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FAST SUBAURORAL DRIFTS OF IONOSPHERIC PLASMA ACCORDING TO DATA FROM YAKUT MERIDIONAL CHAIN OF STATIONS

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Abstract. Using long-term data from Yakut meridional chain of Yakutsk — Zhigansk — Batagay — Tixie ionospheric stations, we study ionospheric signatures of fast subauroral ion drift. Sharp drops or “falls” of critical frequencies (FCF) of the ionospheric F layer are shown to be one of the main signatures of the development of fast subauroral ion drifts near or at the zenith of the observation station. Comparison between long-term ground-based and satellite measurements indicates that there is good agreement between seasonal variation in the probability of occurrence of FCF derived from ground-based data and subauroral ion drifts derived from DMSP satellite data. Such a coincidence implies that both satellite and ground-based measurement methods register the same phenomenon in the boundary layers of the plasmasphere, namely, the appearance and development of electric fields of magnetospheric origin. The local time for recording of FCF derived from ground-based data is shown to closely coincide with the time of occurrence of subauroral polarization streams of plasma according to satellite data. We can therefore conclude that most of the observed FCF events derived from ground-based data refer to intense storms.

Keywords: subauroral ionosphere, meridional chain of stations, falls of critical frequencies, polarization jet.

INTRODUCTION

Narrow streams of fast subauroral ion drifts to the west near the projection of the plasmapause at heights of the ionospheric F-region most pronounced during storms and substorms generate considerable interest in the study of magnetosphere-ionosphere coupling. This phenomenon was first discovered from Cosmos-184 satellite data. We call it the polarization jet (PJ) [Galperin et al., 1973; Galperin et al., 1974]. In 1979, a paper was published which also reported on narrow and fast plasma motions in subauroral latitudes according to data from the Atmosphere Explorer C satellite [Spiro et al., 1979]. In this work, this phenomenon was called the subauroral ion drift (SAID). The terms PJ and SAID are still most commonly used to denote narrow and fast flows of ionospheric plasma directed to the west and observed in subauroral latitudes. In terms of magnetized plasma conditions, such a narrow band of fast westward drift at ionospheric F-region heights was identified with the development of a poleward local electric field at the equatorial boundary of the large-scale convection zone, which was detected by satellites in the same space-time interval [Smiddy et al., 1977; Maynard, 1978; Spiro et al., 1979; Maynard et al., 1980]. The plasma velocity in PJ may reach supersonic values (up to several kilometers per second) at F-region heights.

Many ground-based and satellite measurements of PJ show that it has a latitudinal extension from 100 to 200 km or 1°–2°, is observed mainly in the pre-midnight (18:00–24:00 MLT) sector and at invariant latitudes 55°–65°; the maximum plasma drift velocity in PJ may be as high as 4–5 km/s, but generally is ~1–1.5 km/s. The polarization jet has always been observed equatorward of the auroral electron precipitation boundary. It shifts to lower latitudes as geomagnetic activity goes up. A relationship of PJ with substorm activity and weak red arches has been identified [Stepanov et al., 2016].

Note that there is another term that is often used to describe PJ/SAID due to similar mechanisms of formation. Foster and Burke [2002] have introduced the term SAPS (subauroral polarization stream), which covers all phenomena of westward subauroral ion drifts (both narrow and wider in latitude, up to 10°) and their associated electric fields of magnetospheric origin. Thus, narrow bands of the westward drift (PJ/SAID) may be included into a larger structure of SAPS [Landry, Anderson, 2018].

The purpose of this paper is to analyze multi-year ground-based ionospheric data on sharp FCF of the F2 layer at subauroral latitudes according to data from the Yakut meridional chain of stations and to compare them with satellite measurements of SAID.

