere using various models of the geomagnetic field

No.	C	Date	Time, UT	R, R_E	Z, R_E	D, km
1	2	3	4	5	6	7
Lovozero [67.97° 35.08°]						
1	3	Dec. 17, 2002	01.50	3.9	−2.4	64
2	3	Nov. 17, 2001	03.30	4.3	−1.3	56
3	3	Sept. 4, 2001	08.45	3.9	−2.0	52
4	1	Aug. 3, 2002	11.18	4.8	0.4	62
5	3	July 3, 2002	12.40	3.6	−2.8	50
Tromso [69.66° 18.94°]						
6	1	Jan. 16, 2004	00.15	3.1	−3.7	220
7	3	Oct. 5, 2001	07.04	4.2	−2.0	52
8	3	June 22, 2001	13.39	3.2	−3.1	75
9	3	May 22, 2001	15.27	3.9	−2.1	190
10	1	Apr. 9, 2001	18.50	4.0	−1.6	168

Table 3. Coordinates of the satellites in zone 3 and dimensions of the uncertainty region when they are projected into the ionosphere using various models of the geomagnetic field

No.	C	Date	Time, UT	R, R_E	Z, R_E	D, km
1	2	3	4	5	6	7
Longyearbyen [78.20° 15.82°]						
1	1	July 23, 2002	01.20	11.2	8.3	145
2	4	July 11, 2002	02.30	10.7	7.9	156
3	3	Apr. 15, 2003	08.00	6.8	6.3	148
4	4	Apr. 4, 2002	08.20	5.1	7.8	192
5	1	Mar. 4, 2002	10.00	3.7	8.4	192
6	1	Feb. 13, 2002	10.48	5.6	9.0	186
7	2	Feb. 12, 2003	11.10	5.7	8.4	178
8	3	Jan. 24, 2003	11.30	7.3	7.6	220
9	1	Jan. 13, 2002	12.20	4.9	8.2	128
10	2	Dec 12, 2002	14.30	7.5	6.8	212
11	2	Nov. 11, 2002	16.30	8.1	6.4	208
12	1	Oct. 11, 2002	19.05	8.3	7.4	170
13	2	Sept. 10, 2002	21.00	7.8	8.4	112
14	3	Aug. 22, 2002	22.50	10.3	8.0	100
15	2	Aug. 10, 2002	23.50	8.8	8.9	122

zone 1, there is a tendency to decrease the dimensions of the uncertainty region from the morning hours to the evening hours (Fig. 2b). We leave this issue beyond the study.

For satellites projected into Tromso from zone 2 (Fig. 2c), the projection uncertainty is greater in the morning and evening hours than in the daytime, and varies in the range of 170–220 km. When projecting into Lovozero, this feature is not found. We believe that both of these features are associated with the greater influence on the shape of the Tromso field line of currents of the plasma sheet than for Lovozero, which is located more equatorially than Tromso.

The greatest uncertainty arises when projecting satellites from zone 3 in the vicinity of Longyearbyen at Spitsbergen. Depending on the local time, the dimensions of the uncertainty region varies from 100 to 220 km (see Fig. 2c). In the daytime, the uncertainty is greater than in the night. On the night side, the field lines are strongly extended into the tail and, at distances $R \sim 10\ R_E$, their configuration is less complex than on the day side. In the daytime magnetosphere, the satellite coordinate is $R \sim 6\ R_E$, and the satellite is most likely located on closed field lines deformed (pinched) by the stream of the solar wind.

4. DISCUSSION

Approximately fifty cases of the conjugation of the high-orbit *Cluster* satellite with observatories located in the Lovozero village (Kola Peninsula), near Tromso city (northern part of the Scandinavian Peninsula), and Longyearbyen village (Spitsbergen archipelago) have been analyzed. The purpose of the analysis was to estimate the uncertainty that arises when the satellite is projected into the ionosphere using various models of the geomagnetic field (the Tsyganenko models). Since we do not know the true coordinate of the base of the field line on which the satellite is currently located, we are not talking about the projection error, as was done in [9], i.e., the uncertainty of the correlation of the satellite with an object in the ionosphere. For the quantitative characteristics of the uncertainty, we have adopted the diameter of the region, the center of which is calculated as the arithmetic mean of the coordinates of the bases of the field lines calculated by different Tsyganenko models, and the radius is calculated as the distance from the center to one of the bases.