IONOSPHERIC DATA

We have used long-term ionospheric material obtained at the Yakutsk meridian chain of ionospheric stations. The chain is located at ~130° east longitude at L-parameters from 3.0 to 6.0 and consists of three main stations — Tixie, Zhigansk, and Yakutsk. For many years, it has been a system of three identical combined vertical and backscatter ionosondes spaced by ~600 km along the magnetic meridian. During field studies in 1968–1969 and 1973–1974, ionospheric parameters were also measured at Batagai (Table). The latitudinal position of all these stations covers almost the entire high-latitude ionospheric region and enables us to continuously monitor the structure and dynamics of the main formations in the auroral and subauroral ionosphere. The ionospheric stations Yakutsk (from November 2002 to August 2017) and Zhigansk (from November 2003) have been equipped with digital ionosondes DPS-4 [http://www.digisonde.com].

Table

	Station	Geographic coordinates		L-parameter	Invariant latitude, deg.
		Latitude	Longitude		
1	Tixie Bay	71.6	128.9	5.61	65.1
2	Batagai	67.7	134.6	4.3	61.1
3	Zhigansk	66.8	123.4	4.06	60.4
4	Yakutsk	62.0	129.8	3.05	56.0

The main ionospheric signature of occurrence or development of PJ near the zenith of the observation station is an additional trace of reflections on a vertical sounding ionogram, which is classified as F3s reflection [Shulgina, 1974]. This PJ signature determined from simultaneous satellite and ground-based observations is described in detail in [Reshetnikov et al., 1987; Galperin et al., 1990; Stepanov et al., 2017]. Such sporadic traces are located at a greater distance than those from the regular F2 layer and have lower critical frequencies than the frequency of the regular background F2 layer (Figure 1). During PJ development there may be short-term partial or total absorption of radio waves; the PJ phenomenon may often occur with auroral sporadic E_{sr} and E_{sa} layers. The occurrence of PJ is often followed by the development of a lacuna, which is characterized by the disappearance of reflections in a frequency band on an ionogram, with practically no absorption increase observed. After appearances of sporadic traces on ionograms, critical frequencies of the background F2 layer generally start to decrease rapidly, i.e. within 15–45 min after recording the additional traces the frequencies decrease by 2–4 MHz or more.

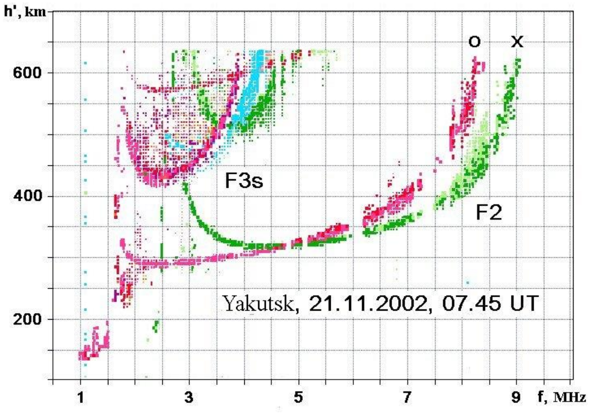

Figure 1. Additional characteristic reflection (F3s) on a vertical sounding ionogram, recorded at the station Yakutsk on November 21, 2002 at 16:45 LT — ionospheric signature of PJ development at the zenith of the observation station

Further, in most cases the ionograms exhibit conditions A (F layer shielded by an underlying layer) or B (total absorption of radio waves), which together with the main ionospheric parameters are seen on the so-called daily f-graphs [Rukovodstvo, 1977]. Thus, FCF is well-defined in the standard processing of ionospheric data. In our work, it is one of the main criteria for selecting events. Examples of the daily variations with FCF of the F2 layer obtained from f-graphs of the stations are given in Figure 2.

Hence, data on the presence or occurrence of PJ near or above the observation station at 14:00–24:00 MLT was selected according to the presence of FCF on daily f-graphs from the ionospheric stations. This facilitates data selection. Note that we have used only the data that has already been processed by the standard method and is stored in the library data archive of the Institute. When selecting an event, we fixed the station name, year, month, date, and local time of the beginning of FCF in the F layer.

It should be noted that we omit atmosphere-ionosphere interactions in the form of negative ionospheric disturbances in our work because we believe that FCF effects are short-term and occur due to geophysical factors during magnetic storms and substorms.

For the station Yakutsk, we have analyzed ionospheric data acquired from1955 to 2015 (a total of about 60 years or 594 months). For the analysis, we have selected 744 FCF events of PJ signatures. For the station Batagai, we have analyzed data for 1968–1969 and 1973–1974 (a total of about 27 months). We have selected 56 FCF events for the analysis. For the station Zhigansk, we have analyzed data for 1976–1979 and 1984 (a total of about 54 months). We have selected 116 FCF events for the analysis. For the station Tixie, we have analyzed data for 1965–1972, 1976–1982, and 1985–1994 (a total of 231 months). We have found 631 FCF events for the analysis.

The total number of FCF events selected from data from the ionospheric stations of the Yakut meridional chain is 1547. Note that the periods without ionospheric data in the processed sets are insignificant and largely attributed to breakdowns and repair of the sounding stations as well as scheduled maintenance or other works in the ionospheric stations. The geophysical factors affecting reflection shielding and absorption of radio waves at the high-latitude stations also greatly contribute to the absence of ionospheric data.

ANALYSIS OF GROUND-BASED MEASURMENTS

One of the key questions for any array of geophysical data is the question about the occurrence (probability) frequency of the phenomenon under study depending on geomagnetic conditions, location of observation stations, local time, etc. After normalizing the data, as the number of obtained and analyzed FCF events varies considerably among the stations, it becomes apparent that the frequency of FCF recording increases from low to high latitudes, i.e. the probability of observation of PJ signatures at the station Tixie is higher than at the stations Zhigansk–Batagai