Satellites at the time of conjugation were located in different regions of the magnetosphere and in different MLT sectors. A cloud of points that characterize the position of the satellites in the magnetosphere was divided into three zones. Points from the first zone correspond to situations, when the satellite at the time of conjugation was on closed field lines above the equatorial plane of the magnetosphere. This is the most favorable region for solving problems related to the need to compare the satellite and terrestrial observations in the northern hemisphere, since the uncertainty of the projection is relatively small and is equal to ~40–50 km in the daytime.

At the latitude of the Lovozero observatory, there is a facility with power line as a radiating antenna. If it is assumed that the dimensions of the region occupied by the radiation generated by the facility are comparable with the antenna dimensions (70–100 km), detection of this radiation by satellites in zone 1 is quite possible, since the choice of the magnetic field model does not greatly affect the accuracy of conjugation. It should also be noted that estimates of the uncertainty were performed for quiet geomagnetic conditions when the level of natural low-frequency electromagnetic noise is low [19].

Experiments on artificial modification of the ionosphere are successful when the frequency of the pump wave is less than the ionospheric plasma frequency (critical frequency). This condition is more often observed in the sunlit ionosphere. For the width of the heating beam of the EISCAT bench of 11.8° (see, e.g., [20]), the diameter of the illumination area at the altitude of the *E* region is about 100 km. Studies of the ionosphere above the mid-latitude Sura heating facility by satellite radiotomography methods have shown that artificial perturbations of the plasma density are excited in the wider horizontal region (±200 km relative to the center of the heating beam) than the region of illumination [21]. Thus, the dimensions of the uncertainty region due to the arbitrariness of the choice of the geomagnetic field model are comparable with the dimensions of the modified region. This means that the probability of hitting a satellite located in zone 1 (see Fig. 2a) with a power tube, the base of which is the region modified by heating at the altitudes of the *F* sheet, is fairly high. However, the uncertainty of the projection will no longer allow one to confidently identify satellite data with artificial ionospheric irregularities that have transverse dimensions, e.g., of about 30 km, which were observed in the experiment at the Sura facility [21], and the nature of which remains unclear.

If we correlate the obtained results with the problem of conjugating the satellite, not with the heating region, but rather with the source of artificial low-frequency disturbances, we can arrive at the following conclusion. When generating artificial pulsations by modulated heating in the band from hundreds of hertz to the 1 kHz, the ionospheric region that is the source of pulsations consists of three zones, the maximum of which has dimensions of several hundred kilometers [22]. If the problem is to fix the generation of pulsations, then we cannot be particularly concerned about which Tsyganenko model to take for conjugating the satellite with the source of pulsations in the ionosphere. However, in order to hit the satellite in the region of very intense disturbances that forms a narrow cylinder with a radius of 20–30 km, the choice of model can be of decisive importance.

The uncertainty in the projection of the satellite from zone 1 increases at night, which becomes critical for studying auroras with transverse dimensions from several kilometers (auroral arc) to several tens of kilometers (pulsating patches). The situation is aggravated by the fact that these auroral structures develop against the background of increased geomagnetic activity, when the configuration of the field lines in the night magnetosphere is distorted by the currents of the magnetospheric tail, which makes the uncertainty even greater than our estimates. As was shown earlier in [12], this circumstance makes it difficult to study these weakly studied phenomena as pulsating auroras. More optimistic is the possibility to supplement with satellite observations studies of structures such as substorm westward traveling surge (*WTS*), diffuse glow undulation, omega-auroras, and other large-scale auroral forms.

Estimates show that when the width of the EISCAT radar beam is 0.5°, the transverse dimensions of the radar measurement region are approximately 1 km, which is ten times smaller than the dimensions of the uncertainty region. This circumstance makes the satellite support of radar measurements practically impossible.

The projection of the satellite into the ionosphere from zones 2 and 3 (see Fig. 2a) is conjugated with greater uncertainty than the projection from zone 1. As noted above, great uncertainty is caused by the influence of the current sheet of the magnetosphere tail on the shape of the field line. In these cases, additional information is required to correctly compare the satellite with the ionospheric object, [15, 16]. The results of a comparison of ionospheric phenomena in the northern and southern hemispheres should be critical [14].