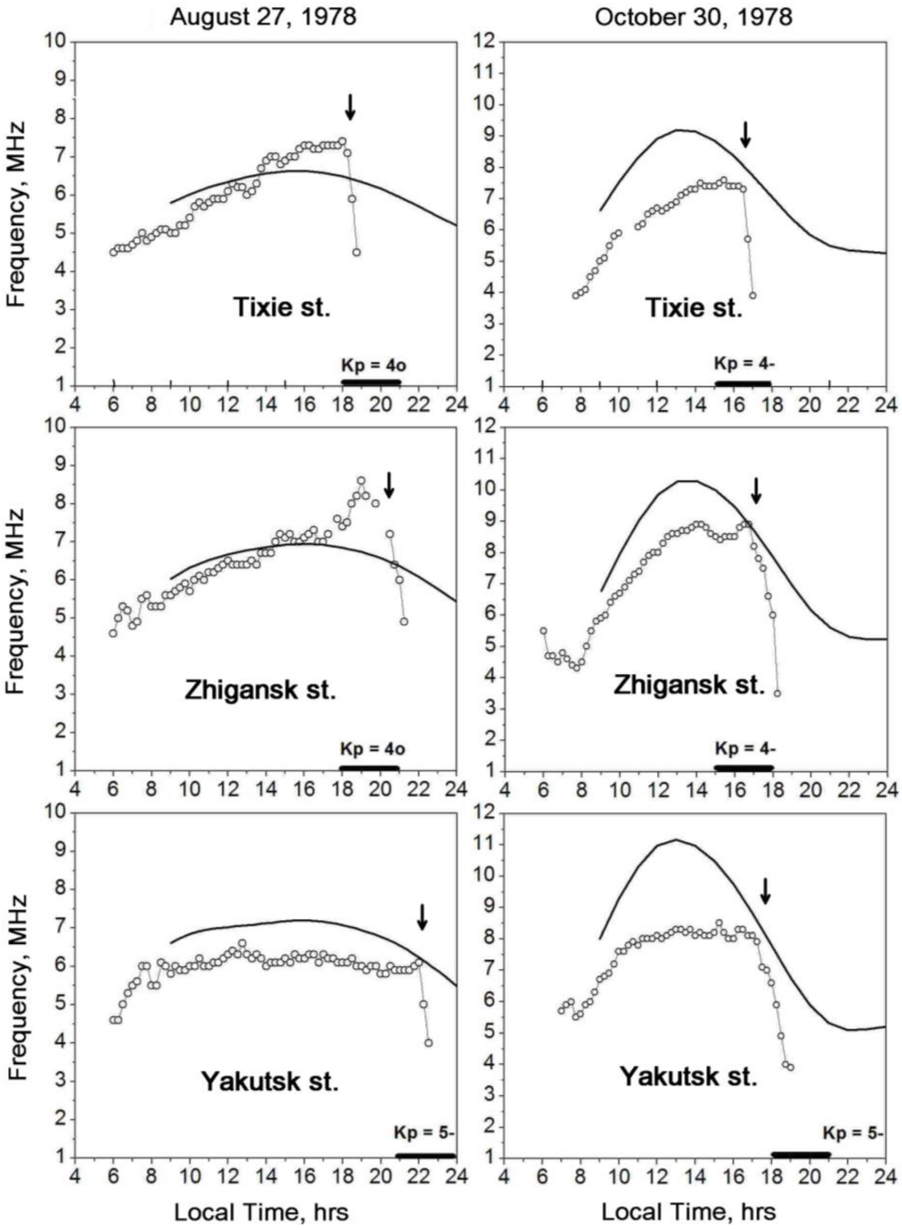

Figure 2. Falls of critical frequencies f_oF2 derived from measurements made at the meridional chain of ionospheric stations Tixie–Yakutsk–Zhigansk on August 27 and October 30, 1978. FCF moments are indicated by arrows. Light circles mark the course of critical frequency; curves show results of calculation of f_oF2 made at the corresponding station using the International Reference Ionosphere IRI-2016; arrows indicate moments of sharp FCF

(data from the stations is combined into one dataset due to their close location in latitude) and Yakutsk. It also becomes apparent that the mean K_p index, at which FCF events are most frequently recorded at the observation stations, increases when they shift to low latitudes. Figure 3 shows the number of FCF observations by months total and separate for the stations. We can see that the occurrence probability of FCF is higher in equinox months (March–April, September–October), and significantly lower in summer and winter months.

Figure 4 on the left in polar coordinates displays the intensity of FCF occurrence probability depending on the local time and invariant latitude; on the right, the intensity of FCF distribution depending on geomagnetic activity and invariant latitude.

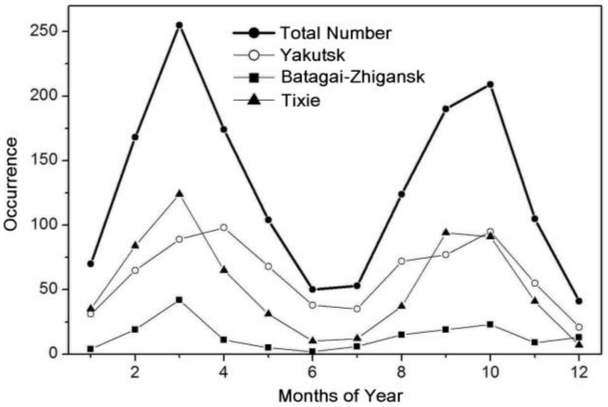

Figure 3. Seasonal course of FCF observations from ionospheric data

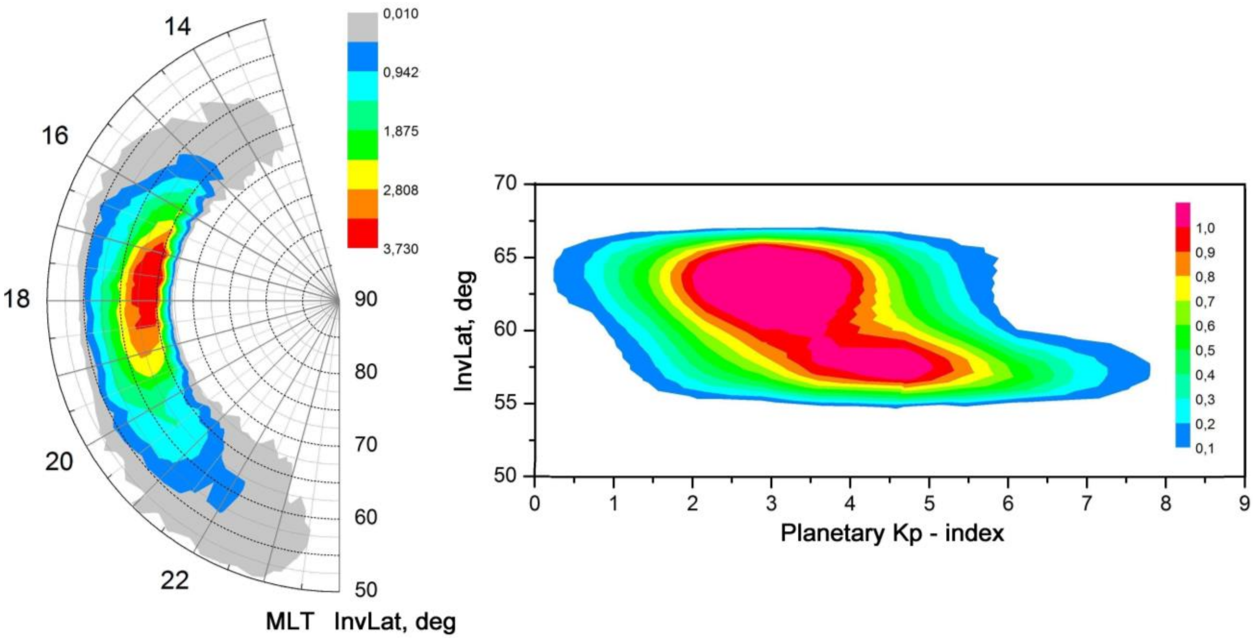

Figure 4. Intensity of FCF occurrence frequency (left) and distribution depending on geomagnetic activity level (right)

It is evident that FCF events from ground-based ionospheric data are mainly recorded during early evening hours (17–19 MLT). With increasing geomagnetic activity, the maximum intensity of FCF occurrence shifts from high to low invariant latitudes.

RESULTS AND DISCUSSION

Using multi-year satellite data, He et al. [2014] have first investigated solar-cyclic, seasonal, and daily variations of SAID. The observations were carried out by DMSP F8-F18 satellites in 1987–2012. The DMSP satellites worked in Sun-synchronous orbits at a height of ~800 km with inclinations of ~99°, and orbital periods of ~100 min. In their study, the authors use the term SAID. The criteria for determining SAID from satellite data are as follows:

– peak horizontal velocity exceeds 1000 m/s;

– width is less than 4°;

– event is located equatorward of the auroral zone in the evening and midnight sectors;

– polar wall of westward ion drifts coincides or abuts upon the equatorial boundary of precipitating electron fluxes.

Using these criteria, the authors have found 18226 SAID events for 26 years of work under the DMSP program. It is currently the largest satellite PJ/SAID database.

The most important result of the comparison between ground-based and satellite measurements is that seasonal variations in the frequency SAID and FCF recording are in close agreement with maxima in equinox months and minima in winter and summer months. This result (Figure 5, *a*) clearly indicates that both ground-based and satellite methods of measurements record the same phenomenon near the plasmapause boundary, which is projected on subauroral latitudes along field lines. Figure 5, *b* shows the normalized distribution of SAID occurrence probability (bar graph), which exhibits a maximum at ~21:15 MLT.

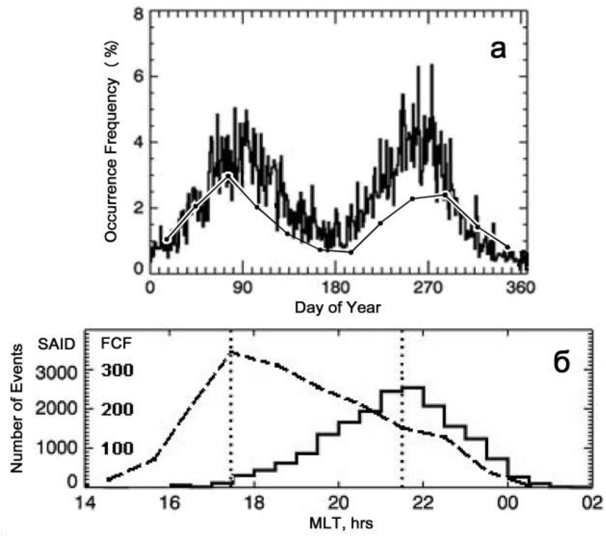

Figure 5. Comparison between ground-based and satellite data: *a* – seasonal course of FCF frequency from ground-based data (black dots) and SAID occurrence frequency; *b* – time of recording of FCF (dashed line) and SAID from DMSP data