CONCLUSIONS

The degree of the uncertainty that arises when mapping high-orbit satellites of the *Cluster* type into the ionosphere using three geomagnetic field models (T89, T98, and T01) was estimated. The choice of models was limited by the possibilities of the Orbit Visualization Tool software package (Swedish Institute of Space Research) used to calculate the geographical coordinates of the base of the field line on which the *Cluster* satellite is located. The quantitative characteristic of the uncertainty is the diameter of the region, the center of which is calculated as the arithmetic mean of the coordinates of the base of the satellite field line calculated using the above three models, and the radius is calculated as the distance from the center to one of the bases.

We analyzed the possibility of using the satellite data to study local ionospheric phenomena, such as auroras; artificial inhomogeneities, as well as the source of VLF waves generated during heating experiments; and ionospheric plasma parameters measured by the EISCAT radars. In addition, the probability of on-board detection of artificial low-friquency signal generated by the ground-based transmitter at the Kola Peninsula was also discussed. Studies have shown that uncertainty is minimal when, during the daytime, the satellite is above the equatorial plane of the magnetosphere at a distance of no more than 5 R_E from the Earth's surface and is projected into the ionosphere of the northern hemisphere. In this case, the area of the uncertainty region is about 50 km and the arbitrariness of the model choice for projecting does not play a decisive role in organizing satellite support for optical observations when studying large-scale phenomena, such as, e.g., *WTS*, as well as heating experiments at the EISCAT heating facility for the artificial modification of the ionosphere and the generation of artificial fluctuations of the VLF band. In all other cases, the uncertainty in determining the position of the base of the field line on which the satellite is located is large, and additional information is required to correctly conjugate the satellite with the object in the ionosphere.

The results of the study can find practical application in planning experiments on conjugation of satellites with heating facilities and injection of electromagnetic waves into the magnetosphere by a ground-based transmitter, radar, and optical observation campaigns.

ACKNOWLEDGMENTS

The input parameters for the Tsyganenko models calculated using the OMNIWeb database (http://omniweb.gsfc.nasa.gov/html/ow_data.html#contact) were submitted for free use by R. Denton and Zh. Qin (VIRBO, http://virbo.org). The OVT program was developed by K. Stasiewicz, M. Khotyaintsev, and Y. Khotyaintsev (Swedish Institute of Space Physics).

REFERENCES

1. Safargaleev, V.V., Sergienko, T.I., Safargaleev, A.V., and Kotikov, A.L., Magnetic and optical measurements and signatures of reconnection in the cusp and vicinity, *Phys.-Usp.*, 2015, vol. 58, no. 6, pp. 612–620.
2. Sergienko, T., Sandahl, I., Gustavsson, B., et al., A study of fine structure of diffuse aurora with ALIS-FAST measurements, *Ann. Geophys.*, 2008, vol. 26, 3185. doi 10.5194/angeo-26-3185-2008
3. Wright, D.M., Davies, J.A., Yeoman, T.K., et al., Detection of artificially generated ULF waves by the FAST spacecraft and its application to the "tagging" of narrow flux tubes, *J. Geophys. Res.*, 2003, vol. 108, 1090. doi 10.1029/2002JA009483
4. Figueiredo, S., Marklund, G.T., Karlsson, T., et al., Temporal and spatial evolution of discrete auroral arcs as seen by Cluster, *Ann. Geophys.*, 2005, vol. 23, pp. 2531–2557.
5. Farrugia, C.I., Sandholt, P.E., and Burlaga, L.F., Auroral activity associated with Kelvin–Helmholtz instability at the inner edge of the low-latitude boundary layer, *J. Geophys. Res.*, 1994, vol. 99, pp. 19403–19411.
6. Golovchanskaya, I.V., Kornilov, I.A., and Kornilova, T.A., East–west type precursor activity prior to the auroral onset: Ground-based and THEMIS observations, *J. Geophys. Res.*, 2015, vol. 120. doi 10.1002/2014JA020081
7. Liu, J., Angelopoulos, V., Frey, H., et al., THEMIS observation of a substorm event on 04:35, 22 February 2008, *Ann. Geophys.*, 2009, vol. 27, pp. 1831–1841.
8. Yahnin, A.G., Despirak, I.V., Lubchich, A.A., et al., Indirect mapping of the source of the fast plasma flow reversal in the magnetospheric plasma sheet onto the auroral display, *Ann. Geophys.*, 2006, vol. 24, no. 2, pp. 679–687.
9. Shevchenko, I.G., Sergeev, V., Kubyshkina, M., et al., Estimation of magnetosphere–ionosphere mapping accuracy using isotropy boundary and THEMIS observations, *J. Geophys. Res.*, 2010, vol. 115, A11206. doi 10.1029/2010JA015354
10. Zhang, Q.-H., Dunlop, M.W., Holme, R., and Woodfield, E.E., Comparison of eight years magnetic field data from Cluster with Tsyganenko models in the inner magnetosphere, *Ann. Geophys.*, 2010, vol. 28, no. 1, pp. 309–326.
11. Ober, D.M., Maynard, N.C., Burke, W.J., et al., Mapping prenoon auroral structures to the ionosphere, *J. Geophys. Res.*, 2000, vol. 105, no. A12, pp. 27519–27530.
12. Safargaleev, V.V., Shibaeva, D.N., Sergienko, T.I., and Kornilov, I.A., On the possibility of coupling satellite and ground-based optical measurements in the region of pulsating auroras, *Geomagn. Aeron. (Engl. Transl.)*, 2010, vol. 50, no. 7, pp. 873–879.