Observation time is from 16:00 to 02:00 MLT. Averaged ground-based measurements of FCF events (dashed line) in the interval from 14:00 to 01:00 MLT yield a maximum of FCF recording at ~17:30 MLT, which is almost 4 hrs earlier than that according to satellite observations. Such a large discrepancy in time gives rise to many questions about mechanisms and factors of occurrence and development of PJ, SAID, and SAPS, implying that there are other factors affecting just the location and local magnetic time of fast subauroral flows of ionospheric plasma.

He et al. [2017] using DMSP satellite data report results of the study of SAPS during intense storms ISs (37 events) and quiet time substorms QSs (30 events). To IS the authors assign storms that have minimum *Dst*< –100 nT; to QS, substorms that have maximum *AE*>500 nT and maximum *Dst*<10 nT throughout the day. The paper also analyzes data on the interplanetary magnetic field, solar wind dynamic pressure, *Dst* and *AE* variations. Characteristics and parameters of SAPS are shown to differ during development of intense storms and quiet time substorms. One of the major differences is the time of SAPS occurrence — under highly disturbed conditions SAPS occurs in early evening hours (17–19 MLT). In Figure 6, the top panel shows the normalized frequency of SAPS occurrence during ISs (outer left Y-axis) and the local magnetic time of FCF occurrence derived from ground-based ionospheric data (dots connected by a line and the number of events along the inner left Y-axis). The bottom panel shows the normalized time of SAPS occurrence frequency during QSs. It is evident that the time of FCF occurrence from ground-based data closely coincides with the time of SAPS occurrence from satellite data during intense storms. Thus, we can conclude that most observed FCF events from ground-based data are assigned to ISs, as they are defined in [He et al., 2017].

CONCLUSIONS

From the analysis of a large array of ground-based ionospheric data and their comparison with satellite data we can draw the following conclusions.

1. We have shown that FCF observed on f-graphs is an ionospheric signature of the development of fast SAID to the west, convenient for the real-time analysis of archive data from ground-based ionosondes.

2. The seasonal course of SAID occurrence frequency from satellite data and the seasonal course of FCF occurrence frequency from ground-based measurements demonstrate identical variations: maxima in equinox months and minima in summer and winter months. This qualitatively confirms that both satellite and proposed ground-based measurement methods record the same phenomenon in boundary regions of the plasmasphere — the occurrence and development of electric fields of magnetospheric origin.

3. The local magnetic time of FCF recording from ground-based data has been demonstrated to coincide with the time of SAPS recording from satellite data during intense storms. Hence, most observed FCF events according to ground-based data occur during intense storms as they are defined in [He et al., 2017].

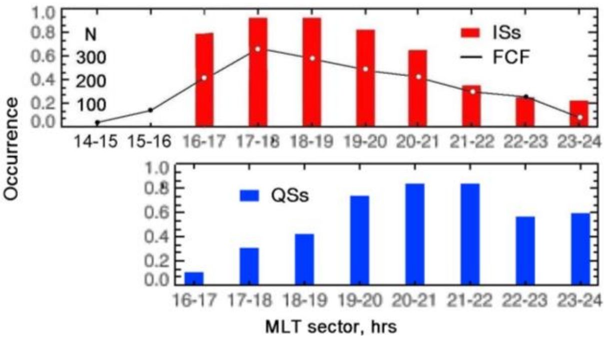

Figure 6. Local magnetic time of FCF from ground data (dots) and normalized occurrence of SAPS during intense storms from DMSP data (bars)

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