13. Blockx, C., Gérard, J.-C., Coumans, V., et al., A comparison between FUV remote sensing of magnetotail stretching and the T01 model during quiet conditions and growth phases , *Ann. Geophys.*, 2007, vol. 25, no. 1, pp. 161–170.
14. Sato, N., Wright, D.M., Carlson, C.W., et al., Generation region of pulsating aurora obtained simultaneously by the FAST satellite and a Syowa–Iceland conjugate pair of observatories, *J. Geophys. Res.*, 2004, vol. 109, A10201. doi 10.1029/2004JA010419
15. Kubyshkina, M.V., Sergeev, V.A., and Pulkkinen, T.I., Hybrid input algorithm: An event oriented magnetospheric model, *J. Geophys. Res.*, 1999, vol. 104, no. A11, pp. 24977–24993.
16. Aikio, A., Mursula, K., Buchert, S., et al., Vaivads, A., and Fazakerley, A., Temporal evolution of two auroral arcs as measured by the Cluster satellite and coordinated ground-based instruments, *Ann. Geophys.*, 2004, vol. 22, no. 12, pp. 4089–4101.
17. Amm, O., Aikio, A., Bosqued, J.-M., et al., Mesoscale structure of a morning sector ionospheric shear flow region determined by conjugate Cluster II and MIRACLR ground-based observations, *Ann. Geophys.*, 2003, vol. 21, pp. 1737–1751.
18. Tsyganenko, N.A., A model of the near magnetosphere with a dawn–dusk asymmetry. 2. Parameterization and fitting to observations, *J. Geophys. Res.*, 2002, vol. 107, no. A8. doi 10.1029/2001JA000220
19. Heppner, J.P., Liebrecht, M.C., Maynard, N.C., and Pfaff, R.F., High-latitude distributions of plasma waves and spatial irregularities from DE2 alternating current electric field observations, *J. Geophys. Res.*, 1993, vol. 98, pp. 1629–1652.
20. Tereshchenko, E.D., Khudukon, B.Z., Rietveld, M.T., et al., The relationship between small-scale and large-scale ionospheric electron density irregularities generated by powerful HF electromagnetic waves at high latitudes, *Ann. Geophys.*, 2006, vol. 24, pp. 2901–2909.
21. Frolov, V.L., Bakhmet'eva, N.V., Belikovich, V.V., et al., Modification of the Earth's ionosphere by high-power high-frequency radio waves, *Phys.-Usp.*, 2007, vol. 50, no. 3, pp. 315–324.
22. Piddyachiy, D., Inan, U.S., et al., DEMETER observations of an intense upgoing column of ELF/VLF radiation excited by the HAARP HF heater, *J. Geophys. Res.*, 2008, vol. 113, A10308. doi 10.1029/2008JA013208

Translated by N. Topchiev